EXPERIENCES FROM USE OF AN LVDC SYSTEM IN PUBLIC ELECTRICITY DISTRIBUTION

Pasi NUUTINEN, Tero KAIPIA,
Pasi PELTONIEMI, Andrey LANA
Antti PINOMAA, Pasi SALONEN,
Jarmo PARTANEN
Lappeenranta University of Technology
Finland
pasi.nuutinen@lut.fi

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

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

ABSTRACT

Experiences from the field setup of utility grid low voltage DC (LVDC) distribution are discussed. LVDC distribution being a novel approach to public electricity distribution, a research platform is realised to enable practical studies. The goal of the setup is to combine the requirements of the fully functional LVDC system and a flexible research platform. The scope of the paper is to discuss experiences from first six months of continuous use of the setup. The paper focuses on comparing how expected and realised results meet and how the setup has been operating in real public network. On the other hand, design flaws and challenges are covered. Finally, future research tasks and the development of the setup towards LVDC smart grid are presented.

INTRODUCTION

Need to conduct practical studies concerning LVDC distribution has been one of the most important drivers for realising the on-site research platform into the public electricity distribution network, operated by the distribution system operator (DSO) Järvi-Suomen Energia Ltd (JSE) and owned by the energy corporation Suur-Savon Sähkö Ltd (SSS). 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 (SGEM) research program. The components of the setup are a 100 kVA rectifying substation supplied with double-tier transformer directly from the 20 kV medium voltage network, a 1.7 km long underground cabled bipolar ±750 V DC network and three 16 kVA customer-end inverters (CEIs) supplying end-users. In Fig. 1, components of the setup are located on the map. The structure, specifications, and implementation of the setup are discussed in [1] and [2].

SETUP REQUIREMENTS

Before the setup was introduced, it was inspected to ensure safety of the electricity end-users and proper functioning of all equipment [1]. Also, CEI functions, control and voltage quality were thoroughly verified in the laboratory [3],[4]. Because the CEIs in the setup are supplying actual customers, electrical safety requirements defined by the standard SFS 6000-6 have to be met. The protection devices of the setup are commercially available ones and rated for this use and the CEIs include several protection functions, which are implemented to prevent both hazardous or harmful customer-end voltages and equipment failures. Because the customer-end network is protected using fuses and circuit breakers (CB), the CEI has to supply adequate short-circuit current for the devices. The current has to be, however, limited to prevent power electronics failures. The short-circuit operation and control is discussed in [3].

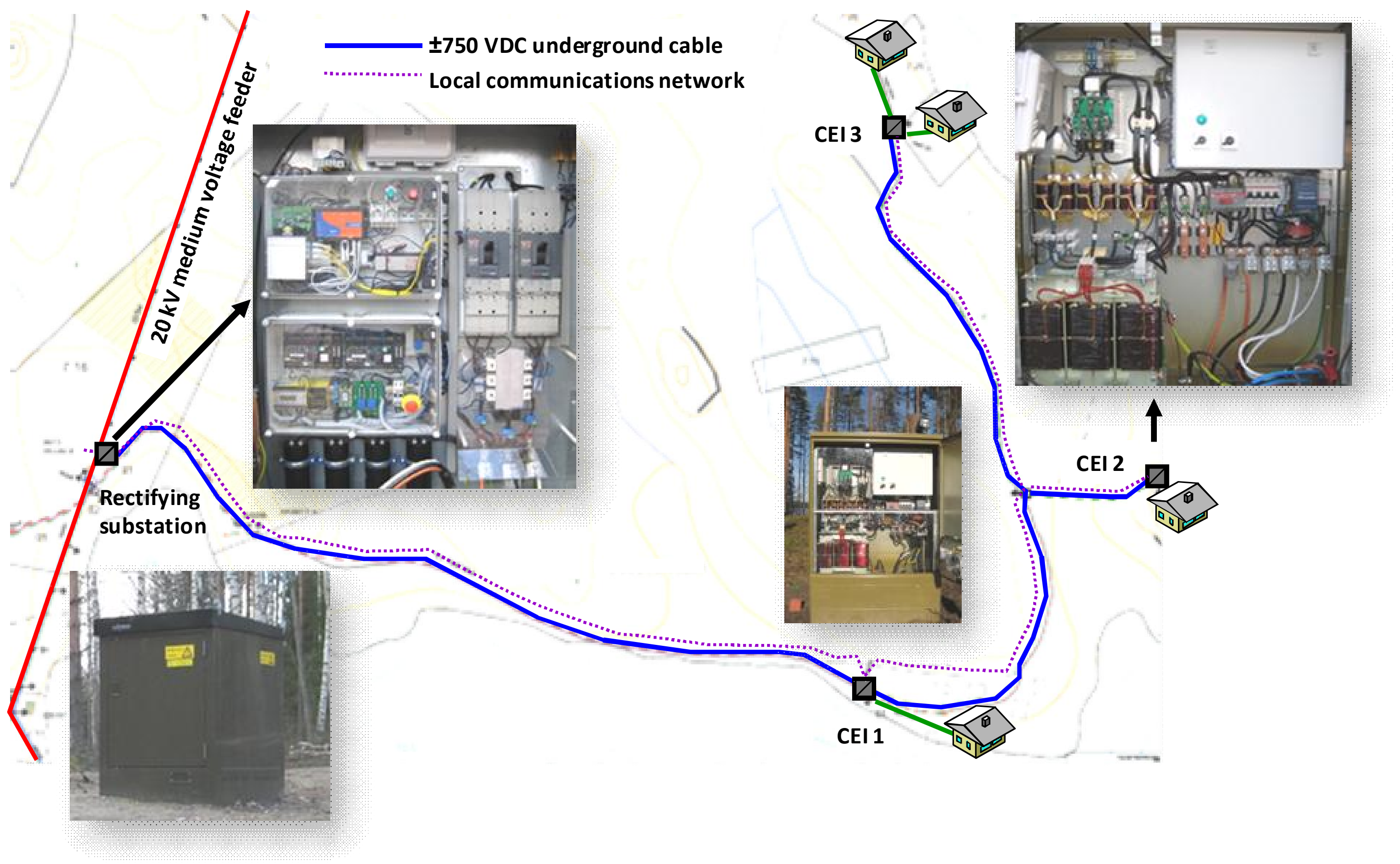


Fig. 1 The LVDC research setup components located on the map.

Customer-end voltage quality

With power electronics, voltage quality requirements can be tightened and therefore, following values were used in design and control

- Frequency: 50 Hz ± 0.1 %
- Voltage level: 230 V ± 1 %
- Harmonic distortion (THD): < 3 %.

Voltage quality of the first CEI was verified in the laboratory with various single-phase and three-phase loads. The control of the output voltage is based on phase voltage measurements only [4]. In addition, current measurements are used to detect short-circuit situations and to control current in short-circuit current supply mode. Because of tightened ± 1 % voltage level requirements, additional voltage unbalance correction is required. Without it, unbalance could be as much as ± 4 % in worst case, such as when a single phase is at nominal load while no load is applied to other phases. However, the voltage error is > 1 % in some operation points and when the load unbalance increased, voltage error reached 2 % values. However, additional voltage unbalance correction helps to reach ±1 % demand in most operation conditions. The voltage unbalance correction and the short-circuit detection will be discussed in future publications.

Remote supervision, management, and fault recognition

Because the setup is located tens of kilometers away both from JSE network control centre and LUT, web-based remote supervision and management portal was developed. Remote control, logging of various measurement data, display of current and voltage waveforms and logging of fault codes are made available with the portal. Fig. 2 presents the measurement data in the portal. In addition, other pages include remote controlling of the setup, waveform recording for fault and transient diagnostics, and graphical visualization of the AMR measurements for 24 h and 1 h timeframes. The web portal will be studied in more detail in a publication available later this year. Also, the setup includes fault ride-through (FRT) features that enable self-healing after faults, if it is possible, to minimise long interruptions in fault situations. In Tab. 1, recognizable faults situations, fault code definitions, and following actions of the CEI after the fault are presented. It can be seen that restarting the CEI is the first action after the fault and shutdown is the last option if the fault could not be cleared. There are, however, some faults that require immediate shutdown to prevent equipment failures and possibly hazardous situations.

OPERATION EXPERIENCES

The setup has been in continuous operation for 5000 hours. The most interesting issues are the customer-end power quality, operation in special situations, and the effects of weather conditions on the system operation and reliability. With web portal, this information was always available and there was no need to visit the setup site.

Operating conditions

One question was how the weather and the air humidity affects the system operation, because the outside temperature could change between -35 °C and +35 °C, and rough weather conditions affect directly to conditions inside the uninsulated cabinets. In the actual network, the power consumption is usually higher, when the temperature is low. Also, the nominal power is used rarely and durations are short. The cooling of the CEI is not designed to be sufficient with nominal load on a warm summer day but secondly, it is too powerful on cold days. Therefore, the cooling fans are controlled to keep the IGBT temperature at 50 °C and the cabinet temperature between 12-35 °C depending on weather conditions. To prevent IGBT overtemperature shutdown (fault code #26), the switching frequency is decreased by two steps if the IGBT temperature rises too high. However, the highest reached IGBT temperature was under 70 °C and the cabinet temperature under 45 °C (fault code #27) during operation time between June and December.

Climatic overvoltages

The system is equipped with surge protectors located on both rectifier and CEI side. Still, the effect of the climatic overvoltages was unknown. After 1 month of operation, a thunderstorm caused several interruptions, auto-reclosings, and both short-term and long-term DC network overvoltages (Fig. 2, fault codes #7 and #24). However, commercial ADSL modem was the only equipment that failed. Though this is a pilot setup, it verified that the LVDC system with power electronics could stand climatic overvoltages if it is properly designed.

Quality of supply

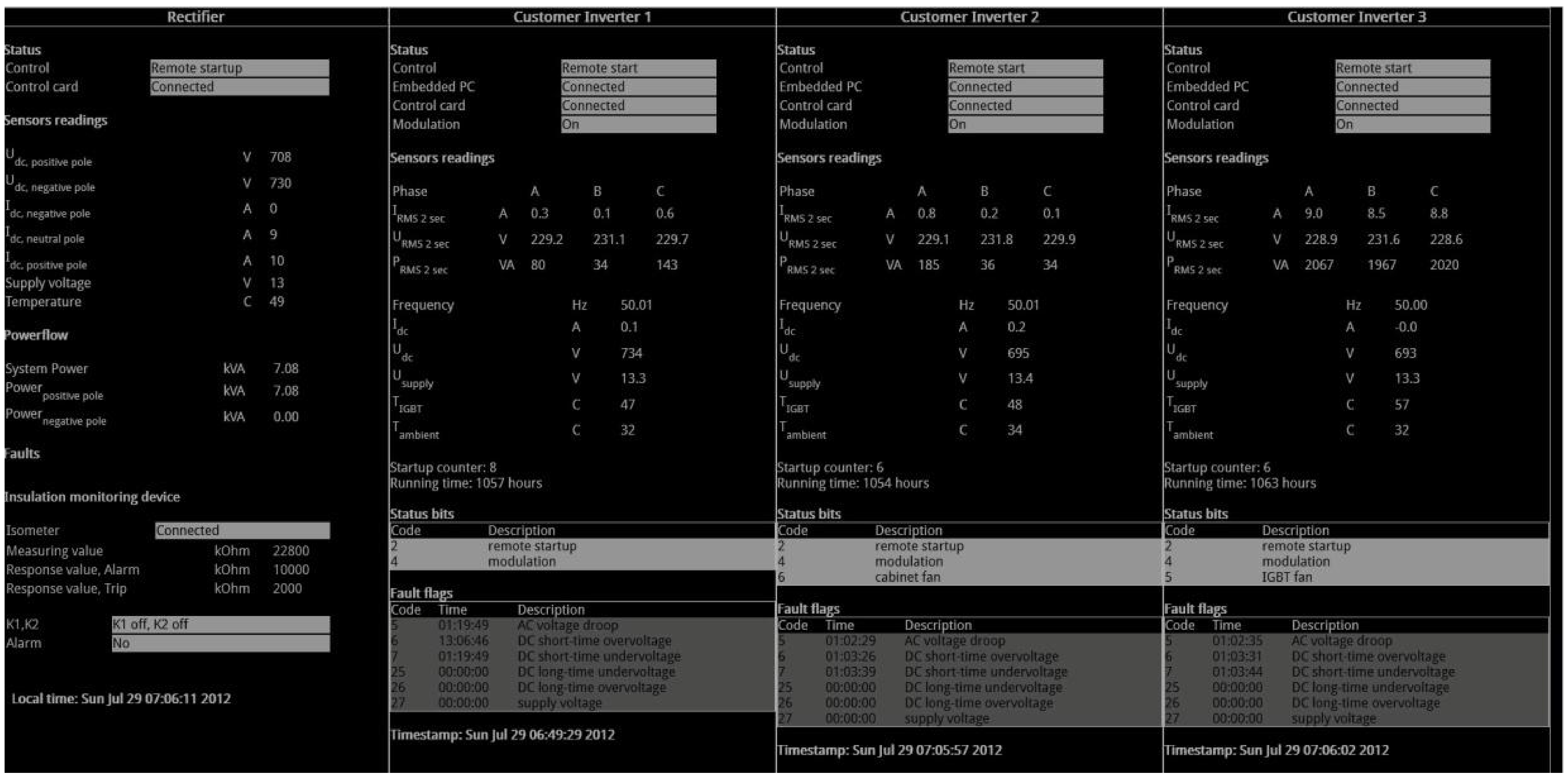
In the web portal, u_{rms} 10 min mean values over 24-hour period and u_{rms} 2 s mean values over one hour period are available. In Fig. 3, phase voltages and powers are presented. When the power consumption is small (b), the phase voltage (a) error is < 1 % most of the time. However, with higher power consumption (d) the phase voltage error is almost 2 %. It can be seen from (a) and (c) that the voltage unbalance is proportional to the relative load unbalance between phases and the absolute power consumption does not affect to the voltage error(c). When the power unbalance was at highest at 19:30 (d), the voltage error exceeds 3 % (c). However, the voltage quality clearly fulfils the requirements (voltage error < 10 %) set by the standard EN 50160 [5] in every situation. Still, improvement of the load unbalance correction will be studied in future publications.

Short interruptions

One of the benefits of the LVDC distribution is the possibility to use energy storages in DC network to exceed short interruptions, such as high-speed auto-reclosings (HSAR), without customer interruption. At the moment, DC network capacitors are dimensioned to supply all customers over HSAR, if total power per DC network pole is less than 1.5 kW. Besides, CEIs decrease the customer-end voltages for 15 % if the DC voltage decreases below 610 V (fault code #6). This increases the time the storage is able to supply the customers. During the operation period, several HSARs have occurred and most of them are exceeded without interruptions, some even without the 15 % voltage drop.

Faults

When the setup was started up for the first time and left operational over night, customers experienced several short (< 1 s) interruptions, which never occurred in laboratory. The reason was a control software error which caused AC overvoltage to which the overvoltage



Rectifier

Status

Control	Remote startup
Control card	Connected

Sensors readings

$U_{dc, positive pole}$	V	708
$U_{dc, negative pole}$	V	730
$I_{dc, negative pole}$	A	0
$I_{dc, neutral pole}$	A	9
$I_{dc, positive pole}$	A	10
Supply voltage	V	13
Temperature	C	49

Powerflow

System Power	kVA	7.08
$Power_{positive pole}$	kVA	7.08
$Power_{negative pole}$	kVA	0.00

Faults

Insulation monitoring device

Isometer		Connected
Measuring value	kOhm	22800
Response value, Alarm	kOhm	10000
Response value, Trip	kOhm	2000
K1,K2		K1 off, K2 off
Alarm		No

Local time: Sun Jul 29 07:06:11 2012

Customer Inverter 1

Status

Control	Remote start
Embedded PC	Connected
Control card	Connected
Modulation	On

Sensors readings

Phase		A	B	C
$I_{RMS 2 sec}$	A	0.3	0.1	0.6
$U_{RMS 2 sec}$	V	229.2	231.1	229.7
$P_{RMS 2 sec}$	VA	80	34	143

Frequency	Hz	50.01
I_{dc}	A	0.1
U_{dc}	V	734
U_{supply}	V	13.3
T_{IGBT}	C	47
$T_{ambient}$	C	32

Startup counter: 8
Running time: 1057 hours

Status bits

Code	Description
2	remote startup
4	modulation

Fault flags

Code	Time	Description
5	01:19:49	AC voltage droop
6	13:06:46	DC short-time overvoltage
7	01:19:49	DC short-time undervoltage
25	00:00:00	DC long-time undervoltage
26	00:00:00	DC long-time overvoltage
27	00:00:00	supply voltage

Timestamp: Sun Jul 29 06:49:29 2012

Customer Inverter 2

Status

Control	Remote start
Embedded PC	Connected
Control card	Connected
Modulation	On

Sensors readings

Phase		A	B	C
$I_{RMS 2 sec}$	A	0.8	0.2	0.1
$U_{RMS 2 sec}$	V	229.1	231.8	229.9
$P_{RMS 2 sec}$	VA	185	36	34

Frequency	Hz	50.01
I_{dc}	A	0.2
U_{dc}	V	695
U_{supply}	V	13.4
T_{IGBT}	C	48
$T_{ambient}$	C	34

Startup counter: 6
Running time: 1054 hours

Status bits

Code	Description
2	remote startup
4	modulation
6	cabinet fan

Fault flags

Code	Time	Description
5	01:02:29	AC voltage droop
6	01:03:26	DC short-time overvoltage
7	01:03:39	DC short-time undervoltage
25	00:00:00	DC long-time undervoltage
26	00:00:00	DC long-time overvoltage
27	00:00:00	supply voltage

Timestamp: Sun Jul 29 07:05:57 2012

Customer Inverter 3

Status

Control	Remote start
Embedded PC	Connected
Control card	Connected
Modulation	On

Sensors readings

Phase		A	B	C
$I_{RMS 2 sec}$	A	9.0	8.5	8.8
$U_{RMS 2 sec}$	V	228.9	231.6	228.6
$P_{RMS 2 sec}$	VA	2067	1967	2020

Frequency	Hz	50.00
I_{dc}	A	-0.0
U_{dc}	V	693
U_{supply}	V	13.3
T_{IGBT}	C	57
$T_{ambient}$	C	32

Startup counter: 6
Running time: 1063 hours

Status bits

Code	Description
2	remote startup
4	modulation
5	IGBT fan

Fault flags

Code	Time	Description
5	01:02:35	AC voltage droop
6	01:03:31	DC short-time overvoltage
7	01:03:44	DC short-time undervoltage
25	00:00:00	DC long-time undervoltage
26	00:00:00	DC long-time overvoltage
27	00:00:00	supply voltage

Timestamp: Sun Jul 29 07:06:02 2012

Fig. 2. Monitoring page of the web portal. Fault codes caused by the thunderstorm are noticeable.

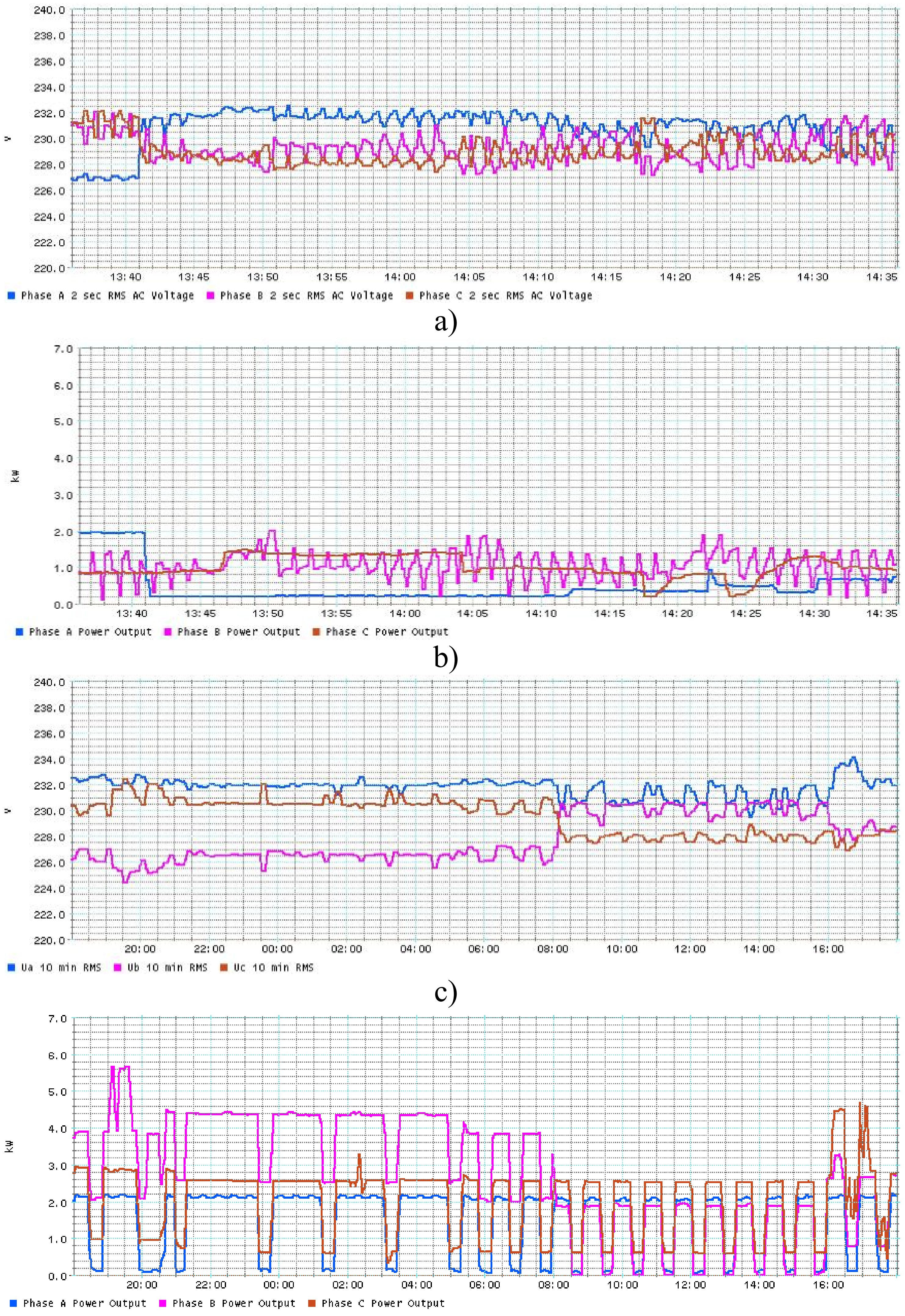


Fig. 3. Phase powers and voltages of one customer over one hour period (a,b) and over a 24-hour period (c,d). One hour curves are not parts of the 24-hour curves but recorded on a different day.

protection responded and restarted the CEI. Therefore, the first operation period proved that FRT functions are required. At first, the web portal included only a few measurements and remote control functions and no indication of faults were received. After that, fault codes (Tab. 1) and restart counter was added to the web portal to ensure that every interruption and CEI restart could be detected.

Current measurements

After 1 month of continuous operation, current sensor at CEI #1 malfunctioned and indicated maximum current. The current level was continuously higher than CEI over-current trip (fault code #13) limit and therefore, the CEI could not restart and the customer experienced interruption of a few hours before the faulty sensor was replaced. After that, the sensors of same CEI were replaced 5 times in two weeks period because of the same fault. To prevent long customer-end interruptions, faulty sensor recognition (fault code #22) was introduced. With recognition, sensor fault causes only 1 s interruption after which the readings of the sensor are ignored. However, if there is a short circuit in the same phase after a sensor fault, uncontrolled current could cause CEI failure.

Customer-end inverter DC circuit breakers

A rare situation was also experienced when a three-phase extension cord got stuck on a snow plow and caused multi-phase short-circuit. The CEI supplied short-circuit current but the required current and the duration was so high that the DC-side CB tripped before the customer-end protection. This caused no safety hazard but the customer experienced interruption before SSS workers reset the CB. This proved that the CB has to be selected properly to stand such situations either by selecting a CB with higher current rating or using a device with C-type characteristics. In the setup, however, faster operation was wanted to ensure that no equipment failures occur.

Insulation monitoring

The DC network insulation monitoring (IM) device controls the same moulded-case circuit breakers located before the rectifier that are used in short-circuit

Tab. 1. CEI fault codes, definitions and following actions.

Fault code	Definition	CEI action
1: Fault in phase a	Indicates faulting phase	Code only
2: Fault in phase b	Indicates faulting phase	Code only
3: Fault in phase c	Indicates faulting phase	Code only
4: AC overvoltage	$u_{AC} > 365$ V for 5 ms	Restart
5: AC short circuit	$i_{AC,\ peak} > 120$ A	Current control
6: AC voltage drop	$U_{DC} < 610$ V	$u_{AC} - 15$ %
7: U_{DC} overvolt., short-term	$U_{DC} > 780$ V	Shutdown, restarts when U_{DC} is OK
8: U_{DC} undervolt., short-term	$U_{DC} < 520$ V	Shutdown, restarts when U_{DC} is OK
9: Sequential startups, U_{DC} fault	Sequential U_{DC} caused start-ups > 3	Shutdown
10: Calibration error, CPU1	u and i values $\neq 0$ while CEI is OFF	Shutdown
11: Short circuit duration	Short-circuit current supply duration > 5 s	Shutdown
12: Short-circuit startups	Sequential short circuits > 5	Shutdown
13: Overcurr. Trip	$i_{AC,\ peak} > 420$ A	Shutdown
14: $u_{a,rms}$ fault	Indicates faulting phase	Code only
15: $u_{b,rms}$ fault	Indicates faulting phase	Code only
16: $u_{c,rms}$ fault	Indicates faulting phase	Code only
17: u_{rms} undervolt., short-term	$u_{rms} < 230$ V - 20 % for 100 ms	Restart
18: u_{rms} overvolt., short-term	$u_{rms} > 230$ V + 15 % for 100 ms	Restart
19: u_{rms} undervolt., long-term	$u_{rms} < 230$ V - 10 % for 2 s	Restart
20: u_{rms} overvolt., long-term	$u_{rms} > 230$ V + 10 % for 2 s	Restart
21: Frequency	$f_{error} > 0.1$ %	Code only
22: Curr. Sensor	$i_{AC} \neq 0$ while CEI is OFF	Ignore sensor
23: $U_{DC,\ mean}$ long-term undervoltage	$U_{DC,\ mean} < 520$ V for 2 s	Code only
24: $U_{DC,\ mean}$ long-term overvoltage	$U_{DC,\ mean} > 780$ V for 2 s	Code only
25: Control supply voltage	$U_{supply} < 11$ V $U_{supply} > 14$ V	Shutdown, restarts when U_{supply} is OK
26: IGBT module temperature	$T_{IGBT} > 95$ °C	Shutdown, restarts when T_{IGBT} is OK
27: Cabinet temperature	$T_{cabinet} > 50$ °C	Code only
28: Calibration error, CPU2	u and i values $\neq 0$ while CEI is OFF	Shutdown
29: Sequential startups, AC fault	Sequential U_{AC} caused start-ups > 3	Shutdown

protection. The IM device has two resistance settings, alarm and trip. Because the standardisation requires at least 1 MΩ earth resistance, device was set to 4 MΩ and 2 MΩ, respectively [1]. In autumn, IM tripped once after long rainy and humid period. It was found that the device trip circuit was incorrectly connected and therefore, also resistance values under 4 MΩ caused trip instead of only alarm. As a result, connections were corrected, alarm value was raised to 10 MΩ, and the IM measurement values were added to the web portal. The measurements have shown that the insulation resistance is proportional to air humidity, though the DC network is underground cabled network. The resistance value decreases below 10 MΩ during humid days and, for example, at -20 °C the value is almost 30 MΩ. It will be investigated if there are some components in the DC network which has an effect on the earth resistance when the humidity is high.

FUTURE RESEARCH AND DEVELOPMENT

The setup is and will be under development. Smallest steps are implementation of software protection, management, and control functions. In future, battery energy storage system (BESS) will be connected to the DC network to provide energy over longer interrupts. Power taken from the MV network could be regulated by charging and discharging the BESS. With BESS alone, power during longer interruptions will be provided. With distributed energy resources (DER), network power flow can be controlled to maximise network energy efficiency and minimise electricity costs. DER, for instance photovoltaic generation (PV), will allow island operation of the LVDC microgrid, which is an important research topic. In this case, the CEI could control customer-end loads to reduce consumption and enable long island operation. With these functions, the setup will be an intelligent LVDC grid.

CONCLUSIONS

In this paper, experiences from use of an LVDC research setup in public electricity distribution are discussed. Because LVDC is a novel approach to LV distribution, practical studies are required to gather knowledge about the concept in real environment. Also, the setup is the first implementation of LVDC distribution and CEI-based supply and therefore, design flaws and component failures were expected. However, results show that the setup has been very reliable for 5000 hours and no component failures have occurred after first month of operation. Also, quality of supply has been high and all special situations, such as HSARs and longer interruptions, have been managed as planned. Therefore, the first implementation of LVDC distribution system has been successful.

REFERENCES

[1] P. Nuutinen, P. Peltoniemi, T. Kaipia, P. Salonen, P. Silventoinen, 2012, “Commissioning Inspection of an LVDC Distribution Network”, Proceedings NORDAC 2012 Conference, 10-11 September 2012

[2] T. Kaipia, P. Nuutinen, A. Pinomaa, A. Lana, J. Partanen, J. Lohjala, M. Matikainen, 2012, “Field Test Environment for LVDC Distribution - Implementation Experiences,” Proceedings CIRED Workshop 2012, 29-30 May 2012

[3] P. Nuutinen, P. Peltoniemi, P. Silventoinen, "Short-Circuit Protection in a Converter-Fed Low-Voltage Distribution Network", IEEE Trans. on Power Electron., April 2013, vol. 28, 1587-1597

[4] P. Peltoniemi, P. Nuutinen, J. Pyrhonen, 2012, "Observer-based Output Voltage Control for DC Power Distribution Purposes", IEEE Trans. on Power Electron., April 2013, vol. 28, 1914-1926

[5] National Standard - series Std, 2011, EN 50160 - Voltage Characteristics of Electricity Supplied by Public Distribution Systems