FIELD TEST ENVIRONMENT FOR LVDC DISTRIBUTION – IMPLEMENTATION EXPERIENCES

Tero KAIPIA, Pasi NUUTINEN,
Antti PINOMAA, Andrey LANA,
Jarmo PARTANEN
Lappeenranta University of
Technology – Finland
tero.kaipia@lut.fi

Juha LOHJALA
Suur-Savon Sähkö Ltd. – Finland
juha.lohjala@sssoy.fi

Mika MATIKAINEN
Järvi-Suomen Energia – Finland
mika.matikainen@sssoy.fi

ABSTRACT

Low-Voltage Direct Current (LVDC) distribution network is a novel approach to the LV distribution. This paper presents the practical experiences from the implementation of a field environment research platform for ±750 V LVDC electricity distribution system in actual distribution network environment. The paper illustrates the main design of the field test environment as well as the challenges encountered during the construction and commission of the platform. The main objectives in the work have been to realise a real environment test bed for the development of the LVDC technology for public electricity distribution (utility networks), to determine the major gaps in the national standardisation and in the availability of components, and to gain knowledge of the different phases of the implementation process itself.

INTRODUCTION

The benefits of using modern power electronics based distinct LVDC distribution systems in different applications are presented in numerous scientific articles, but the amount of practical experiences from implementation of LVDC system have been limited so far. Most of the published experiences concern implementation of LVDC in data centres, that is, completely different application environment compared to public electricity distribution. Gathering, analysing and sharing the practical experiences of all applications is, however, equally crucial for the development of the LVDC equipment, design methods and system standardisation.

The introduced LVDC field test environment is a part of the local distribution network owned by a Finnish energy corporation Suur-Savon Sähkö Ltd. (SSS Ltd.) and operated by its subsidiary distribution company Järvi-Suomen Energia Ltd. The platform has been realised in collaboration with Lappeenranta University of Technology (LUT) as a part of the Finnish national *Smart Grids and Energy Markets* research program.

The SSS Ltd. was a pioneer in the utilisation of the 1 kV AC LV distribution in Finland [1] and has long traditions in research collaboration with the LUT. The development of the LVDC network was started 2005 in Finland [1-2] and the SSS Ltd. has been involved since 2006. After profound theoretical studies and experiences gained in laboratory environment, the planning of the introduced field test environment was started in January 2010.

The global interest towards LVDC distribution has increased rapidly during past years. An indication of this is, for instance, the foundation of the IEC LVDC strategy group (SG 4) in year 2009, to guide the development of LVDC standardisation. The IEC SG 4 has recommended that the standardisation of LVDC systems should be done by application areas based on market needs and availability of practical experiences. Thus, wide ranging practical experiences are needed.

Realisation of the actual network environment research platform enables verification and development of system design principles, equipment structures and installation techniques. Most importantly, information of the suitability of power electronics into harsh distribution network conditions is gained.

LVDC DISTRIBUTION CONCEPT

In the utility networks, the LVDC system replaces the present-day 400 V low voltage AC networks and also lateral parts of the medium voltage network. The opportunity to use of the up to 1.5 kV DC voltage and power electronic voltage conversions instead of the maximum 1 kV AC voltage and traditional transformers significantly increases the technical performance of the low voltage distribution. From the DSO perspective, the LVDC technology and the converters in the system (1) provide means to improve the power quality and supply security experienced by the electricity end-users, (2) improve the economy of the power distribution, (3) provide platform for flexible integration of small scale renewable generation and energy storages, and (4) form a infrastructure for intelligent network management and electricity market functionalities. The economical benefits are case sensitive, but roughly saying, the LVDC becomes a profitable alternative to the common Finnish rural area 20/0.4 kV AC network structures when the transmission distance is over 1 km.[2] Fig. 1 illustrates the principled structure of an active LVDC electricity distribution system.

The LVDC system is recommended to be constructed as terrain isolated (IT) underground cabled system due to electric safety reasons [3]. The common LV underground power distribution cables are also rated for DC use. An underground cabled network is less vulnerable to weather phenomena than overhead line network that reduces, for instance, the number of equipment failures due to lightning overvoltages. Underground cabling has also other benefits discussed later in this paper.

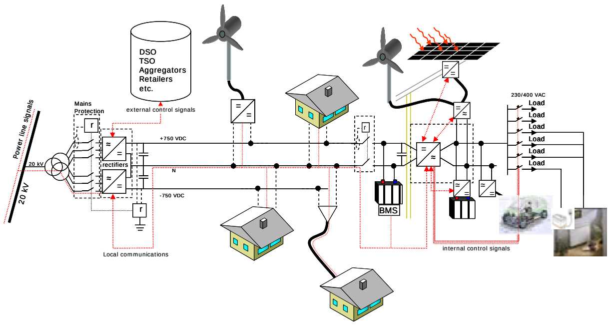

Fig. 1 Principled structure of an active LVDC electricity distribution system.

FIELD TEST ENVIRONMENT

The field test platform design has to combine the requirements of the fully functional distribution system with the requirements of a flexible research platform. From the converter technology perspective, ability to test different converter structures and their operation in non-ideal ambient conditions are the main goals. Interconnection of energy storages and generation into different parts of the LVDC network, and island operation of the system has also been raised as important research questions. Furthermore, the opportunity to test novel network protection functions and interactive customer gateway functionalities has been considered important.

In selection of the system structures, the most important design criteria were to enable realisation of the platform by applying existing and commercially available network components, to ensure electric safety in all situations, and to realise the setup so that no changes are required within the end-users' electric installations. No deterioration in the electric safety was allowed compared to the existing AC installations. The installations are designed according to the national low voltage standard series SFS 6000 based on HD 60364, IEC 60364, IEC 60664. The EN 50160 standard was used as a basis for the voltage quality requirements, but some limit values were altered.

System engineering

Converting an existing 1 kV supply area [1] into LVDC use was considered to offer the best available test site, as the 1 kV AC and the LVDC applications in rural networks are quite similar. The basic criteria in selecting the topology and the location were:

- The field platform should be a part of actual distribution network
- There should be opportunity to connect at least two household customers with their own CEIs into the DC mains
- The length of the DC mains should be on the economical application range of the LVDC system (~over 1 km)
- The location should be accessible
- The customers connected should unanimously agree to participate into the research

The basic topology of the realised field test setup is presented in Fig. 2 and the main technical design criteria in Tab. 1.

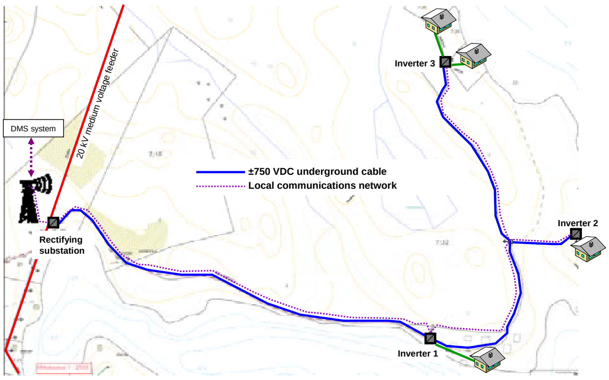

Fig. 2 Field installation of the LVDC distribution system

The main structure of the system follows the basic concept of public LVDC distribution system.The realised LVDC installation comprises of a 100 kVA rectifying substation, a 1.7 km long underground cabled ±750 VDC network and, at the moment, three customer-end inverters (CEI) responsible for providing 230/400 V AC voltage supply for the four end-users. The setup includes an ICT system for control and supervision of the network and the converters, as well as, a protection system realised based on principles presented in [3]. The system is fed from the 20 kV medium voltage network through double-tier converter transformer. The LVDC network is realised as unearthed system (IT). Fig. 3 illustrates the main power circuit connections.

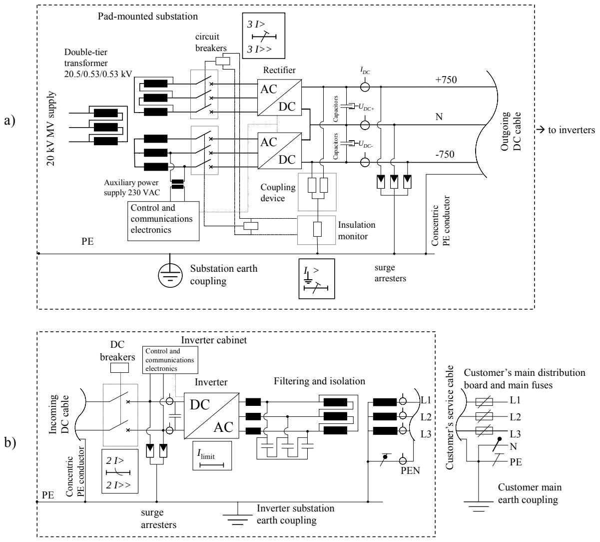

Fig. 3. Schematic diagrams of the main power circuits of the field test platform; rectifying substation (a) and inverter substations (b)

Typical PVC insulated underground cables are used. The cables have three colour-coded aluminium phase conductors and a concentric copper PE conductor. The concentric PE conductor connects together the earth electrodes of rectifying substation and CEI cabinets. This arrangement reduces the EM radiation caused by CEI. The cables are dimensioned for 1/0.4 kV AC use, which means that the cross sections are at least enough for the DC use.

Tab. 2 presents the connection of the cable conductors in AC and LVDC use. The idea was to maintain the same colour order of conductors in bus bar connections in the LVDC as is used in AC systems.

Tab. 1 Technical design criteria

Parameter	Value
Earthing	
- DC	IT
- End-user installation	TN-(C)-S
Supply transformer	3-phase double-tier 50 Hz transformer
- Nominal power	100 kVA
- Connection	Dd0y5
- Ratio	20.5(±2x2.5%)/0.53/0.53 kV
- Impedance	4 %
Rectifier	12-pulse half controlled thyristor bridge
- Nominal power	100 kVA
- short circuit capacity	>2 kA
- DC voltage	$U_N = \pm 750$ VDC
- Variation	+ 10 %, -20 % during normal operation - 30 % during MV supply interruptions (island operation)
- Distortion	Pulsation max 10 % , no THD limit
- Measurements	
- voltages	AC supply, DC+ and DC-
- currents	DC+, DCN, DC-
-temperature	Ambient, thyristor
CEI	3-phase IGBT six-pack module
- Nominal power	16 kVA
- short circuit capacity	250 A RMS, 5 seconds
- Output AC voltage	$U_N = 230/400$ V
- Frequency	50 Hz ± 0.2 %
- Variation	± 1 % within measurement and control accuracy during normal operation -15 % during MV supply interruptions (island operation)
- Distortion	THD_{max} 5 %
- Isolation transformer	3-phase 50 Hz dry-transformer
- Nominal power	16 kVA
- Connection	Dyn11
- Ratio	400/400
- Impedance	<4 %
- Measurements	
- voltages	AC phase voltages, DC supply
- currents	DC supply, AC phase and neutral (high and low bands), AC residual current (L1-3+N)
-temperature	Ambient, IGBT

Tab. 2 Colour coding of cable conductors in different LV systems (with commonly used earthing scheme).

Colour	AC use *)		LVDC use (IT)
	1 kV (IT)	0.4 kV (TN-C)	
Brown	L1	L1	Minus(-) pole
Black	L2	L2	Middle(M/zero)
Light grey/white	L3	L3	Plus(+) pole
Concentric	PE	PEN	PE

*)According to standard SFS 6000-5-52

The DC mains have relatively large capacitors that act both as smoothing capacitors and energy storages. The capacitors are divided between the CEIs and the rectifier. All the reactive power demand at customer-end is satisfied by the CEI capacitors; only the active power demand is transmitted through the DC cables. The DC capacitors are dimensioned to store enough energy for short period (~0.5 s) island operation of the system with average load level. This aims on riding through the short un-energised time due to transient MV faults cleared with the high-speed auto-reclosures without interruptions in customers' supply.

The electric safety is ensured by using both traditional relay protection and protections integrated into the converters as a back-up. The protection system composes of the mains circuit breakers and the insulation monitor relay, located at the rectifier substation, and of the DC circuit breakers located at each CEI. Moulded case breakers with internal overcurrent relays are used. The main breakers are typical 1 kV AC breakers also familiar from industry. The DC circuit breakers are originally designed for photovoltaic power plants, but due to their high enough DC rating and good breaking capacity they are suitable for power distribution purposes too. The insulation monitor relay gives an external trip signal for the main breakers if the insulation resistance drop under standardised minimum value 1 MΩ.

The converters have been designed especially for the field test platform and assembled at LUT. Thus, it has been possible to realise the converters without any limitations due to prior design for a commercial application. Moreover, realisation of the converters from scratch provided an exceptionally good learning opportunity for the whole research team.

The converters are not protected against variable ambient conditions with any special arrangements. For instance, the humidity and the temperature in the installations are not controlled. The idea has been to test how the used electronics withstand the typical distribution network conditions. However, attention has been paid in selection of individual electronic components; for instance, the ambient temperature range of the components is selected as wide as possible and the most crucial circuit boards are protected against corrosion and moist by lacquering.

The rectifier was wanted to be kept as simple as possible. The core of the rectifying substation is the 100 kVA half-controlled 12-pulse thyristor bridge rectifier supplied with double-tier transformer. The rectifier output voltage is controlled with the thyristors only during the system start-up in order to limit the charging currents of the large DC capacitors.

The CEI are connected either to plus or minus pole of the DC mains. The connection has been selected based on load curve based system losses calculations so that DC mains losses are minimised. Due to existing cabling, both DC poles are however available at CEI, so the connection can be changed if needed.

The three-phase CEIs are based on common 330 A RMS IGBT six-pack switch modules that feed the 16 kVA bulky 50 Hz galvanic isolation dry transformers. According to the Finnish LV standardisation the recommended single phase short circuit current in the customers' connection points should be above 250 A RMS to ensure fast enough operation of the typical fuses and circuit breakers in the in-house networks. The short circuit current in the secondary of the isolation transformers is limited with the inverter control to prevent IGBT faults. Together with the residual current measurement the CEI also acts as back-up protection against faults in end-users installations.

Due to the galvanic isolation and the short circuit current capacity, the end-users installations can remain fuse-protected TN-(C)-S systems. The isolation transformers provide a neutral connection for single phase loads. The galvanic isolation also protect against hazards due to simultaneous DC and AC earth faults and reduces the common-mode voltages typical for inverter fed systems.

The CEI are in key role as they form the AC voltage used in supply of customers' loads and set limits for the voltage variation allowed in the DC mains. The control of the CEI has been discussed in many publications, most importantly in [4]. The control electronics of the CEI have been designed to provide flexible platform for the development of control algorithms. The control board is designed to enable single-phase or three-phase CEI control. Therefore, different CEI structures can be implemented with same control electronics.

At the moment, a voltage droop has been implemented into CEI control. If the DC-voltage drop below 80 % of the nominal, the customer's AC voltage is reduced accordingly up to 15 % from nominal. If the DC voltage drops more than 30 % the CEI will stop. The CEIs also enable external relay or contactor control, which makes, for example, load control or controlled circuit breaker operation possible. The converter setups are discussed detailed in [5].

For the system level control and supervision, each converter has an embedded PC that is connected via optical fibre network to the rectification substation using an IP-based protocol. The rectifier-end PC is the master controller of the whole system. The physical architecture of the ICT system is illustrated in Fig. 4. The communications from to the remote control web-portal is established either with ADSL connection or with back-up 3G wireless connection. The system can also be connected with a commercial SCADA system.

The ICT system is designed for enabling the development of communication-based network protection algorithms as well as for implementing the interactive customer gateway functionalities.

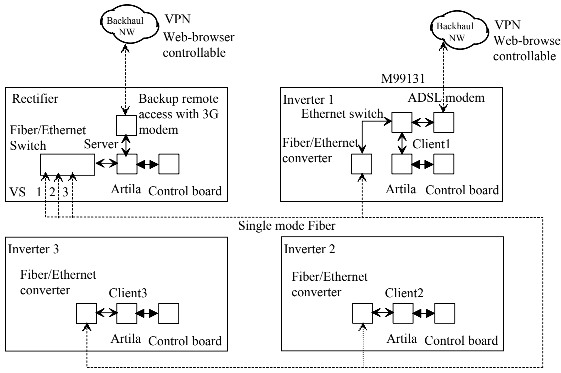

Fig. 4. The physical architecture of the communications network and the information system

EXPERIENCES SO FAR

A field test platform for LVDC distribution has been successfully implemented. The commission tests are still unfinished, but so far all the tested basic functionalities have worked properly.

The conformity to IEC 61000-series EMC standardisation has not yet been validated. Especially the emissions of the CEIs, both radiating and conductive, measured from the DC mains may exceed the recommendations. However, as a precaution there are filters for conductive common mode high frequency interferences and the used cable type reduces radiating emissions.

The JSE Ltd. has interviewed the involved customers. The customers' attitude towards the tests has mainly been positive, however also concerns of the possible hazards to end-use appliance have been raised.

The research team is working together with the Finnish electric safety authority and the Finnish national standardisation organisation. The goal is to compile a document presenting the standardisation needs of the LVDC distribution system. A special concern is the rating of all LV installation equipment for DC use.

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