Abstract

Antti Pinomaa

Power-line-communication-based data transmission concept for an LVDC electricity distribution network – Analysis and implementation

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Communications play a key role in modern smart grids. New functionalities that make the grids ‘smart’ require the communication network to function properly. Data transmission between intelligent electric devices (IEDs) in the rectifier and the customer-end inverters (CEIs) used for power conversion is also required in the smart grid concept of the low-voltage direct current (LVDC) distribution network. Smart grid applications, such as smart metering, demand side management (DSM), and grid protection applied with communications are all installed in the LVDC system. Thus, besides remote connection to the databases of the grid operators, a local communication network in the LVDC network is needed. One solution applied to implement the communication medium in power distribution grids is power line communication (PLC). There are power cables in the distribution grids, and hence, they may be applied as a communication channel for the distribution-level data.

This doctoral thesis proposes an IP-based high-frequency (HF) band PLC data transmission concept for the LVDC network. A general method to implement the Ethernet-based PLC concept between the public distribution rectifier and the customer-end inverters in the LVDC grid is introduced. Low-voltage cables are studied as the communication channel in the frequency band of 100 kHz–30 MHz. The communication channel characteristics and the noise in the channel are described. All individual components in the channel are presented in detail, and a channel model, comprising models for each channel component is developed and verified by measurements. The channel noise is also studied by measurements. Theoretical signal-to-noise ratio (SNR) and channel capacity analyses and practical data transmission tests are carried out to evaluate the applicability of the PLC concept against the requirements set by the smart grid applications in the LVDC system. The main results concerning the applicability of the PLC concept and its limitations are presented, and suggestion for future research proposed.

Keywords: Power line communication, high frequency, channel model, low-voltage direct current, electricity distribution network, smart grid, HomePlug

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“Anna mun kaikki kestäää
anna minun kestäää edes puolet”

Juice Leskinen (1950–2006)
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Lappeenranta, December 2013
Antti Pinomaa
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List of publications

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The publications are in a chronological order. In this doctoral thesis they are referred to as Publication I, Publication II, Publication III, Publication IV, Publication V, Publication VI, and Publication VII.
## Abbreviations and Symbols

### Roman letters

- \( c \) distributed capacitance
- \( f \) frequency
- \( f_r \) resonance frequency
- \( f_{sw} \) switching frequency
- \( f_h \) highest frequency
- \( f_l \) lowest frequency
- \( g \) distributed conductance
- \( h \) initial coefficient of distributed resistance
- \( k \) initial coefficient of distributed conductance
- \( l \) distributed inductance
- \( n \) number of samples
- \( n_{lump} \) number of lumps
- \( r \) distributed resistance
- \( s \) standard deviation
- \( \tan \delta \) dissipation factor
- \( \bar{x} \) mean
- \( x_i \) single sample
- \( A \) frequency-dependent coefficient matrix
- \( B \) bandwidth
- \( B \) frequency-dependent coefficient matrix
- \( C \) capacitance
- \( C \) frequency dependent coefficient matrix
- \( C_{Ch} \) channel capacity
- \( C_d \) high-frequency capacitance of diode
- \( C_{DC,C} \) high-frequency capacitance of DC link capacitor
- \( C_{d-t} \) high-frequency capacitance of diode-thyristor
- \( C_{F,CS} \) high frequency capacitance of fuse and current sensor
- \( C_{IGBT} \) high-frequency capacitance of IGBT
- \( C_t \) high-frequency capacitance of thyristor
- \( C_{CM, HF} \) high-frequency capacitance of common-mode choke
- \( C_{CM, 1F} \) low-frequency capacitance of common-mode choke
- \( C_{p,D} \) parallel high-frequency capacitance of small-signal diode circuit
- \( D \) frequency-dependent coefficient matrix
- \( G_{Ch} \) channel gain
- \( H \) transfer function of communication channel
- \( I_{in} \) input current
- \( I_{out} \) output current
- \( I_n \) nominal current
- \( I_{rms} \) root mean square current
- \( I_{sc} \) short circuit current
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{\text{sat}}$</td>
<td>saturation current</td>
</tr>
<tr>
<td>$L$</td>
<td>inductance</td>
</tr>
<tr>
<td>$L_{\text{Co}}$</td>
<td>high-frequency inductance of coupling interface</td>
</tr>
<tr>
<td>$L_d$</td>
<td>high-frequency inductance of diode</td>
</tr>
<tr>
<td>$L_{\text{DC},C}$</td>
<td>high-frequency inductance of DC link capacitor</td>
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<tr>
<td>$L_{\text{d-t}}$</td>
<td>high-frequency inductance of diode-thyristor</td>
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<tr>
<td>$L_{\text{IGBT}}$</td>
<td>high-frequency inductance of IGBT</td>
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<tr>
<td>$L_{\text{F,CS}}$</td>
<td>high frequency inductance of fuse and current sensor</td>
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<tr>
<td>$L_{\text{F,PS}}$</td>
<td>high frequency inductance of fuse and power source</td>
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<tr>
<td>$L_t$</td>
<td>high-frequency inductance of thyristor</td>
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<tr>
<td>$L_{\text{CM, HF}}$</td>
<td>high-frequency inductance of common-mode choke</td>
</tr>
<tr>
<td>$L_{\text{CM, 1F}}$</td>
<td>low-frequency inductance of common-mode choke</td>
</tr>
<tr>
<td>$L_{\text{P,D}}$</td>
<td>parallel high-frequency inductance of small-signal diode circuit</td>
</tr>
<tr>
<td>$L_{\text{S,D}}$</td>
<td>serial high-frequency inductance of small-signal diode circuit</td>
</tr>
<tr>
<td>$L_E$</td>
<td>cable length</td>
</tr>
<tr>
<td>$P_N$</td>
<td>noise power</td>
</tr>
<tr>
<td>$P_n$</td>
<td>nominal power</td>
</tr>
<tr>
<td>$P_S$</td>
<td>signal power</td>
</tr>
<tr>
<td>$P_{TX}$</td>
<td>transmission power</td>
</tr>
<tr>
<td>$R$</td>
<td>resistance</td>
</tr>
<tr>
<td>$R_{\text{Co}}$</td>
<td>high-frequency resistance of coupling interface</td>
</tr>
<tr>
<td>$R_d$</td>
<td>high-frequency resistance of diode</td>
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<tr>
<td>$R_{\text{DC},C}$</td>
<td>high-frequency resistance of DC link capacitor</td>
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<tr>
<td>$R_{\text{d-t}}$</td>
<td>high-frequency resistance of diode-thyristor</td>
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<td>$R_{\text{F,CS}}$</td>
<td>high frequency resistance of fuse and current sensor</td>
</tr>
<tr>
<td>$R_{\text{F,PS}}$</td>
<td>high frequency resistance of fuse and power source</td>
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<tr>
<td>$R_{\text{IGBT}}$</td>
<td>high-frequency resistance of IGBT</td>
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<tr>
<td>$R_t$</td>
<td>high-frequency resistance of thyristor</td>
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<tr>
<td>$R_{\text{CM, HF}}$</td>
<td>high-frequency resistance of common-mode choke</td>
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<tr>
<td>$R_{\text{CM, 1F}}$</td>
<td>low-frequency resistance of common-mode choke</td>
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<tr>
<td>$R_{\text{P,D}}$</td>
<td>parallel high-frequency resistance of small-signal diode circuit</td>
</tr>
<tr>
<td>$S$</td>
<td>signal power</td>
</tr>
<tr>
<td>$S_{11}$</td>
<td>scattering parameter for power reflection coefficient at input port</td>
</tr>
<tr>
<td>$S_{12}$</td>
<td>scattering parameter for power attenuation from output port to input port</td>
</tr>
<tr>
<td>$S_{21}$</td>
<td>scattering parameter for power attenuation from input port to output port</td>
</tr>
<tr>
<td>$S_{22}$</td>
<td>scattering parameter for power reflection coefficient at output port</td>
</tr>
<tr>
<td>$U_{\text{in}}$</td>
<td>input voltage</td>
</tr>
<tr>
<td>$U_{\text{out}}$</td>
<td>output voltage</td>
</tr>
<tr>
<td>$U_S$</td>
<td>source voltage</td>
</tr>
<tr>
<td>$U_n$</td>
<td>nominal voltage</td>
</tr>
<tr>
<td>$Z_0$</td>
<td>characteristic impedance</td>
</tr>
<tr>
<td>$Z_C$</td>
<td>impedance of capacitor</td>
</tr>
<tr>
<td>$Z_{CM}$</td>
<td>impedance of common-mode DC choke</td>
</tr>
<tr>
<td>$Z_{\text{IGBT}}$</td>
<td>impedance of IGBT</td>
</tr>
</tbody>
</table>
Abbreviations and Symbols

$Z_{in,oc}$ input impedance of cable with other end open circuited
$Z_{in,sc}$ input impedance of cable with other end short circuited
$Z_L$ load impedance, impedance of inductor
$Z_P$ parallel impedance
$Z_S$ serial impedance, source impedance

Greek alphabet

$\alpha$ attenuation coefficient
$\beta$ propagation coefficient
$\phi$ phase angle
$\gamma$ propagation constant
$\delta$ skin depth
$\varepsilon_0$ permittivity of vacuum
$\varepsilon_r$ relative permittivity
$\varepsilon'$ real part of complex permittivity
$\sigma$ dielectric conductivity
$\lambda$ wavelength
$\mu_0$ permeability of vacuum
$\omega$ angular frequency

Abbreviations

ADSL Asymmetric digital subscriber line
AES Advanced encryption standard
AM Amplitude modulation
AMI Automated metering infrastructure
AMR Automatic meter reading
ARQ Automatic repeat request
AWGN Additive white Gaussian noise
BB Broadband
BER Bit-error ratio
BPL Broadband over power line
BPSK Binary phase shift keying
CEI Customer-end inverter
CENELEC European Committee for Electrotechnical Standardization
CSMA Carrier sense multiple access
CSMA/CA Carrier sense multiple access with collision avoidance
CSMA/CD Carrier sense multiple access with collision detection
DBPSK Differential binary phase shift keying
DER Distributed energy resources
DES Data encryption standard
DFT Discrete Fourier transform
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>DSM</td>
<td>Demand side management</td>
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<tr>
<td>DQPSK</td>
<td>Differential quadrature phase shift keying</td>
</tr>
<tr>
<td>DR</td>
<td>Demand response</td>
</tr>
<tr>
<td>DSL</td>
<td>Digital subscriber line</td>
</tr>
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<td>DSO</td>
<td>Distribution system operator</td>
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<tr>
<td>DSP</td>
<td>Digital signal processor</td>
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<tr>
<td>EMI</td>
<td>Electromagnetic interference</td>
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<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
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<tr>
<td>EV</td>
<td>Electric vehicle</td>
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<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
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<tr>
<td>FD</td>
<td>Frequency domain</td>
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<tr>
<td>FEC</td>
<td>Forward error correction</td>
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<td>FFT</td>
<td>Fast Fourier transform</td>
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<tr>
<td>FSK</td>
<td>Frequency shift keying</td>
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<tr>
<td>FTP</td>
<td>File transmission protocol</td>
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<tr>
<td>HF</td>
<td>High frequency</td>
</tr>
<tr>
<td>HTTP</td>
<td>Hypertext transfer protocol</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and communication technology</td>
</tr>
<tr>
<td>IDFT</td>
<td>Inverse discrete Fourier transform</td>
</tr>
<tr>
<td>IED</td>
<td>Intelligent electric device</td>
</tr>
<tr>
<td>IFFT</td>
<td>Inverse fast Fourier transform</td>
</tr>
<tr>
<td>ICI</td>
<td>Inductive coupling interface</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated gate bipolar transistor</td>
</tr>
<tr>
<td>IP</td>
<td>Internet protocol</td>
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<td>ISI</td>
<td>Inter-symbol interference</td>
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<tr>
<td>LVDC</td>
<td>Low-voltage direct current</td>
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<tr>
<td>LAN</td>
<td>Local area network</td>
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<tr>
<td>LF</td>
<td>Low frequency</td>
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<tr>
<td>LTI</td>
<td>Linear time-invariant</td>
</tr>
<tr>
<td>LV</td>
<td>Low voltage</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium access control</td>
</tr>
<tr>
<td>MF</td>
<td>Medium frequency</td>
</tr>
<tr>
<td>MTL</td>
<td>Multiconductor transmission line</td>
</tr>
<tr>
<td>MV</td>
<td>Medium voltage</td>
</tr>
<tr>
<td>NB</td>
<td>Narrowband</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal frequency division multiplexing</td>
</tr>
<tr>
<td>OPERA</td>
<td>Open PLC European Research Alliance</td>
</tr>
<tr>
<td>PE</td>
<td>Protective earth</td>
</tr>
<tr>
<td>PEX</td>
<td>Cross-linked polyethylene</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical layer</td>
</tr>
<tr>
<td>PLC</td>
<td>Power line communication</td>
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<tr>
<td>PRIME</td>
<td>PoweRline Intelligent Metering Evolution</td>
</tr>
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<td>PSD</td>
<td>Power spectral density</td>
</tr>
<tr>
<td>PSK</td>
<td>Phase shift keying</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>PVC</td>
<td>Polyvinyl chloride</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse width modulation</td>
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<tr>
<td>QAM</td>
<td>Quadrature amplitude modulation</td>
</tr>
<tr>
<td>QI</td>
<td>Quad interval</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of service</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature phase shift keying</td>
</tr>
<tr>
<td>RB</td>
<td>Rectifier bridge</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>ROBO</td>
<td>Robust OFDM</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory control and data acquisition</td>
</tr>
<tr>
<td>SDR</td>
<td>Software-defined radio</td>
</tr>
<tr>
<td>SG</td>
<td>Smart grid</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
</tr>
<tr>
<td>SP</td>
<td>Solar panel</td>
</tr>
<tr>
<td>SVM</td>
<td>Space-vector modulation</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission control protocol</td>
</tr>
<tr>
<td>TD</td>
<td>Time domain</td>
</tr>
<tr>
<td>TEM</td>
<td>Tranverse electromagnetic</td>
</tr>
<tr>
<td>TM</td>
<td>Tone map</td>
</tr>
<tr>
<td>UDP</td>
<td>User datagram protocol</td>
</tr>
<tr>
<td>UGC</td>
<td>Underground cabling</td>
</tr>
<tr>
<td>USB</td>
<td>Universal serial bus</td>
</tr>
<tr>
<td>USRP</td>
<td>Universal software radio pheripheral</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless local area network</td>
</tr>
<tr>
<td>WT</td>
<td>Wind turbine</td>
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</table>
1 Introduction

Power line communication (PLC) has been widely applied both in public and indoor electricity distribution networks as a data transmission solution for various applications (Ferreira and Lampe, 2010). With the PLC, there is a communication channel provided by the power lines. For instance, remote automatic meter reading (AMR) can be mentioned as a typical and one of the oldest applications of PLC in traditional alternating current (AC) electricity distribution networks. Today, the variety of applications, and thus the needs for communications in power grids are increasing along with the development of traditional electricity distribution networks toward smart grids (SGs). So far, the usage of PLC in low-voltage direct current (LVDC) electricity distribution networks or the smart grid system concept in the scale of traditional AC low-voltage distribution grids has not been studied or applied to in practice. This chapter highlights the research objectives and methods of work adopted in this doctoral thesis. First, modern power grids with smart applications and functionalities are covered, and the novel LVDC smart grid concept is presented. Next, PLC in power grids starting from the first applications in electricity distribution networks is described. After the determination of the background, the outline of the thesis is provided, and the appended original publications are introduced. Finally, the scientific contributions of this doctoral thesis are discussed.

1.1 LVDC distribution network

Smart grids have received increasing public attention over the last decade. According to (Li et al., 2010), modern power grids have to become smarter in order to provide affordable, reliable, and sustainable electricity power supply throughout the public electricity network chain, from high-voltage transmission networks and medium- and low-voltage distribution grids to in-house networks on customer premises. In this context, the term ‘grid’ covers not only the physical electricity power transmission and distribution networks, but also the communication networks and intelligent electric devices (IED) with applications that support the functions of the physical network. The development of distribution grids and the pursuit of smart grids result from the tightening requirements set by society, customers, and authorities for the quality and economic efficiency of electrical power distribution. As a result, common targets of smart grids are to improve the reliability of electric power supply for end-users, and in the energy market, to develop new ways to cut down energy consumption. Finally, the target is to make both the power supply and demand more flexible with new functionalities. The development of electric power distribution grids has been continuing for over a century from the initial designs of local low-voltage DC networks to three-phase medium- and high-voltage AC networks (U.S. Dept., 2003). Today, power grids are modern and interconnected networks equipped with various voltage levels and complex electrical components (Li et al. 2010). In addition, the basic structure of the distribution grids has changed. The power flow in the grids is no longer only from the power plants to the customers, but also from customers to the grid. This is
results from the increasing number of small-scale power generators, solar panels, and electrical vehicles (EVs) that all work with DC, and are connected to the grids. The initial designs of DC grids disappeared, because before the invention of power electronics there were no DC transformers available. Therefore, low-voltage direct current (LVDC) electricity distribution has gained more attention only lately. It has been proposed to replace traditional power networks in many applications, including datacenter supply (Salato et al., 2012). Furthermore, LVDC distribution has become more common along with the increasing number and development of residential microgrids (Kakigano et al., 2012), with respect to the direct connection of distributed generation units to the power grids (Byeon et al., 2013; Deilami et al., 2011). A control method for this kind of a microgrid (µGrid) is proposed for instance in (Baochao et al., 2012). Together with this development of low-voltage DC µGrids, the system complexity has increased, and therefore, bidirectional data flows are required to monitor and control the operation of the µGrid. In addition, these applications set technical performance requirements for the communication network implemented to the system.

The LVDC distribution system concept applies DC distribution in a larger scale than the solutions proposed above or in the literature. The idea behind the LVDC concept is that with the use of low-voltage DC and power electronic devices for power conversions in the low-voltage distribution network, certain advantages can be achieved over the traditional 20/0.4 kV AC distribution. Briefly, these are savings in grid investments, decreased network operating costs, and improved quality of electricity distribution. In the LVDC distribution network, parts of the overhead MV grid branches and complete low-voltage AC distribution networks are replaced with a low-voltage DC grid implemented with underground low-voltage cables. The operation principle of the LVDC system is the following. The medium-voltage AC is transformed, rectified, and smoothed to low-voltage DC. Next, DC is distributed to customers with low-voltage underground cables, which have a voltage rating of 900 VDC against earth and 1500 VDC against conductors, and can thus be applied in the LVDC network (LVD 73/23/EEC, 1973). With 1500 VDC, still rated as low-voltage in (LVD 2006/95/EC, 2006), the power transfer capability of a bipolar LVDC system (+750, 0, −750 VDC) is 15–20 times that of traditional 400 VAC distribution (Kaipia et al., 2006; Kaipia et al., 2007a). The DC is converted back to low-voltage AC with a customer-end inverter (Kaipia et al., 2007b). The basic structure of an active LVDC electricity distribution system is illustrated in Figure 1.1. The LVDC system provides an option to install distributed generation units, such as wind turbines (WT), solar panels (SP), and electric vehicles easily to the grid; the synchronization is not difficult with power electronics. Power conversion is required to match the voltage level with the grid voltage; in the case of a solar panel or an EV to optimize the production. However, DC to AC conversions and thereby synchronization are not required.

In addition to distributed generation units, smart applications such as automatic meter reading and demand side management (DSM) with customer load control commonly applied in smart grids are also implemented to the LVDC system concept. Besides these, new applications and functionalities have emerged, proposed, and developed to
be installed in smart grids, such as communication-based grid protection. To control and monitor the operation of the grid, and provide these functionalities between the grid operator and the customer, bidirectional remote and local communication networks with the required IEDs are needed. These applications, functionalities, and related services together form the context of a smart grid. The customer equipped with an active customer gateway with SG functions plays an important role in the proposed concept (Kaipia et al., 2010).

Figure 1.1: Basic structure of an active LVDC electricity distribution system.

1.2 Motivation of the work

According to (Bose, 2010), a communications network is commonly considered one of the cornerstones of smart grids; most of the applications on the grids are implemented with and rely on communications. Communication network architectures in smart grids are discussed in (Wang et al., 2011); the main aspects required for the communication technology for the system are high reliability, low latency, and a certain throughput. Smart grid applications implemented with communications are studied widely for traditional AC grids (Salehi et al., 2012) and new DC microgrids (Wang et al., 2012). The requirements of data transmission vary depending on the application. These data transmission requirements concerning a few main SG functionalities are gathered in Table 1.1. The plus signs from one to three given for the listed functionalities and the requirements of a communication network denote low priority (+), high (++), and absolute priority (+++).

Table 1.1: Requirements of data transmission for different functionalities in smart grids.

<table>
<thead>
<tr>
<th>Functionality</th>
<th>AMR</th>
<th>DSM (load signals)</th>
<th>Fault monitoring</th>
<th>Grid protection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>++</td>
<td>+</td>
<td>+++</td>
<td>+</td>
</tr>
<tr>
<td>Latency</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>+++</td>
</tr>
<tr>
<td>Jitter</td>
<td>+</td>
<td>+</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Reliability</td>
<td>++</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
</tr>
</tbody>
</table>
Introduction

The functionalities listed above are also implemented to the new LVDC distribution smart grid system platform. Thus, a local data transmission network with a connection to remote databases on the LVDC system is required. Today, PLC is one of the most suitable and commonly used data transmission methods in smart grids. The other main communication technology in electricity distribution networks is commercial wireless mobile technologies (Haidine et al., 2011). Both of these approaches have obviously their advantages and disadvantages; the main drawback of the mobile technologies is that they are dependent on a third party, that is, the network operators, and the available bandwidth in the mobile network is shared with mobile phone users. This decreases the reliability and quality of service (QoS) of mobile networks. Furthermore, in the case of an island situation there is not necessarily wireless infrastructure available. In this sense, the situation is the same as when the first power transmission and distribution networks were built and PLC was implemented to them. A disadvantage of PLC is that the communication medium is the same as the power distribution network. If there is a fault or interruption in the distribution electricity network, the communication may be also down. With wireless mobile technology, the communication between the nodes that are the CEIs and the rectifier in the LVDC system, and thus, the network architecture would be point-to-point, while with PLC, there would be a data concentrator somewhere in the DC grid, and the architecture would be point-to-multipoint. This architecture would be more preferable, because for example the grid protection implemented with communication requires a low-latency local network. Thus, in this doctoral thesis, the focus is on PLC, the applicability of which as the data transmission network for the LVDC concept is studied. Furthermore, to the author’s knowledge, no PLC-based communication solution for LVDC electricity distribution system has been presented in the literature so far.

1.2.1 PLC techniques

In the literature, there are numerous publications related to the application of PLC in traditional AC distribution systems; at all levels of electricity distribution chain, from high and medium voltage (HV/MV) to low-voltage distribution networks. The application of PLC in electricity distribution grids is an old invention (Brown, 1999); the history of PLC dates back to the 19th century. The very first PLC application was remote electricity supply metering for the purpose of monitoring voltage levels in the London-Liverpool telegraph system in 1838, proposed by Edward Davy (Fahie, 1883). The first PLC patent on a power line signaling electricity meter was applied by Joseph Routin and C. E. L. Brown in UK in 1897 (Routin and Brown, 1897). Today, the PLC technologies are evolving within the increasing number of applications and features in public power networks. PLC is used in the grid supervisory control and data acquisition (SCADA), monitoring, and implementation of automatic metering infrastructures (AMI) (Haidine et al., 2012).

According to (Hrasnica et al., 2004), PLC can be categorized based on the bandwidth. Commonly, modern narrowband (NB) PLC techniques, such as the recently published PRIME (Arzuaga et al., 2010) and G3-PLC (Razazzian et al., 2010; Hoch, 2010)
1.3 Research methods and objective of the work

In this doctoral thesis, a PLC concept for the LVDC distribution system is proposed. The hypothesis is that the PLC concept is applicable to the purpose, that is, the concept is able to meet all the performance requirements set by the LVDC system applications and functions (listed in Table 1.1). Certain applications require different features from the communication system that is applied to the grid. For example, the grid protection function requires information exchange with short latencies between the rectifier and the CEIs in the grid ends. In addition, the communication network is required to provide certain throughput for data logging, and control and monitoring applications. Moreover, the reliability of the communication is the most essential factor. On the other hand, the LVDC grid structure with the power electronic devices, that is, the rectifier and the customer-end inverters in the ends of the grid pose challenges to the PLC. Based on these requirements, the PLC concept consisting of the network structure and applicable PLC techniques is defined by the analysis of channel characteristics and noise in the operating in a low-frequency band of 9–500 kHz (CENELEC band in Europe; 3–148.5 kHz (EN, 1991) and FCC band in U.S.; 14–480 kHz (Federal Communications Commission (FCC), 1998)), are considered to be more viable over the broadband (BB) PLC for smart grid applications in distribution systems (Haidine et al., 2011). The NB techniques use a lower frequency band in communication than the broadband techniques, and the signal attenuation is lower. Thus, with the NB PLC it is possible to achieve longer data transmission distances between PLC modems, but the data rates are lower, from a few to tens of kilobytes (Razazian et al., 2010; ERDF, 2009).

BB PLC provides high data rates and is more commonly used in the Internet access, and in-home networks (Hrasnica et al., 2004; Di Bert et al., 2012). In the literature there are a few studies related to the application of BB PLC in the high-frequency (HF) band in smart grids; for instance the HF band PLC in an AMR field trial on an underground power distribution line is studied in (Lee et al., 2011), and in electric vehicles is discussed in (Barmada et al., 2013). The channel studied in (Barmada et al., 2013) is rather similar to the LVDC distribution system, but the length of the in-vehicle power line channel is short (few meters) compared with the LVDC grid lengths. The main challenge with the HF band PLC in distribution grids with long distances is that the signaling power is restricted because of undesirable radiation of energy, and the PLC signal is attenuated in the power cables and lines as a function of frequency. Because of the signal attenuation, the communication signaling ranges are short and therefore, PLC repeaters with short intervals up to a few hundred meters must be used. Today, the new (NB&BB) PLC modems are equipped with the support of commonly used communication protocols, such as the Internet protocol (IP); the PLC network is IP based, and the modems operate as bridges over the network. This brings flexibility to the service providers; other communication protocols, such as IEC-61850, which is commonly used in electrical substation automation (Higgins et al., 2008) can be implemented over the IP network.
channel. The analysis is based on measurements carried out in the LVDC laboratory setup at Lappeenranta University of Technology (LUT) and in an LVDC field installation system built by LUT in cooperation with a Finnish distribution system operator (DSO) Suur-Savon Sähkö Oy. The general structures of the LVDC laboratory setup and LVDC field installation system are illustrated in Figure 1.2. To support the channel analysis, a channel model for the LVDC PLC channel is constructed. Furthermore, the applicability of the PLC concept against the requirements set by different applications is evaluated by a theoretical channel capacity analysis based on the analysis of the channel characteristics and noise in the channel, and by practical latency and data transmission tests carried out in the LVDC laboratory setup and in the LVDC field installation system between the PLC modems customized for the concept.

Figure 1.2: Basic structures of a PLC channel in an LVDC laboratory setup a), and LVDC field grid b).

1.4 Outline of the thesis

The doctoral thesis consists of a summary section and the appended original publications. The relations between the chapters and the appended publications and a description of how each publication responds to the research objectives and which research methods are applied are given in Figure 1.3. The contents of the summary are divided into five chapters as follows.

Chapter 1 introduces the definition of smart grids and communication solutions commonly applied in smart grids, focusing on the PLC. The LVDC system studied at LUT as a smart grid research platform is presented. The chapter provides the background and motivation of the thesis with the research objective and methods, and provides the scientific contributions.

Chapter 2 presents the proposed PLC concept for the LVDC electricity distribution system (Publications III, IV, and VII). First, the structure and features of the LVDC system from the PLC point of view are introduced. The advantages and challenges of the concept are studied. Based on a general analysis of the channel characteristics of the LVDC PLC and noise in the channel, the PLC concept architecture is proposed with the suitable PLC
1.4 Outline of the thesis

... technologies, including standards and communication protocols applied to the system.

Figure 1.3: Contents of the doctoral thesis and illustration of how the appended publications are related to the context.

Chapter 3 is devoted to study of the LVDC PLC channel characteristics. The PLC channel in the LVDC laboratory is described in detail. The power line channel is divided into the communication channel and noise sources (in this case the power-electronic devices in the channel ends). First, a detailed analysis is performed of the channel characteristics based on measurements carried out in the LVDC laboratory system (based on the methods applied in Publications I and II). Next, a channel model approach for the system is introduced. A two-conductor transmission line analysis is made and a model for low-voltage power cables typically used in LV distribution systems is implemented with a circuit simulator. Lumped parameters for the cable model are defined based on the input impedance measurements. Consequently, a two-port input impedance model for each individual channel component is formed, and parameters for each model are derived by the input impedance measurements (Publications III–VI).

Chapter 4 addresses testing of the applicability of the proposed PLC concept. The question of how the concept can meet the functional requirements set by the application implemented to the LVDC system is answered with...
theoretical estimations with the constructed channel model. Noise in the PLC channel and its effects on the PLC performance are studied by noise sample measurements. Based on the channel characteristics, the information capacity of the communication channel and the communication range between the HF band PLC modems are estimated. To verify and support the theoretical estimation, practical data transmission tests including data rate and latency tests between commercial HF band PLC modems are performed in both the LVDC laboratory setup and the field installation grid. With these studies, the reliability, latency, and throughput aspects of the PLC concept are covered (Publications III–VI).

Chapter 5 is the final chapter before the appended publications. Conclusions and suggestions for future work are made.

A brief description of the summarized contents of the publications comprising this doctoral thesis is given, and the contribution of the author and the coauthors to the publications is reported in the following. The other coauthors not listed below have participated in the project cooperation. Furthermore, the coauthors have contributed to the preparation of the publications by revision comments and suggestions. These publications comprise one journal article, five international conference papers, and one book in which the author has written one subsection.

Publication 1 addresses the application of a software-defined radio (SDR) in motor cable communication. SDRs are used as a transmitter and a receiver in the motor cable communication channel formed with inductive couplers and high-pass filters connected to the ends of the motor cable between the motor and the inverter in a frequency-converter-fed electric drive. Based on the high-frequency band channel characteristics, the licence-free ISM (industrial, scientific, and medical) radio-frequency band is chosen to be used as the carrier frequency. The data rates and bit-error-ratio (BER) of two modulation schemes between SDRs coupled to the channel ends and the motor and inverter are examined by data transmission tests. In addition, the effect of coding is analyzed. According to the experiments, the SDR is a feasible low-cost platform for designing, testing, and analysis of data transmission links.

The motor cable communication test setup between the motor and the frequency converter was built and measurements were carried out by the author, the coauthor Mr. Baumgartner, and Dr. Kosonen. The results were analyzed and the manuscript was mainly written by the author and the coauthor Mr. Baumgartner. The other coauthors, Prof. Ahola and Dr. Kosonen, contributed to the preparation of the final version of the manuscript by revision comments and suggestions.
**1.4 Outline of the thesis**

**Publication II** concentrates on the analysis of the channel characteristics for motor cable communication with inductive signal coupling. Data transmission in the motor cable between a motor and an inverter in a variable-speed electric drive is a feasible communication method for diagnostics or motor control. The analysis of the channel characteristics is based on measurements carried out in the laboratory test setup and theoretical simulation models. A feasible frequency band for motor cable communication with inductive couplers is proposed for different cable lengths typically used in industrial LV motor drive applications.

The PLC data transmission link for the motor cable communication test setup between the motor and the frequency converter was built and measurements were carried out by the primary author Dr. Kosonen. The results were analyzed and the manuscript was mainly written by the primary author. The coauthors, Prof. Ahola and the author contributed to the preparation of the final version of the manuscript by revision comments and suggestions.

**Publication III** introduces an LVDC system with the requirements for communication set by the LVDC concept and applications integrated into the system. PLC is considered a feasible communication solution for the LVDC, and a communication architecture for the LVDC system is proposed. An inductive PLC coupling method for the system is introduced, and PLC channel characteristics are studied in an LVDC laboratory system prototype by measurements. In addition, noise in the channel is analyzed in brief. Based on the measurements, a PLC-based network for the LVDC is proposed. Further, the feasibility of the concept is assessed theoretically by a signal-to-noise ratio (SNR) analysis in the LVDC system, and the theoretical channel capacity of the PLC channel is studied. Finally, the data transmission throughput between the PLC modems coupled to the LVDC system is tested. The main contribution of this publication is to study the PLC network structure for the LVDC system.

The LVDC laboratory prototype system was constructed by the coworkers Mr. Nuutinen and Dr. Peltoniemi in the research project. The measurements for the analysis of channel characteristics and implementation of the PLC data transmission link to the LVDC laboratory setup were carried out by the author and the coauthor Prof. Ahola. The results were analyzed and the manuscript was mainly written by the author. The coauthors Prof. Ahola and Dr. Kosonen contributed to the preparation of the final version of the manuscript by revision comments and suggestions.

**Publication IV** continues and deepens the study of the PLC network for the LVDC system. The LVDC distribution system is presented, and PLC modems
with the analysis of the inductive coupling method for the system are described. The measurements for the analysis of the PLC channel characteristics in the LVDC system are presented. Based on these, the applicability of the HF band and NB PLC techniques for the system is discussed. As a result, the HF band PLC is found to be the more suitable one for the application. In addition, an IP-based PLC concept consisting of an inductive coupling method that applies standardized commercial HomePlug 1.0 PLC modems, network structure, and power supply for the devices within the concept is presented for LVDC distribution systems. In addition, the suitability of the PLC concept and its advantages and limitations are studied.

The measurements were carried out by the author and the coauthor Prof. Ahola. The results were analyzed and the manuscript was mainly written by the author. The coauthors Prof. Ahola and Dr. Kosonen contributed to the preparation of the final version of the manuscript by revision comments and suggestions.

**Publication V** pursues the applicability study of the PLC concept, and focuses on the modeling of the HF signal propagation in the PLC channel in an LVDC laboratory prototype system implemented with one-phase customer-end inverter. A two-port modelling method is applied to each component in the PLC channel in the LVDC system. Modeling of HF signal propagation in a low-voltage power cable with the two-conductor transmission line model implemented with a circuit simulator is presented. The HF band LVDC PLC channel model applied in the circuit simulator is constructed.

The input impedance measurements were carried out and the corresponding two-port input impedance model for each component in the LVDC PLC channel was built by the author. The channel model including a model for the power cable applied with the circuit simulator was formed by the author with the coauthors. The main contribution of this publication is the simulation model and its verification by measurements. The publication was mainly written by the author. The coauthors Prof. Ahola and Dr. Kosonen contributed to the preparation of the final version of the manuscript by revision comments and suggestions.

**Publication VI** focuses on the noise in the PLC channel in the LVDC laboratory and the field installation system upgraded with a three-phase inverter and improved common-mode EMI filtering. An LVDC PLC channel noise analysis is carried out by measuring noise signal samples from the terminals of the inductive couplers by an oscilloscope. The noise waveforms of the measured noise samples are analyzed. In addition, the variation of the frequency-domain noise power spectral densities (PSDs) related to time is analyzed by calculating a periodogram for the segments
of noise samples. The effects of noise on the performance of the HF band PLC are studied. A theoretical PLC performance analysis is carried out by an SNR analysis with measurements of the channel characteristics and noise PSDs estimated from the measured noise samples in the upgraded LVDC system. The noise analysis is compared and supported by data transmission tests between the HF band PLC modems coupled to the channel ends both in the laboratory and the field installation. The applicability of the PLC concept is verified.

The channel characteristic and noise sample measurements in the upgraded LVDC laboratory setup and the LVDC field installation system were carried out by the author. The contents of this publication were produced and written by the author. The coauthor Mr. Nuutinen contributed to the measurements carried out in the LVDC field installation system. The coauthors Prof. Ahola and Dr. Kosonen contributed to the preparation of the final version of the manuscript by revision comments and suggestions.

Publication VII presents the LVDC PLC channel characteristics including special features of the channel and an analysis of how the channel characteristics differ from the PLC channels in traditional AC electricity distribution systems. The LVDC PLC constitutes one subsection of the second edition of the book *Power Line Communications: Principles, Standards and Applications from Multimedia to Smart Grid* (Wiley & Sons). The material to the book is written by the author. Professor Ahola and Dr. Kosonen contributed to the preparation of the text by revision comments and suggestions.

The author has also been a coauthor in the following publications on closely related topics. These publications are excluded from the thesis.


1.5 Scientific contributions

The scientific contributions of this doctoral thesis are:

- Proposal for a HF band power line communication concept for an LVDC electricity distribution system (Publications III, IV and VII).
- Study and implementation of an inductive coupling method applied to form an HF band PLC channel in bipolar LVDC grid between short-circuited neutral DC conductors (Publications III and IV).
- Measurements and analysis of PLC channel characteristics in the LVDC system (Publications III–VI).
- Noise analysis of the noise in the PLC channel from the terminals of PLC couplers in the LVDC laboratory and the field installation system (Publication VI).
- Study of channel component models in the LVDC system, and based on these, the design of a two-conductor channel model in the frequency band of 100 kHz–30 MHz (Publication V).
- Theoretical information capacity analysis of the LVDC communication channel (Publications III and IV).
- Throughput and latency analysis of the studied PLC concept in the LVDC laboratory and the field installation system (Publications IV and VI).
- Application of software-defined radios (SDR) to study the PLC modulation schemes and their performance in a motor cable communication channel between a frequency converter and a motor (Publication I).
- Analysis of HF band PLC channel characteristics in motor cable communication with an inductive coupling between a frequency converter and a motor (Publication II).
2 PLC concept for an LVDC distribution system

In this chapter, a PLC-based data transmission concept for an LVDC distribution system is introduced. The characteristics of the PLC concept including selection of a viable frequency band and the PLC coupling method are covered. The analysis is based on the LVDC PLC channel structure and the performance requirements set on the communications by the LVDC smart grid dimensions and applications.

2.1 Data transmission concept

The structure and design of the PLC network architecture are basically determined by the architecture of a bipolar LVDC distribution system. The length of the bipolar LVDC power grid may be 1–5 km from the rectifier to the customer-end inverters (CEIs). The LVDC grid between the rectifier and the CEIs is typically constructed by underground low-voltage cables with a maximum length of 500 meters; the cables and the conductors are coupled together in over-ground cable-connection cabinets (CCC) on the grid branches. This provides an opportunity to install PLC repeaters to the grid. The proposed data transmission concept is illustrated in Figure 2.1 (Publication IV). For the sake of interoperability of devices and applications in the LVDC grid, and the extensibility of the LVDC PLC-based network, the data transmission network is IP based. In addition, the cross-section structure and coupling method of the AXMK underground low-voltage power cables (commonly used in LV distribution grids) in constructing the LVDC grid between the rectifier and the CEIs provide an alternative to divide the PLC network into segments of a certain length. This is made possible by applying inductive PLC couplers to connect the PLC modems to the LVDC channel. The PLC signal repetition function in the LVDC grid branches is handled by commercial Ethernet switches, which are placed in an over-ground cable connection cabinet. The power supply for the PLC modems and Ethernet switches in these cabinets is provided by an additional DC/DC converter (Figure 2.1b). The architecture makes it possible to freely communicate with IP between the nodes.

Figure 2.1: PLC data transmission concept in the bipolar LVDC distribution system (a). The contents of the cable connection cabinet, where the short-circuited N conductor loops of two cable reels and the network segments are connected with the inductive couplers, PLC modems, and an Ethernet switch (b).
2.2 LVDC PLC Channel

The simplified PLC data transmission concept in the bipolar LVDC system is illustrated in Figure 2.2. For the sake of simplicity, only one power cable branch is presented. The bipolar LVDC distribution system, in general, consists of a double-tier MV/LV transformer, which is supplied from the MV distribution line branch grid. The AC power is converted to DC by a rectifier bridge (RB), and the DC power is transferred through an underground low-voltage power cable to a CEI implemented with insulated gate bipolar transistors (IGBTs). The CEI supplies the customer loads with 230 VAC. Recommendable cables to be installed in the traditional LV underground cabling (UGC) electricity distribution networks, and which are thus also applicable to the bipolar LVDC system, are AXMK with four phase conductors, and/or AMCMK with three phase conductors and concentric protective earth (PE) conductor low-voltage UG power cables delivered in cable reels of 500 m. As proposed in the PLC concept in Publications III and IV, and illustrated in Figure 2.1, the PLC channel is formed by applying inductive couplers connected differentially between the short-circuited AXMK...
2.2 LVDC PLC Channel

Figure 2.3: Cross-section of cross-linked polyethylene (PEX) insulated AXMK 4x16 mm² and polyvinylchloride (PVC) insulated AMCMK 3x16+10 mm² underground cables commonly used in low-voltage AC electricity distribution grids. Signal couplings for the input impedance measurements are depicted; the NN and LN couplings for the AXMK cable and the LN and NPE coupling for the AMCMK cable.

cable N conductors (from here on referred to as NN coupling) in the DC network. However, the AXMK cables are not always available. For example, power supply cables with three-phase conductors, which are also commonly used in low-voltage underground distribution networks, do not provide such short-circuited conductor loops. Hence, the PLC channel is formed with the inductive couplers coupled between the neutral (N) and other DC (L) conductor (from here on referred to as LN coupling). The LN coupling is studied with an AMCMK (3x16+10 mm²) cable and also with the AXMK (4x16 mm²) cable. The PLC concept when the AMCMK cable with three-phase conductors is used for DC power transmission between the rectifier and the CEI is depicted in Figure 2.2b. The AMCMK cable PE conductor is connected to the casing of the rectifier and the CEI in the channel ends. The cross-sections of the AXMK and AMCMK low-voltage power cables with the proposed cable conductor coupling alternatives are depicted in Figure 2.3.

The selection of an optimal frequency band for PLC between the rectifier and the CEIs in the LVDC grid is a sum of several factors, comprising the required bandwidth, latency, available commercial technology, and consequently, signal attenuation in the power cable, noise power spectral density (PSD) in the channel, and allowed available signaling power. All these factors have an effect on the quality of the communication channel, and thus the selection of the optimal frequency band.

2.2.1 Low-voltage power cable as a PLC medium

When low-voltage power cables are used for power line communications, signal attenuation in the cable is the most important parameter. It defines mainly the maximum signaling range, when the network topology, available transmission power, and the noise PSD at the receiver are known. Low-voltage cables are lossy; the signal propagating in the cable is attenuated because of the losses in the cable insulation
material and its characteristics. The signal attenuation in the cable increases as a function of frequency. In addition, the terminations of the low-voltage cables are never matched at the frequencies used in PLC because of the time-varying loads in the LVDC distribution network. Thus, there are impedance mismatches in the channel ends, that is, in the conductor terminals. Further, in the case of a branched grid topology, such as distribution grids, steep notches owing to the multipath propagation and impedance mismatches in the channel ends and branches are generated in the frequency response of the communication channel. Accordingly, these frequencies are unfavorable for the PLC.

The loss mechanisms experienced by a signal propagating in the cables can be divided into resistive losses of the conductors, dielectric losses of the insulation, radiation losses, and insertion and coupling losses. From these, the main loss mechanisms of low-voltage power cables at the signal frequencies used for PLC are the dielectric, resistive, and insertion losses (Ahola, 2003). The insertion losses are caused by transmission line discontinuities, such as mechanical connections or cable type changes, and their amount is dependent on the cables and the topology of the LVDC grid, the applied signal frequencies, and the load terminations, which are the rectifier and the CEIs in the LVDC system. The resistive losses of the conductors are caused by the finite conductivity of conductors. Because of the skin effect, the current is forced to flow on the surface of the conductor at high frequencies. The behavior of the conductor resistive losses can be presented with the relation \( r \sim \sqrt{f} \). The cable insulation material causes dielectric losses. According to (Ahola, 2003), the signal attenuation in PVC-insulated low-voltage power cables increases steeply with the frequency in the frequency band of 100 kHz–30 MHz, which makes it challenging to apply HF band PLC techniques in the long cable distances. However, the underground DC low-voltage cable network in the LVDC system provides an opportunity to repeat the PLC signal within 500 meters and thereby an advantage in the case of PEX-insulated AXMK cable NN couplings when the communication network is divided into segments. Thus, the application of the HF band PLC is studied.

2.3 Noise in the LVDC PLC channel

Noise and its effects on the PLC performance have been extensively studied. Modeling and analysis of the noise with its effects on the broadband PLC are studied in (Andreadou and Pavlidou, 2010) and (Meng et al., 2005). According to (Tang et al., 2003), the noise in power line communication media is presented by a nonadditive white Gaussian noise (non-AWGN). According to (Zimmermann and Dostert, 2002; Andreadou and Pavlidou, 2010), noise in power-line channels can be divided into five categories:
2.3 Noise in the LVDC PLC channel

1) Colored background noise with a relatively low-frequency variant PSD, caused by numerous weak noise sources.

2) Narrow-band noise consisting of sinusoidal signals with modulated amplitudes. The sources of the NB noise are broadcast stations, and the noise levels vary with the time of the day.

3) Periodic impulsive noise that is asynchronous to the mains frequency, generally caused by switched-mode power supplies. The impulses have generally a repetition rate of 50–200 kHz.

4) Periodic impulsive noise that is synchronous to the mains frequency, commonly caused by switching actions of rectifier diodes used in many electrical appliances. The duration of impulses that have a repetition frequency of 50 and 100 Hz (synchronous to the mains cycle) are short (microseconds).

5) Asynchronous impulsive noise, caused by switching transients in the distribution network. The impulses can be 50 dB higher compared with the background noise, with the duration between microseconds and a few milliseconds.

The noise in the LVDC PLC channel is mainly impulsive. The noise is generated by the rectifier bridge (usually implemented with diode-thyristor bridges) in one end, and the CEIs implemented with IGBTs in the other ends of the branched DC grid. The LVDC PLC channel is quite analogous to the channels in motor-cable communication in inverter-fed electric drives, between the motor and an inverter, as presented in Publications I and II, and studied in (Ahola, 2003; Kosonen, 2008). The main difference is that in this application, the communication is carried out within the inverter DC link. In motor cable communication (Publication II), the data transmission is carried out between the IGBTs and the load (after DC-AC conversion). However, the impulsive noise generated by the inverter switchings of the IGBTs, and to a certain degree, also the change in the impedance are conducted to the DC side. At the inverter, high-frequency noise is produced by the high switching frequency and steep voltage rise times. According to (Bartolucci and Finke, 2001), the output voltage rise and fall times of a PWM inverter with the new IGBTs may be between 0.1 and 10 µs. Typically, the switching frequency $f_{sw}$ (between different states) of the inverter IGBTs is from a few up to tens of kilohertz. According to (Silventoinen, 2001), the inverter acts mainly as a common-mode emission source in the frequency range of 9 kHz and 30 MHz. Furthermore, the noise generated by the inverter is impulsive and asynchronous to the mains frequency. The impulsive noise signals are injected into the supplying network according to the switching instants of the IGBTs, proportional to the $f_{sw}$. Thus, the impulsive noise generated by the inverter contains impulses with a repetition to $f_{sw}$ and its harmonics. In addition, according to (Lana et al., 2010), the CEI generates 100 Hz harmonics from the 50 Hz AC voltage to the DC side.

In the other channel end, there is a rectifier bridge, and thus, the whole LVDC system is analogous to a DC voltage link inverter, as discussed in (Ahola, 2003). The conducting and commutating state changes in the rectifier bridge connected to phases P1, P2, and P3 generate harmonic impulsive noise synchronous to the mains frequency of the channel. The rectifier generates mainly current and voltage harmonics into the
supplying AC network and also to the output, the DC side. Commonly, there are DC link capacitors connected to the output of the rectifier-bridge between the N and DC conductors in the bipolar LVDC system. The harmonic components are generated by each diode-thyristor rectifier conducting, and simultaneously, the DC capacitor charging. The frequency content of the harmonic components depends on the sizes of the DC link capacitors and inductors, and the load of the inverter (Ahola, 2003). The commutation of the rectifier generates impulsive noise with a wide frequency spectrum. The frequency content of the commutation covers a higher frequency band than those of the harmonics. According to (Silventoinen, 2001), the rectifier is a major noise source of differential mode emissions conducted in the frequency band of 9 kHz–2 MHz. Thus, the impulsive noise generated by the commutation is more harmful to the PLC than the harmonics. In addition to the impulsive noise generation because of the switchings between different states, the rectifier and the CEIs as active components act as time-varying impedance terminations in the channel ends. Thus, the LVDC PLC channel, as a linear periodically time-varying system is analogous to the indoor PLC channels (because of the effect of the mains voltage ~230 VAC), which are widely studied, for instance in (Cortés et al., 2009; Barmada et al, 2011). Accordingly, the LVDC system, in other words, the DC grid, is a harsh environment to the PLC; the PLC modems are connected next to the rectifier and the CEIs. According to Publications I and II, the majority of noise power is concentrated on the frequency band of 0–5 MHz in such a channel. In addition, the impulsive noise components generated by the switching of inverters to the DC grid are significantly stronger in the frequency range from kilohertz to megahertz frequencies compared with the traditional AC grids. Hence, the application of NB-PLC in the CENELEC band (used in Europe) could be very challenging within the concept. This of course depends on the content of the noise frequency spectrum.

### 2.4 Signal coupling method

Choosing the optimal PLC signal coupling method for the application is based on the LVDC PLC channel description and noise in the channel. The coupling method of the AXMK cable conductors in the bipolar LVDC system (Figure 2.2) and the cross-section of the AXMK and AMCMK low-voltage power cables (Figure 2.3) provide basically the following alternatives for the PLC coupling:

1) PLC couplers connected between the N conductors or between the ±DC conductors; the cable conductor structure is symmetric from the PLC perspective.

2) PLC couplers connected between N and –DC or between +DC and N; the cable conductor coupling is asymmetric.

The second alternative is analogous to the LN coupling in the AMCMK low-voltage underground cable. However, owing to the connection of the low-voltage underground cables to the CEIs in the bipolar LVDC system, the PLC signal coupling between the
The short-circuited loops between the AXMK NN conductors, that is, the NN coupling provide the following advantages over the LN couplings to the PLC signal couplings:

1) The communication channel/network can be divided into segments of a certain length (max 500 m) without branches, while the channel with the LN coupling includes branches.
2) The loads and load impedance changes caused by the CEIs do not affect the impedance of the PLC channel, which remains constant.

In addition, because of the short circuit between the NN conductors, capacitive PLC couplers cannot be used, but inductive ones are appropriate and provide the following advantages with the NN conductor loops (Publication IV):

1) Low-impedance channel for the HF current signal.
2) Installation advantage; no galvanic coupling is required for LV cables, and inductive couplers are not prone to over-voltages that might occur on the grid.
3) The common-mode interferences in the N conductors, which are currents generated by the PE devices attached to the grid, are canceled by each other with the transformer coupling formed by the inductive couplers.

For these reasons and based on the analysis of the LVDC PLC channel characteristics and noise in the channel discussed above, inductive couplers are chosen to be studied for the PLC concept. The inductive couplers have previously been studied in motor cable communication between an inverter and an electric motor in (Kosonen, 2010). The designed inductive coupler for motor cable communication is tuned for the LVDC PLC concept. The inductive coupling interfaces (ICI) couple the PLC modems differentially to the underground low-voltage cables between two phase conductors NN or LN as illustrated in Figures 2.1 and 2.2, and in series with the PLC channel and its impedance terminations. Therefore, the inductive couplers are not commonly used in consumer applications, which are based on connection to an electrical wall socket. Inductive couplers have mainly been applied to broadband communication in the HF band in MV electricity distribution grids (see e.g. Lee et al., 2010).
2.5 Architecture of the PLC-based data transmission network

Based on an analytical study of the LVDC PLC channel, the UGC segment lengths, channel noise characteristics, and the proposed inductive coupling method, the frequency band applicable to the PLC concept is the HF band of 3–30 MHz. Consequently, HF band PLC is chosen for the basis of the PLC concept. The architecture and management of the PLC data transmission network concept as well as devices used to form the PLC network are proposed. The main features of the PLC concept, gathered from Publication IV, are presented in Table 2.1.

<table>
<thead>
<tr>
<th>Network devices, architecture and management</th>
<th>Features</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Network architecture</td>
<td>Segmented IP and PLC-based; extendable network Dynamic IP addresses by router</td>
<td>500 m network segments, repeaters on grid branches</td>
</tr>
<tr>
<td>Communication network components</td>
<td>Commercial Ethernet router and switches</td>
<td>Requires DC/DC power supply in CCCs</td>
</tr>
<tr>
<td>Applicable PLC techniques</td>
<td>HomePlug 1.0 (4.49–20.7 MHz)</td>
<td>Sufficient data rate for SG apps. No synchronization to AC cycle Operate as bridges over network</td>
</tr>
<tr>
<td></td>
<td>HomePlug Green Phy</td>
<td>Designed for SGs, Not tested in the LVDC network</td>
</tr>
<tr>
<td>Network management</td>
<td>DES encryption Device IPs based on MAC addresses, managed by router</td>
<td>Network crashes prevented The same encryption keys with modem pairs</td>
</tr>
</tbody>
</table>

The objective was to find an applicable commercial PLC technique. A suitable PLC technique for the concept is a commercial HomePlug 1.0 protocol by HomePlug® Powerline Alliance, primarily used in the in-house broadband over powerline (BPL). HomePlug 1.0 does not apply frequency synchronization to the AC voltage cycle, which is applied in the newer HomePlug standards/definitions (Lee et al., 2003; HomePlug, 2005). This is the synchronization of the medium access control (MAC) layer; the MAC frame is adapted for the link conditions, and the SNR for the impulsive noise synchronous to the mains cycle (Katar et al., 2006; Tonello, 2009). This synchronization to the AC cycle function is not viable for the LVDC distribution system. In HomePlug 1.0 physical (PHY) layer, an orthogonal frequency division multiplexing (OFDM) multicarrier technique for communications in the frequency band between 4.49 and 20.7 MHz is applied. OFDM is one of the most common techniques in new NB-PLC and BPL technologies (Chang and Liu, 2012; Bingham, 1990). In the OFDM, information is distributed among many closely spaced narrowband subcarriers, where data are transmitted in parallel. The main advantages of the OFDM are the effective use of the spectrum, its ability to tolerate the effects of impulsive noise, and amplitude and phase distortions (Saltzberg, 1967), and finally, robustness in multipath environments (Steer, 2007). The frequency band reserved for communications in HomePlug 1.0 is divided into 84 evenly spaced subcarriers, eight of which are permanently masked to avoid interference with amateur radio bands. The bandwidth of...
2.5 Architecture of the PLC-based data transmission network

each subcarrier is 195.3125 kHz, and the duration of a single symbol is 8.4 µs, consisting of 5.12 µs for an OFDM symbol, and 3.28 µs for the cyclic prefix (CP). The HomePlug 1.0 PHY layer detects the channel conditions by using channel estimation for adaption by avoiding poor subcarriers, and selects an appropriate modulation method and coding rate for the remaining subcarriers. The maximum data rate of HomePlug 1.0 is 13.78 Mbps in the PHY layer, and 6.3 Mbps in the transmission control protocol (TCP) layer. These data rates are sufficient for smart grid applications integrated into the LVDC system. In addition, the novel HomePlug Green PHY designed especially for In-Home smart grid powerline communications could also be used as a basis of the LVDC PLC concept (HomePlug GP, 2012). The main features of the two HomePlug specifications and the key differences between them are listed in Table 2.2 (Lee et al., 2003; HomePlug GP, 2012; Zyren, 2011).

Table 2.2: Main features of HomePlug 1.0 and HomePlug Green PHY.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>HomePlug 1.0</th>
<th>HomePlug GP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrum</td>
<td>4.49–20.7 MHZ</td>
<td>2–30 MHZ</td>
</tr>
<tr>
<td>Modulation</td>
<td>OFDM</td>
<td>OFDM</td>
</tr>
<tr>
<td>Subcarriers</td>
<td>84</td>
<td>1155</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>195.3125 kHz</td>
<td>24.414 kHz</td>
</tr>
<tr>
<td>Supported subcarrier</td>
<td>DQPSK, DBPSK</td>
<td>QPSK only</td>
</tr>
<tr>
<td>modulations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data FEC</td>
<td>¾ and ½ convolution</td>
<td>Turbo code</td>
</tr>
<tr>
<td></td>
<td>code and Reed-Solomon code</td>
<td>Rate ½ only</td>
</tr>
<tr>
<td></td>
<td>ROBO: ½ convolution</td>
<td>ROBO modes: Mini;</td>
</tr>
<tr>
<td></td>
<td>code and Reed-Solomon code</td>
<td>*#5, Standard; *#4,</td>
</tr>
<tr>
<td></td>
<td>each bit repeated four times</td>
<td>High speed; *#2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(*degree of repeat copies)</td>
</tr>
<tr>
<td>Supported data rates</td>
<td>ROBO 1.02 Mbps</td>
<td>ROBO: 3.8–9.8 Mbps</td>
</tr>
<tr>
<td></td>
<td>4.59–13.78 (dependent on modulation and coding)</td>
<td>(dependent on degree of repeat coding)</td>
</tr>
</tbody>
</table>

HomePlug 1.0 modems operate as transparent network bridges across the connection in the channel and make it possible to implement an IP-based network with standardized Ethernet packets over the LVDC PLC network. The segmented IP-based PLC concept also provides extendibility; Ethernet-based techniques and branches to the network can be added in parallel or in series with the PLC concept keeping the network architecture simple at the same time. Furthermore, the PLC concept of the LVDC grid can be extended simply and transparently to the customers’ IP-based network. More specific features of the LVDC PLC data transmission network are listed in Publications III and IV.
2 PLC concept for an LVDC distribution system
3 LVDC PLC Channel

In this chapter, the LVDC PLC channel is studied in detail, and its general channel model is described. The channel is analyzed by dividing it into individual components, and the HF characteristics of each channel component are modeled based on input impedance measurements. Accordingly, models for individual channel components are constructed. The applied frequency band is 100 kHz–30 MHz.

3.1 LVDC PLC channel modeling

Generally, modeling of PLC channels in the frequency domain is approached by two methods. The channel can be modeled by an echo model, where the model parameters are obtained by measurements (Phillips, 1999; Zimmermann and Dostert, 2002b). The analytic model presented in (Zimmermann and Dostert, 2002b) represents complex transfer functions of typical power line networks. The individual paths of signal components in the network are composed by superposition.

The other approach to modeling the channel is based on two-port models presented in (Banwell and Galli, 2001). In the studied LVDC PLC concept, the channel and its structure are rather simple and well known. The NN coupling in the AXMK power cable is a special case; the channel structure remains unchanged, only the channel length varies. Furthermore, the channel does not contain branches and can thus be considered analogous to the motor cable communication channel studied in (Kosonen, 2008). Moreover, the effects of impedance changes in the channel ends between the N and L conductors have no effect on the NN loop channel characteristics. In the LN coupling, the impedance terminations in the channel ends and the branches in the channel have an effect on the frequency-dependent and time-varying impedance of the channel.

Thus, and according to (Ahola, 2003), the appropriate modeling method in the frequency domain in channels where the topology is known as in the motor cable communication channel covered in (Konaté et al., 2010) is a bottom-up approach. The bottom-up method is based on a theoretical derivation of model parameters, and this versatile and flexible modeling method clearly describes the relationship between the network behavior and the model parameters (Ahola et al., 2004).

The proposed data transmission concept implemented to the LVDC laboratory setup built at Lappeenranta University of Technology is illustrated in Figure 2.2. The components used in the setup are listed in Table 3.1.
Table 3.1: Components used in the LVDC laboratory setup and in the PLC channel.

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Operation parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-voltage transformer</td>
<td>Trafotek DdOy11 3PU300/330</td>
<td>( P_n = 18/18 ) kVA</td>
</tr>
<tr>
<td>Diode-thyristor rectifier</td>
<td>Semikron SKKH13216E</td>
<td>( P_n = 2 ) kV, ( I_{sc} = 100 ) A</td>
</tr>
<tr>
<td>Rectifier end DC capacitors</td>
<td>EPCOS B43310-A5129-M</td>
<td>( U_n = 450 ) V</td>
</tr>
<tr>
<td>Low-voltage power cable</td>
<td>AXMK 4x16 mm², 198 m</td>
<td>( U_n = 900 ) VDC</td>
</tr>
<tr>
<td></td>
<td>AMCMK 3x16+10 mm², 122m</td>
<td>( U_n = 900 ) VDC</td>
</tr>
<tr>
<td>CEI end DC capacitor</td>
<td>Cornell Dubliner 947C471K102CDMS</td>
<td>( U_n = 1000 ) V</td>
</tr>
<tr>
<td>CEI IGBT bridge</td>
<td>Semikron SKiM 400GD126DM</td>
<td>3-phase IGBT</td>
</tr>
<tr>
<td>Isolation transformer</td>
<td>Dyn11 400/400 V</td>
<td>( P_n = 16 ) kVA, ( I_{sc} = 200 ) A</td>
</tr>
<tr>
<td>PLC couplers: Ferrite rings</td>
<td>Ascom powerline IC-R-27-200</td>
<td>( I_{sat} = 200 ) A</td>
</tr>
</tbody>
</table>

3.2 Low-voltage underground cable

The channel modeling approach chosen for the LVDC PLC channel is based on the analysis of low-voltage power cables applied in the concept. In the PLC concept, the PLC modems are coupled differentially between two conductors of the cable. For this reason and the fact that each CEI is supplied between +DC/−DC and 0 V, the two-conductor transmission line analysis is selected despite the fact that the AXMK and AMCMK low-voltage cables used in the LVDC system are multiconductor transmission lines (MTL). The number of conductors of both these cables is four. Application of MTL equations for a four-conductor cable is introduced for example in (Paul, 1994), and (Sartenaer and Delogne, 2001). According to them, the per-unit length parameters can be determined by applying analytical or numerical methods. These methods are relatively complex, and because of the PLC coupling and the CEI connection between two cable conductors, the application of the two-conductor transmission line analysis is justified and chosen for the first approximation. Despite the simplicity of the two-conductor model analysis compared with the MTL analysis, the signal attenuation in the cable and the cable characteristic impedance can be determined with it. In addition, the two-conductor analysis can also be selected for the modeling approach of the cables, and further, of the termination impedances; the rectifier and the CEIs, and the PLC couplers, which are all connected between the neutral (0 V) and the +DC pole or −DC pole. Generally, this simplifies the modeling of termination impedances.

3.2.1 Transmission line parameters

Distributed cable parameters, which define for example the signal attenuation in the cable, can be derived from the two-conductor transmission line model. In the two-conductor model, the crosstalk with the conductors not used in the signaling is neglected (Ahola, 2003). The differential length of dx of the two-conductor transmission line with the lumped parameter approach is depicted in Figure 3.1, from which the transmission line equations can be derived. The voltage and current in the transmission line can be presented with partial differential equations (Heaviside, 1899):
3.2 Low-voltage underground cable

Figure 3.1: Descriptive circuit of the differential length $dx$ and the lumped parameters $r$, $l$, $g$, and $c$ of the two-conductor transmission line model.

\[
\frac{\partial u(x,t)}{\partial t} = -ri(x,t) - l \frac{\partial i(x,t)}{\partial t}, \tag{3.1}
\]

\[
\frac{\partial i(x,t)}{\partial t} = -gu(x,t) - c \frac{\partial u(x,t)}{\partial t}, \tag{3.2}
\]

where $r$, $l$, $g$, and $c$ are the distributed resistance, inductance, conductance, and capacitance of the transmission line, respectively. The variables $x$ and $t$ denote place and time. For the sinusoidal and stationary voltage and current, we may write

\[
U(x) = U^+ e^{-\gamma x} + U^- e^{\gamma x}, \tag{3.3}
\]

\[
I(x) = \frac{1}{Z_0} (U^+ e^{-\gamma x} - U^- e^{\gamma x}), \tag{3.4}
\]

where $U$ and $I$ are the sinusoidal voltage and current, $Z_0$ is the characteristic impedance, and $\gamma$ the propagation constant. The electromagnetic wave propagates both in the $+$ and $-$ directions along the transmission line length $x$. The propagation constant $\gamma$ defines the propagation speed and attenuation of the electromagnetic wave according to

\[
\gamma = \sqrt{(r + j\omega l)(g + j\omega c)} = \alpha + j\beta, \tag{3.5}
\]

where $\alpha$ is the attenuation coefficient and $\beta$ is the propagation coefficient. The characteristic impedance of the transmission line is

\[
Z_0 = \sqrt{\frac{r + j\omega l}{g + j\omega c}}. \tag{3.6}
\]
In addition to the two-conductor transmission line theory, the characteristic impedance of the line and cable parameters can be determined by performing input impedance measurements for the transmission line. Input impedances of the cable are measured when the other end of the cable is first open circuited and then short circuited. When the cable end is open, the current at the cable end is zero, and when the cable end is short circuited, the voltage at the cable end is zero. The complex input impedance for the open circuit \( Z_{in,oc} \) and for the short circuit \( Z_{in,sc} \), with the cable length \( Len \), are given by

\[
Z_{in,oc} = Z_o \cotanh(\gamma Len),
\]

\[
Z_{in,sc} = Z_o \tanh(\gamma Len).
\]

The characteristic impedance \( Z_0 \) of the line can be solved from (3.7) and (3.8) by

\[
Z_0 = \sqrt{Z_{in,oc} Z_{in,sc}}.
\]

Now, the propagation constant can be written as

\[
\gamma = \frac{1}{Len} \arctanh \sqrt{\frac{Z_{in,sc}}{Z_{in,oc}}},
\]

The real part of the propagation constant is the attenuation coefficient \( \alpha \), and the imaginary part is the propagation coefficient \( \beta \) as presented in (3.5). The distributed inductance \( l \) and the capacitance \( c \) of the cable can be determined with the characteristic impedance \( Z_0 \) and the propagation constant \( \gamma \) from (3.9) and (3.10), respectively, by

\[
l = \frac{\text{Im}[Z_o \gamma]}{\omega},
\]

\[
c = \frac{\text{Im}[\gamma Z_o]}{\omega}.
\]

Accordingly, the distributed resistance \( r \) and the conductance \( g \), which together specify the attenuation coefficient \( \alpha \) that determines the losses of the cable, can be defined with (Collin, 1992; Wei and Li, 2006)

\[
r = \text{Re}[Z_0 \gamma],
\]

\[
g = \text{Re}[\frac{\gamma}{Z_0}].
\]
3.2 Low-voltage underground cable

The attenuation coefficient $\alpha$ comprises the resistive losses of conductors and the dielectric and resistive losses of the insulation material. The attenuation coefficient is obtained from (3.5) as

$$\alpha = \Re[\gamma].$$ (3.15)

3.2.2 Cable input impedance measurements

The cable parameters and the attenuation coefficient and characteristic impedance of the transmission line are determined by input impedance measurements carried out for two underground cable types used in the LVDC laboratory setup, and commonly used in low-voltage AC distribution networks. The cables are AXMK 4x16 mm$^2$ of 198 m and AMCMK 3x16+10 mm$^2$ of 122 m. Based on the measurements, a two-conductor transmission line model is constructed for the cables. From the PLC perspective, the frequency band of 100 kHz–30 MHz and the coupling between the NN and LN conductors are the most interesting ones. The observed frequency band covers the commonly used PLC techniques in applications of this kind. The focus of the study on the NN and LN coupling cases only is justified by the application in question; the CEIs in the bipolar LVDC system are connected to the DC grid from between the ±DC pole and N. The cross-sections of the AXMK and AMCMK cables with the measured signal couplings are illustrated in Figure 2.3. The input impedances for the (N, N) and (L, N), signal couplings were measured; first, the cable end was left open and then short circuited. The input impedance measurements were carried out with an HP 4194A impedance analyzer and an HP 41941A impedance probe kit. A linear frequency sweep with 401 data points including frequency, absolute value, and phase for the frequency band of 100 kHz–30 MHz was stored. The input impedance measurements for the NN and LN coupling cases in the AXMK cable and the LN coupling case in the AMCMK cable are illustrated in Figures 3.2–3.4. The cable parameters and attenuation coefficients for the AXMK and AMCMK low-voltage power cables were calculated from the input impedance measurements. The attenuation coefficient curves as a function of frequency for the AXMK and AMCMK cables are plotted in Figure 3.5. From the calculated attenuation coefficients in the cables, signal attenuations per-length in dB/m can be presented. This is a more illustrative way to present and estimate the PLC signaling range. The attenuation coefficients given by (3.15) as the signal attenuation per-length (500 m) in the AXMK and AMCMK cables are depicted in Figure 3.6.
Figure 3.2: Input impedance $|Z|$ and phase as a function of frequency between 100 kHz and 30 MHz for the AXMK 4x16 mm$^2$ cable of 198 m. The signal coupling is (N, N).

Figure 3.3: Input impedance $|Z|$ and phase as a function of frequency between 100 kHz and 30 MHz for the AXMK 4x16 mm$^2$ cable of 198 m. The signal coupling is (L, N).
Figure 3.4: Input impedance $|Z|$ and phase as a function of frequency between 100 kHz and 30 MHz for the AMCMK 3x16+10 mm$^2$ cable of 122 m. The signal coupling is (L, N).

Figure 3.5: Attenuation coefficients for the AXMK 4x16 mm$^2$ and AMCMK 3x16+10 mm$^2$ cable as a function of frequency in the frequency band between 100 kHz and 30 MHz. Attenuation coefficients are calculated from the input impedance measurements.
The signal attenuation coefficients of the measured cables increase as a function of frequency. This signal attenuation is also seen to cut the oscillation resonance peaks in the input impedance measurements in Figures 3.2–3.4, and is caused by the losses in the cable as a function of frequency. With long cables (length \( L_e \)) compared with the applied signal wavelengths (\( \lambda \ll L_e \)) at high signal frequencies, the electromagnetic wave reflected back from the impedance mismatch in the cable end is attenuated almost completely before it reaches the signal source point again. The attenuation is stronger with the AMCMK cable (oscillation in the input impedance has gone flat after 15 MHz) compared with the AXMK cable, even though the cable is 76 m shorter (Figure 3.4). Furthermore, as it can be seen in Figure 3.5, the signal attenuation in the AMCMK low-voltage cable is significantly stronger compared with the AXMK cable. This is mainly because of the dielectric losses in the insulation material used in the cables. The difference in the signal attenuation coefficient \( \alpha \) as a function of frequency between the (N, N) and (L, N) conductors in the AXMK cable is around 0.0015 \( 1/m \) at 20 MHz, and between the AXMK and AMCMK (L, N) coupling cases around 0.01 \( 1/m \), respectively, as seen in Figure 3.5. The insulation material in the AMCMK cable is PVC, while PEX is used in the AXMK cable. According to (Ahola, 2003), with the PVC-insulated MCMK low-voltage motor cables, the attenuation at the 20 MHz is approximately 110 dB/km. Based on the measurements carried out for the AMCMK cable, again, the attenuation is around 140 dB/km, while the attenuation for the (N, N) and (L, N) couplings in the AXMK cable is 45 dB/km and 55 dB/km, respectively. The dissipation
factor $\tan \delta$ describes the dielectric losses, and can be solved by (Bartnikas and Srivastava, 2003)

$$\tan \delta = \frac{\sigma}{\omega \varepsilon},$$

where $\sigma$ is the dielectric conductivity of the cable insulation material, $\omega$ the angular frequency, and $\varepsilon'$ the real part of complex permittivity of the cable insulation material. According to (Dostert, 2001), the general dielectric characteristics of PVC are heavily dependent on temperature, frequency, and the composition of the insulation material. According to (Harper, 1975), the dissipation factor $\tan \delta$ of the PEX is lower than for PVC; at 1 MHz $\tan \delta = 0.09–1$ ($\varepsilon_r = 3.5–4.5$) for PVC, and for PE $\tan \delta > 0.0005$. Furthermore, in the PE, the dielectric constant $\varepsilon_r$ (2.25–2.35) and the dissipation factor remain almost constant as a function of frequency and temperature. Moreover, as it can be seen from Figure 3.6, the signal attenuation in the (L, N) coupling is slightly stronger (around 5 dB at 20 MHz) compared with the (N, N) coupling in the AXMK cable. This is probably due to the cable conductor symmetry. In the (N, N) coupling, the cable cross-section is symmetrical from the propagating signal perspective. Thus, the resistive and dielectric losses between the N conductors could be smaller compared with the (L, N) coupling.

3.3 Cable modeling

The basic assumption in the cable modeling is that the majority of the HF signal power propagates between the two conductors. The signal conducted to the other unused cable conductors is neglected. A two-conductor simulation model for the studied cables in the time domain is formed with lumped parameters (Figure 3.1). The cable model is formed with single lumps connected in cascade, and is implemented with the circuit simulator in the OrCad PSpice. A single lump of the two-conductor cable model implemented with the circuit simulator is illustrated in Figure 3.7. The single lump contains the frequency-dependent resistance $r$ and the conductance $g$ implemented with Laplace units (GLAPLACE), and the inductance $l$ and the capacitance $c$. The circuit simulator provides the following advantages in the channel modeling: the channel characteristics can be analyzed and modeled both in the time and frequency domain, and the simulator provides ready-to-use components.
Figure 3.7: Single lump of a two-conductor cable model implemented with the circuit simulator. The distributed resistance $r$ and the conductance $g$ and their frequency dependencies are presented with GLAPLACE units.

The number of lumps ($n_{lump}$) in the cable model depends on the cable length $Len$ and the applied frequency band (e.g. wavelengths $\lambda$) to be modeled with a certain frequency resolution. With each lump, the measurement points consisting of the complex values for voltages and currents can be modeled for a certain limited frequency range. Thus, in the case of a frequency band between 100 kHz and 30 MHz, the number of lumps has to be higher, at least half of the length of the cable to be modeled. This is defined in the characteristics of the circuit simulator. Accordingly, the number of lumps used in the modeling is set equal to the cable length $Len$ in meters (1/m), and is thus 198 lumps for the AXMK cable and 122 for the AMCMK cable. Furthermore, the frequency-dependent $r$ and $g$ (and $l$ and $c$) have an effect on the cable model, and it is therefore logical to present them as $\Omega/m$ and $S/m$ (and $H/m$ and $F/m$), respectively. With this arrangement, the cable model is fitted with the measurements that are shown later on.

With the model, the behavior of current and voltage in $IN+$ and $IN−$ is affected in every lump (for certain frequency range) by the inductance $l$ and the capacitance $c$, which both are defined by the cable input impedance measurements by equations (3.11) and (3.12) for both cables and couplings. In addition, $l$ and $c$ are assumed to remain constant as a function of frequency. The model takes also into account the current skin effect, which affects the current skin depth $\delta$ and the resistance $r$ (the losses in conductors) as a function of frequency, as presented in (Ahola, 2003). In addition, the initial coefficients $h$ and $k$ for calculating the frequency-dependent resistance $r$ and the conductance $g$, which defines the attenuation coefficient $a(f)$ of the cable, are presented in the model (Figure 3.7). The attenuation coefficient comprises $a_s(f)$ generated by conductor losses (skin effect), which is expected to be proportional to $\sqrt{f}$, and $a_d(f)$ generated by dielectric losses within the insulation material, and is proportional to $f$ as presented in (Mello and Grivet, 2006). Therefore, the attenuation coefficient is formed and represented by

$$a(f) = a_r(f) + a_G(f) = r \cdot \sqrt{f} + g \cdot f.$$ (3.17)

Input impedances, first the cable end open circuited and then short circuited, are modeled. The model is tuned by $l$ and $c$, and initial values for $r$ and $g$ calculated from
3.4 Modeling of channel impedance terminations

The input impedance measurements. The cable parameters from the cable models are gathered and compared with the ones obtained from the cable input impedance measurements to validate the cable models. Table 3.2 lists the mean values for $l$, $c$, and $Z_0$ calculated from the measured input impedances that are used for the model parameters, and the modeled ones calculated from the modeled cable input impedances. In addition, the parameters for calculating the values for $r$ and $g$ in the model, the initial values for $h$ and $k$ are given. The values for $h$ and $k$ are tuned and iterated from the $r$ and $g$ calculated from the measurements by (3.13) and (3.14). Moreover, the correlation between the calculated signal attenuation coefficients $\alpha$ in the measured and modeled input impedances as a function of frequency for the AXMK NN and LN couplings, and the AMCMK LN coupling are listed in Table 3.2. As it can be seen, there is a close correlation between the measured and modeled values in the AXMK cable case. The attenuation coefficient in (3.17) does not fit very well the AMCMK LN coupling. Thus, the equation for the attenuation coefficient as a function of frequency $\alpha(f) \sim f^{0.6}$ for PVC-insulated cables presented in (Ahola, 2003) was applied to calculate the distributed $r$ in the cable model for the AMCMK cable case.

Table 3.2: Distributed $r$, $l$, $g$, and $c$, and characteristic impedance $Z_0$, with correlation of the attenuation coefficients $\alpha$ between the measured and modeled values for the AXMK and AMCMK cables in the frequency band of 100 kHz–30 MHz. The number of lumps used in the modeling is one per meter.

| Signal coupling | AXMK 4x16 mm² |  |  |  |  |  |  |
|-----------------|---------------|---------------|---------------|---------------|---------------|-------------|
| NN              | $r$ (\(\mu\Omega/m\)) | $l$ (nH/m) | $g$ (pS/m) | $c$ (pF/m) | $Z_0$ (\(\Omega\)) | Correlation in $\alpha$ |
| Measured        | 425.8         | 40.1          | 102.5        |  |  | 0.9974      |
| Modeled         | $h=14.29$    | $k=1,419$    | 39.9         | 103.3        |  |  | 0.9948      |
| LN              | $r$ (\(\mu\Omega/m\)) | $l$ (nH/m) | $g$ (pS/m) | $c$ (pF/m) | $Z_0$ (\(\Omega\)) | Correlation in $\alpha$ |
| Measured        | 384.1         | 43.73         | 94.66        |  |  | 0.9948      |
| Modeled         | $h=13.53$    | $k=3.03$     | 43.47        | 93.99        |  |  | 0.9643      |

AMCMK 3x16+10 mm²

| Signal coupling | LN |  |  |  |  |  |  |
|-----------------|-----------------|---------------|---------------|---------------|---------------|-------------|
| Measured        | 348.5           | 91.92         | 61.4          |  |  | 0.9643      |
| Modeled         | $h=69.93$      | $k=4.09$      | 90.82         | 62.06         |  |  | 0.9643      |

3.4 Modeling of channel impedance terminations

The transmission chain parameter matrices are commonly applied to the modeling of the transfer function of the channel. This analysis is applicable to transverse electromagnetic (TEM) waves, which have only transversal electrical and magnetic fields and no longitudinal fields. Resulting from the LV underground cable models, the components of the channel impedance terminations are modeled with a two-port approach. The relation between the input voltage $U_{in}$ and the current $I_{in}$ and the output voltage $U_{out}$ and the current $I_{out}$ is described in Figure 3.8a (Konaté et al., 2010), and can be present with
Figure 3.8: Two-port network channel model for the LVDC PLC channel (a). Transmission-matrix-based channel model for the concept (b).

\[
\begin{bmatrix}
U_{in} \\
I_{in}
\end{bmatrix} =
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}
\begin{bmatrix}
U_{out} \\
I_{out}
\end{bmatrix}.
\]

(3.18)

where \(A, B, C,\) and \(D\) are the frequency-dependent coefficient matrices. The frequency-dependent input impedance of the two-port network can be described with

\[
Z_{in} = \frac{AZ_L + B}{CZ_L + D},
\]

(3.19)

where \(Z_L\) is the load impedance. The transfer function of the channel can now be written as:

\[
H = \frac{U_{out}}{U_S} = \frac{Z_L}{AZ_L + B + CZ_L Z_S + DZ_S}.
\]

(3.20)

The channel components in the PLC medium are modeled by taking the two-port approach similarly as for the low-voltage power cables. The two-port models comprising the electrical parameters as presented in (Konaté et al., 2010; Kosonen, 2008) are formed for each component in the channel terminations. The parameters for the two-port models, that is, the serial and parallel impedances \(Z_s\) and \(Z_p\), are defined.
3.4 Modeling of channel impedance terminations for each channel component by input impedance measurements. The serial impedance $Z_s$ is measured when the component output is short circuited, and $Z_s$ and $Z_p$ are measured when the output is open circuited as illustrated in Figure 3.9. As Figure 3.9 shows, the transmission matrix for the serial and parallel impedances $Z_s$ and $Z_p$ can be calculated by

$$
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix} 1 & Z_s \\ 0 & 1 \end{bmatrix}.
$$

(3.21)

$$
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 1/Z_p & 1 \end{bmatrix}.
$$

(3.22)

Figure 3.9: Two-port impedance model with serial $Z_s$ and parallel $Z_p$ impedances.

For the modeling, the input impedance measurements for each channel component are carried out with the HP4194A and impedance probe HP41941A similarly as for the low-voltage cables. The parameters for a channel model are derived from the measurement results. The parameters $C$, $L$, and $R$ of each model are defined according to the measurements. When the phase $\phi$ of the impedance magnitude at a certain frequency is $\phi \approx -90^\circ$ or $\phi \approx 90^\circ$, the impedance is considered capacitive or inductive, respectively. Thus, the parameter values can be calculated by

$$
Z_C = \frac{1}{j2\pi fC},
$$

(3.23)

$$
Z_L = j2\pi fL,
$$

(3.24)

where $C$ is the capacitor value and $L$ the inductor value. In addition, both these parameters can be fitted at the serial and parallel resonance frequency $f_r$ with

$$
f_r = \frac{1}{2\pi \sqrt{LC}}.
$$

(3.25)

The serial and parallel resonances can be found from the input impedance measurements; a serial resonance occurs when the impedance changes from capacitive
to inductive, while a parallel resonance takes place when the impedance changes from inductive to capacitive. Furthermore, the resonance frequencies can be used in the designing of the model. The amplitude of the impedance at the resonance frequencies ($\phi = 0^\circ$) defines the resistance of the model.

3.4.1 Rectifier bridge

The distribution rectifier can be implemented with two sets of three half-controlled diode-thyristor bridges together forming a 12-pulse rectifier bridge; both of the 6-pulse bridges rectify the three-phase AC voltages to both DC poles from both secondary windings of the double-tier transformer used in the bipolar LVDC system. Thus, only the other half of the 12-pulse rectifier is modeled; the 6-pulse rectifier bridge is connected between the N and L conductors, and forms thus the channel termination between the two-conductor lines. The main state of the rectifier is the conducting state, which takes the main part of the AC cycle, and the other part is the commutation state, when the phases that are conducting are changed (Mohan, 2003). A single conducting state lasts $T/3$ seconds ($T$ is 20 ms with the 50 Hz AC cycle), which means that the duration of one conducting state is 6.67 ms. This time interval also includes two commutation states, at the beginning and end of a single conducting state. Thus, the durations of the commutation states are significantly shorter compared with the conducting state $<< 6.67$ ms. This operation makes the rectifier impedance termination time variant. HomePlug 1.0 is chosen as the basis of the PLC concept (Publications IV and VI), and therefore, the assumption that there is no commutation state during the data frames is valid; the duration of a single HomePlug 1.0 symbol is 8.4 $\mu$s, and the maximum number of data symbols in one HomePlug 1.0 packet varies between 20 and 160 symbols (duration 0.235–1.411 ms) (Lee et al., 2003). Thus, for the modeling purposes, only the conducting state is analyzed. The structure of the rectifier end with the diode-thyristor bridges, the DC link capacitors and the double-tier transformer in the conducting state with the HF current signal paths, is illustrated in Figure 3.10a (Publication VI). The main impedance path of the HF current is through the DC capacitors, and the diodes and thyristors. The schematic of the rectifier end comprising two-port input impedance models for the main HF current paths is presented in Figure 3.10b (Publication VI). These two-port models for the DC capacitor and thyristor are similar to the models for the capacitor and IGBT on/off, presented in (Kosonen, 2008). The diodes (nonconducting and conducting states) of the rectifier bridge are modeled with similar models as for thyristors.

In the modeling, the impedance of the transformer that supplies the rectifier as the termination of the channel is higher than the input impedances of the rectifier bridge legs. According to (Liu et al., 1992), the input impedance of a transformer is a function of frequency and consists of sequential parallel and serial resonances. This is also seen in the input impedance measurements of the transformer between the phases P1 and P2 (the primary and other secondary windings were left open) illustrated in Figure 3.11.
3.4 Modeling of channel impedance terminations

Figure 3.10: Basic structure of the rectifier, with the main HF current signal paths when conducting (a). The two-port input impedance model for the DC capacitor, and the rectifier in the conducting state, with the diodes and the thyristors conducting and nonconducting (b).

Figure 3.11: Input impedance and phase of the double-tier distribution transformer measured from the low-voltage side in the LN signal coupling and in the frequency band of 100 kHz–30 MHz.
Furthermore, according to (Dostert, 2001), the distribution transformers are almost perfect barriers at frequencies above 20 kHz. Thus, the assumption that only a minority of the HF current flows through and between the transformer windings is valid. Hence, in this analysis, the channel termination at the rectifier end consists only of the diode-thyristor bridges.

The input impedance measurements are carried out and parameters for the model in the LN coupling case are determined by (3.23)–(3.25) for the diode-thyristor bridge (Semikron SKKH 132 16E), when the bridge is conducting and nonconducting to cover its whole operation range in a normal mode. The input impedance measurement setup for the channel impedance terminations is presented in Appendix A. Input impedance measurements are carried out for the diode-thyristor component, over the diode and over the thyristor. The measured and modeled input impedances for each case when

1) the diode-thyristor bridge is nonconducting,
2) the diode is nonconducting and conducting, and
3) the thyristor is nonconducting and conducting,

in the frequency band of 100 kHz–30 MHz are illustrated in Figures 3.12–3.14. In addition, the input impedance measurements with the models formed for the DC link capacitor of 12000 µF (EPCOS B43310-A5129-M) used as an energy storage in the rectifier end in the LVDC laboratory system are illustrated in Figure 3.15. Similarly, the model is formed for the DC capacitor of 470 µF (Cornell Dubilier 947C471K102CDMS) used in the CEI end. The model parameters for each model (models presented in Figure 3.10) and correlation between the modeled and measured input impedances as a function of frequency derived for the diode-thyristor rectifier and the DC capacitors in both channel ends are listed in Tables 3.3 and 3.4. As Figures 3.12–3.15 and the calculated correlations between the modeled and measured impedances show, the models are very accurate. According to Figure 3.15, the serial resonance frequency for the DC link capacitor is lower than 100 kHz, which is the case also with the CEI end capacitor. Thus, these capacitors are modeled only with $L$ and $R$ for the observed frequency band.

Table 3.3: Parameters applied to the input impedance model and correlation of $Z$ between the simulated and measured impedances first for the nonconducting diode-thyristor leg (d-t), and nonconducting and conducting cases for the diode only (d) and the thyristor only (t) in the frequency band of 100 kHz–30 MHz.

<table>
<thead>
<tr>
<th>$C_{d-t,off}$ (nF)</th>
<th>$L_{d-t,off}$ (nH)</th>
<th>$R_{d-t,off}$ (Ω)</th>
<th>Corr. in $Z$</th>
<th>$C_d$ (nF)</th>
<th>$L_d$ (nH)</th>
<th>$R_d$ (Ω)</th>
<th>Corr. in $Z$</th>
<th>$C_t$ (nF)</th>
<th>$L_t$ (nH)</th>
<th>$R_t$ (Ω)</th>
<th>Corr. in $Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.42</td>
<td>134.4</td>
<td>0.5</td>
<td>0.9996</td>
<td>3.28</td>
<td>124.4</td>
<td>0.7</td>
<td>0.9918</td>
<td>2.77</td>
<td>113.9</td>
<td>1.118</td>
<td>0.9989</td>
</tr>
</tbody>
</table>
3.4 Modeling of channel impedance terminations

Figure 3.12: Measured and modeled input impedance and phase of a nonconducting diode-thyristor bridge leg (Semikron SKKH 132 16H) in the frequency band of 100 kHz–30 MHz. The parameters applied to the model are: $L_{d-t,off}=134$ nH, $C_{d-t,off}=1.422$ nF, and $R_{d-t,off}=0.5$ Ω.

Figure 3.13: Measured and modeled input impedance and phase of a diode in the frequency band of 100 kHz–30 MHz. The parameters applied to the model are: $L_d=124.4$ nH, $C_d=3.28$ nF, and $R_d=0.7$ Ω.
Figure 3.14: Measured and modeled input impedance and phase of a thyristor in the frequency band of 100 kHz–30 MHz. The parameters applied to the model are: $L_t=113.9$ nH, $C_t=2.77$ nF, and $R_t=1.118$ Ω.

Table 3.4: Parameters derived for the input impedance models of the DC link capacitors in the rectifier and inverter end in the frequency band of 100 kHz–30 MHz.

<table>
<thead>
<tr>
<th>MF / Type</th>
<th>$U_n$ (V)</th>
<th>$L_{DC,C}$ (nF)</th>
<th>$C_{DC,C}$ (nF)</th>
<th>$R_{DC,C}$ (Ω)</th>
<th>Correlation in $Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPCOS / B43310-A5129-M</td>
<td>450</td>
<td>132.7</td>
<td>-</td>
<td>0.05154</td>
<td>0.9944</td>
</tr>
<tr>
<td>Cornell Dubliner / 947C471K102CDMS</td>
<td>1000</td>
<td>146.5</td>
<td>-</td>
<td>0.05153</td>
<td>0.9990</td>
</tr>
</tbody>
</table>
3.4 Modeling of channel impedance terminations

Figure 3.15: Measured and modeled input impedance and phase of a 12000 µF DC link capacitor in the frequency band of 100 kHz–30 MHz. The parameters applied to the model are: $L_{DC,C}=132.7$ nH and $R_{DC,C}=0.05154$ Ω.

3.4.2 Customer-end inverter

The CEIs form the impedance termination at the other channel ends. The inverter connection to the AXMK (or AMCMK) cable in the LN coupling is illustrated in Figure 3.16. The CEI seen from the PLC coupler side comprises a common-mode EMI filter prototype implemented with a single iron core, where both the 0 V and –750 VDC conductors are looped with six turns. The model for the CEI is also complicated one to model, because it is an active component. The CEI input impedance changes according to the state changes of the IGBT switches. The 1-phase CEI prototype and the input impedance model for it are studied and formed in Publication V. The IGBT component used in the three-phase CEI in the laboratory LVDC system is SKiM 400GD126DM manufactured by Semikron. It is a single IGBT module, which contains six IGBTs.

Space-vector modulation (SVM) is used as the basis of the IGBT switchings. There are eight possible switching cases, two of which are zero vectors (producing 0 V to the inverter output) and six active switching vectors (producing AC voltage from DC to the customer loads) for the IGBT switches $T_1…T_6$ applied in three-phase IGBT module (Holmes, 1996). Each switching case can be set with the digital signal processor (DSP), and input impedance measurements are carried out for each case. The input impedance model for the whole IGBT module is formed according to (Kosonen, 2008); the model consists of $C_{IGBT}$, $L_{IGBT}$, and $R_{IGBT}$. The input impedance model for the whole CEI end is presented in Figure 3.17. The switching state case 6 is depicted in Figure 3.16; the
states of the IGBT switches are from top to bottom for legs from left to right: on, off, off, on, and on, off. The input impedance measurement and the modeled one for the switching state case 6 are illustrated in Figure 3.18.

The input impedances for other five active and two zero vector states of the inverter, presented in Appendix B, are very close to the results presented in Figure 3.18, and thus, the same IGBT model is used for all the active states. This is due to the fact that in each switching case in normal operation, the other upper or lower switch of a single leg is closed and the other is open. The zero vector states are also close to the active state cases (Appendix B). Furthermore, the AC chokes, small capacitors, and the isolator transformer connected to the output of the IGBTs do not have any effect on the
impedance termination that the IGBTs form in the channel end. This is seen in Figure 3.18; the impedance and phase curves are almost identical. There are also current sensors to measure the current flowing to the CEI, and fuses to protect the CEI and the power supply module that is used to power the CEI control board. These all affect the total impedance termination of the CEI. Thus, input impedance measurements are carried out for all these components, and input impedance models are formed for them.

Figure 3.17: Input impedance model for HF current paths of a CEI end channel termination.

Figure 3.18: Measured and modeled input impedance and phase of an IGBT module in the frequency band of 100 kHz–30 MHz. The parameters applied to the model are: \( C_{\text{IGBT}} = 19.91 \text{ nF} \), \( L_{\text{IGBT}} = 529.4 \text{ nH} \), and \( R_{\text{IGBT}} = 0.83418 \Omega \). The correlation between the modeled and measured impedances is 0.9981.
The input impedance model for the fuse and the DC/DC power supply module and for the fuse and the current sensor are depicted in Figure 3.17. The measured and modeled input impedances of these two impedance terminations are presented in Appendix B.

To complete the model for the CEI end, the input impedance model for the common-mode EMI filter is formed. The schematic of the CM DC choke two-port model is depicted in Figure 3.17. The model consists of serial and parallel impedances. The values for parallel $C_{HF}$, $L_{HF}$, and $R_{HF}$, and for serial $L_{IF}$ and $R_{IF}$ are derived similarly as for other channel termination impedances. The modeled input impedance values for $Z_{CM,p}$ (impedance between N and L when output is left open) and $Z_{CM,s}$ (impedance over the DC choke in the N pole when the output L line in this case is left open), and the correlation with the measured impedances are listed in Table 3.5. The measured input impedances and phases over the DC choke in the N conductor (L is left open) with modeled ones are illustrated in Figure 3.19. As it can be seen in the correlation in Z in Table 3.5, and in Figure 3.19, the modeled impedances are close to the measured ones.

Table 3.5: Parameters derived for the input impedance models of a common-mode DC choke in the frequency band of 100 kHz–30 MHz.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
<th>Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{HF}$</td>
<td>45.16 pF</td>
<td>$L_{HF}$</td>
<td>1.128 µH</td>
<td>$R_{HF}$</td>
<td>60.24 Ω</td>
<td>0.9853</td>
</tr>
<tr>
<td>$L_{IF}$</td>
<td>720.8 µH</td>
<td>$R_{IF}$</td>
<td>1.29 kΩ</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.19: Measured and modeled input impedance and phase of a CM DC choke in the frequency band of 100 kHz–30 MHz. The parameters applied to the model are: $C_{CM,HF} = 45.16$ pF, $L_{CM,HF} = 1.128$ µH, and $R_{CM,HF} = 60.24$ Ω, and $L_{CM,1F} = 720.8$ µH, and $R_{CM,1F} = 1.29$ kΩ. The correlation between the modeled and measured impedances for the open-circuit case in the N conductor over the CM choke is 0.9853.
3.4 Modeling of channel impedance terminations

3.4.3 Inductive coupling interface

The inductive coupling interfaces are connected in series with the two conductors of the low-voltage power cable ends. The inductive couplers consist of commercial ferrite rings (Ascom powerline type IC-R-27-200, with air gaps to prevent saturation), which provide the galvanic isolation from the LV cable, and simultaneously operate as a high-pass filter. In addition, the coupling interface includes six small-signal diodes, which operate as an analogue transient-protection against voltage spikes induced from the LV cable, introduced in (Kosonen, 2008) and Publications I–II, and applied in Publications III–VI. The schematic of the inductive coupling interface applied to the LVDC PLC channel and the two-port input impedance model are illustrated in Figure 3.20a. The input impedance measurements and a model for the inductive couplers (only the ferrite rings (Figure 3.20b)) are first carried out and parameterized. The input impedance measurement results with the modeled ones for inductive couplers for open-circuited and short-circuited cases (secondary winding open and short circuited) are depicted in Figure 3.21; as it can be seen, the measured and modeled ones are identical, and their correlations are very close to each other. The two-port models and input impedances for small-signal diodes (Figure 3.20c) used in the coupling interfaces are presented in Appendix B.

Figure 3.20: Schematic of the inductive coupling interface for the LVDC PLC channel coupled differentially between two conductors of the AXMK cable (a). The diodes $D_1$–$D_6$ are small-signal diodes and act as an over-voltage protection. The two-port input impedance model of the inductive couplers (b) and the diodes (c).
Figure 3.21: Measured and modeled input impedance and phase of the inductive couplers for short- and open-circuited cases in the frequency band of 100 kHz–30 MHz. The parameters applied to the model are: $L_{1,coup} = 235.9$ nH, $L_{2,coup} = 375.6$ nH, and $R_{1,coup} = 0.5$ Ω. The correlation between the modeled and measured impedances for open- and short-circuit cases are 0.9989 and 0.9997, respectively.
4 PLC concept performance evaluation

In this chapter, the applicability and technical performance of the LVDC PLC concept are evaluated. The evaluation is carried out for two cases; the LVDC laboratory setup, and the LVDC field installation. The concept applicability is tested with theoretical simulations and analysis, and by practical data transmission tests. With these methods, the technical performance of the concept against the functional requirements set by the LVDC smart grid applications is discussed.

The LVDC PLC channel is studied in the LVDC laboratory test setup demonstrated in Figure 2.2 and its specifications in Table 3.1. The CEI is connected to resistive loads, which can be varied with 2 kVA steps between 0 and 18 kVA (Figure 3.16). For the sake of simplicity, and because this is a research setup, there is only one branch in the LVDC laboratory system. As proposed in the PLC concept, the PLC channel is formed of inductive couplers connected differentially 1) between the short-circuited N conductors of the AXMK cable and 2) between the N and L conductors of the AXMK and AMCMK cables. The LVDC PLC channel in the LVDC field installation is more complex than the laboratory setup; the channel contains branches, and there are active loads varying randomly with time in the CEI channel ends. The LVDC PLC data transmission network in the field installation is presented in Figure 4.1. The cable type used in the LVDC field installation is AMCMK 3x95+21 mm², but the rest of the components used in the field installation are identical with the LVDC laboratory setup.

4.1 Channel model

The channel model can now be constructed by connecting the developed two-port input impedance models of each channel component in cascade according to Figure 3.8b. The channel model is implemented with the circuit simulator in the OrCad PSpice environment. The constructed channel model with the circuit simulator comprising all individual components in the AXMK and AMCMK LN coupling cases is illustrated in Figure 4.2. For the sake of simplicity, the impedance models of the rectifier bridge, the CM EMI filter, the DC link capacitors, the fuses (F), the current sensor (CS) and the power supply (PS), and the IGBT module in the CEI end are only provided with single impedances. In the AXMK cable NN coupling case, the channel model consists only of the short-circuited cable conductors and the inductive couplers in the channel ends.

In order to verify the simulation results, the LVDC PLC channel characteristics are measured in the laboratory setup. The measurements were carried out for the frequency band of 100 kHz–30 MHz and the signal couplings AXMK NN and LN and AMCMK LN. The measurements were carried out by a network analyzer Agilent 4395A and an Agilent 87511A S-parameter test device. The measurement information was stored into 201 data points comprising the frequency and scattering parameters (S-parameters) for each measurement when the LVDC system was turned off (to protect the measurement instrument). The source power was set to 10 dBm and the intermediate filter to the
bandwidth of 30 kHz, the sweep time was set to a second. The S-parameters $S_{12}$ and $S_{21}$ indicate the power loss in the studied channel from the input (the terminals of the inductive coupling interfaces connected to the ends of the AXMK/AMCMK cable conductors at the rectifier end) to the output (the CEI end), and vice versa. The source and load impedances were set to 50 $\Omega$ in both the measurement and simulation. The channel gain results were verified by measuring the gain of the channel with an HP4194A impedance analyzer, using its gain-phase measurement (with 401 data points) from the inductive coupling terminals; similar results were gathered. The measured PLC channel gains from the terminals of the inductive couplers consisting of the small-signal diode over-voltage transient protection circuits for the NN and LN coupling cases in the 198 m long AXMK cable, and the LN in the 122 m long AMCMK cable are depicted in Figure 4.3. During all measurements, the system was turned off; all the CEI IGBTs were open (model in Appendix B), and the rectifier bridge was in nonconducting state. Thus, this is also taken into account and is the case in the channel gain modeling.

Figure 4.1: Architecture of the rectifier station, cable connection on the grid branch, and the CEI in the bipolar LVDC field installation grid with the proposed PLC data transmission network.
4.1 Channel model

Figure 4.2: Schematic of the channel model in the LN coupling case consisting of the two-port models of the rectifier and the CEI channel ends and the cable model implemented with the circuit simulator environment.

Figure 4.3: Channel gain from the rectifier to CEI measured from the terminals of the coupling interfaces in the LVDC laboratory setup. The frequency band observed is between 100 kHz and 30 MHz. Channel gains are measured for the NN and LN coupling cases of the 198-meter-long AXMK cable and for the LN coupling case of the 122 meter-long AMMCK cable.

As it can be seen from Figure 4.3, the channel gain in the LN coupling of the AMCMK cable case is up to 15 dBs lower compared with the ones of the AXMK cable, even though the AMCMK cable is 76 m shorter. This is mainly caused by the higher signal attenuation in the AMCMK cable that is due to its insulation material. The simulated channel gain for the AXMK NN and LN couplings with the measured ones are
illustrated in Figures 4.4 and 4.5. Correspondingly, the simulated channel gain for the AMCMK LN couplings with the measured one is illustrated in Figure 4.6. As these figures show, the channel models are very close to the measured ones. The only significant difference between the measured and modeled channel gains is in the AXMK NN coupling case at the frequencies between 12 and 16 MHz. This might be caused by the circuit simulator; the simulated short circuit could be ideal, whereas the actual short circuit between the AXMK cable N conductors in the applied frequency band may not be that ideal. In addition, the inaccuracy in each channel component input impedance model accumulates in the channel model. Furthermore, the case when the system is ‘on’ is simulated with the two-port models of the diode-thyristor bridge and the CEI in the conducting and switching mode states, respectively, and illustrated in Figures 4.5 and 4.6. In addition, the difference between the ‘off’ and ‘on’ modes is insignificant. This is probably due to the CM choke, which presents the first impedance termination, and forms the main impedance barrier in the CEI channel end in the applied band. Thus, the effects of impedance terminations after the CM choke on the channel gain are mitigated. However, the differences between different CEI switching states are also negligible as seen in Appendix B. Moreover, the slight differences in the simulated channel gain when the system is turned ‘off’ and ‘on’ in the LN coupling cases (notch around 4 MHz) are probably caused by the rectifier bridge when it is conducting (different impedance models compared with the ones when every leg of the rectifier bridge are in nonconducting state (Figures 3.12–3.14).

Figure 4.4: Measured and simulated channel gain in the AXMK NN coupling case from the rectifier to the CEI in the LVDC laboratory system. The frequency band observed is between 100 kHz and 30 MHz. The correlation between the modeled and measured channel gain is 0.9617.
4.1 Channel model

Figure 4.5: Measured and simulated channel gain in the AXMK LN coupling case from the rectifier to the CEI in the LVDC laboratory system. The frequency band observed is between 100 kHz and 30 MHz. The correlation between the modeled and measured channel gain is 0.9598.

Figure 4.6: Measured and simulated channel gain in the AMCMK LN coupling case in the frequency band of 100 kHz–30 MHz. The correlation between the modeled and measured channel gain is 0.9501.
4.2 Noise in the channel

The noise, which is mainly impulsive because of the presence of PE devices in the LVDC PLC channel, was analyzed by measuring noise samples with a Rohde&Schwarz RTO 1014 oscilloscope from the terminals of the inductive coupling interfaces toward a 50 Ω termination. The duration of the measured noise sample was 20 ms, which is based on the mains frequency cycle, and contains the information about the noise variation in time. The sample rate was 100 MS/s, and thus, the noise can be analyzed up to 50 MHz with a sufficient resolution without aliasing according to the Nyquist sampling theorem (Proakis and Manolakis, 1996). Furthermore, the recorded noise sample is divided into segments of 10 µs. One segment covers the duration of single HomePlug 1.0 symbol 8.4 µs (Lee et al., 2003), and the following newer HomePlug standards (HomePlug, 2005). A periodogram is calculated for each time-domain noise sample segment to see the variation in the noise PSDs both in the time and frequency domains.

The noise samples were measured in different load conditions in the LVDC laboratory system in the NN and LN in the AXMK cable, and the LN case in the AMCMK cable. The recorded noise sample of 20 ms in the time domain and the variation in the noise PSDs in the time domain in the maximum load condition (18 kVA resistive loads connected to the CEI) for the AXMK NN and LN couplings are presented in Publication VI. Accordingly, the noise measurements were repeated in the LVDC field installation in the channel ends at the rectifier and each CEI in different load conditions (Publication VI). According to the results presented in Publications VI and VII, the noise varies as a function of time comprising impulses generated by the switchings of the CEI IGBTs. These impulses and their variations in time have an influence on the performance of the PLC; the noise variation and high impulses make the SNR at the receiver worse, and the channel conditions are either better or worse for some packets transmitted in the channel. Furthermore, it is notable that the impulsive noise in the LVDC PLC channel is cyclostationary with the period related to the mains cycle, including the impulses generated by the RB and CEI switchings (Publication VI). This, together with the above-mentioned channel time variation, leads to the fact that the SNR is periodical in time similarly as in indoor PLC channels (Cortés et al., 2009).

The noise PSDs in the laboratory system were stronger compared with the results in the LVDC field installation system; in the laboratory, the channel does not have branches, and the channel is shorter. Thus, the effects of the inverter on the noise PSD in the rectifier end are stronger, and vice versa. In addition, the laboratory system is connected to the laboratory grid, which is a harsher environment than the field LVDC system, which is connected to the public MV grid. Furthermore, the recorded noise samples (in the laboratory) in the AXMK and AMCMK LN coupling cases contain noise impulses with stronger amplitudes, and thus, the PSDs are also higher compared with the AXMK NN coupling case. The reason for this is that the channel conditions in the LN coupling cases are worse. Common-mode currents are cancelled out or mitigated in the short-circuited NN conductor loop.
4.3 Channel SNR analysis

The theoretical achievable communication range can be determined by a theoretical signal-to-noise ratio (SNR) analysis. The SNR as a function of frequency at the receiver can be calculated by

\[ SNR(f) = P_{Tx,\text{dBm}}(f) + G_{\text{Ch,\,dB}}(f) - P_{N,\text{dBm}}(f), \]  

(4.1)

where \( f \) is the frequency, \( P_{Tx,\text{dBm}}(f) \) the transmission PSD, \( P_{N,\text{dBm}}(f) \) the noise PSD at the inverter terminals, and \( G_{\text{Ch,\,dB}}(f) \) the channel gain. HomePlug 1.0 definitions follow the regulations of the U.S. Federal Communications Commission (FCC); spectral compatibility is regulated by the FCC (Part 15 rules), and the compliance with the radiated power requirements results in \(-50 \text{ dBm/Hz}\) for the transmission PSD for emissions from access and in-house BPL systems (Lee et al., 2003). This is also used in the analysis as a flat \( P_{TX} \) in the observed band. Because of the PE devices in the PLC channel ends, the noise in the channel is mainly impulsive, which is not taken into account in (4.1) or in Publications III and IV, where the noise in the frequency domain is expressed as in terms of stationary noise with an averaged power spectral density. Thus, the SNRs are analyzed first for the 500 m long cables with the variation of noise PSD in time measured in the laboratory grid at the CEI end in the maximum load condition. The SNRs are evaluated for the HomePlug 1.0 data transmission band covering each of the 84 subcarriers used for communications between 4.49 and 20.7 MHz. The estimated SNR for the 500 m long cable segments of the AXMK NN and LN coupling and the AMCMK LN coupling are depicted in Figures 4.7–4.9. As it can be seen in Figures 4.7–4.9, the SNRs of the majority of the HomePlug 1.0 subcarriers at the receiver are positive in the AXMK cable case. The situation is opposite with the AMCMK cable; with the 500 m cable segment, the majority of subcarriers are negative, and thus not applicable to data transmission.

Similarly, the SNRs are estimated for the channel segments in the LVDC field installation grid. In the LVDC field grid, the amplitude of noise voltages and thus the noise PSDs recorded are lower compared with the laboratory ones. Hence, this could have a positive effect on the SNRs in the actual LVDC system. The estimated SNRs at the receiver for each cable segment; 180, 320, 420 m (between the CCC and the CEIs), and 815 m (between the rectifier and the CEI1) with the recorded noise samples in the grid with the corresponding noise conditions presented in Publication VI, and gathered in Table 4.3, are illustrated in Figures 4.10–4.13. In this analysis, the noise conditions in the transmitter and their effects on the PLC channel performance are excluded, and only the effects of noise in the receiver are taken into account. Moreover, the fact that the grid is branched, and thus, part of the signalling power is injected to the other power cable segments depending on their impedances, is not taken into account. Consequently, overestimated SNRs are given throughout the whole frequency band and over the 20 ms time period observed.
Figure 4.7: SNR at the receiver as a function of frequency in the HomePlug 1.0 band estimated for a 500 m long AXMK NN coupling channel in the maximum load condition in the LVDC laboratory system.

Figure 4.8: SNR at the receiver as a function of frequency in the HomePlug 1.0 band estimated for a 500 m long AXMK LN coupling channel in the maximum load condition in the LVDC laboratory system.
4.3 Channel SNR analysis

Figure 4.9: SNR at the receiver as a function of frequency in the HomePlug 1.0 band estimated for a 500 m long AMCMK LN coupling channel in the maximum load condition in the LVDC laboratory system.

Figure 4.10: SNR at the receiver as a function of frequency in the HomePlug 1.0 band estimated for a 180 m long AMCMK LN coupling channel in the idle mode in the LVDC field installation system.
Figure 4.11: SNR at the receiver as a function of frequency in the HomePlug 1.0 band estimated for a 320 m long AMCMK LN coupling channel in the load condition in the LVDC field installation system.

Figure 4.12: SNR at the receiver as a function of frequency in the HomePlug 1.0 band estimated for a 420 m long AMCMK LN coupling channel in the load condition in the LVDC field installation system.
4.3 Channel SNR analysis

Figure 4.13: SNR at the receiver as a function of frequency in the HomePlug 1.0 band estimated for 815 m long AMCMK LN coupling channel in the load condition in the LVDC field installation system.

In addition, the estimated SNRs are analyzed with the statistical data collected from Figures 4.7–4.13. The maximum, minimum, mean, and standard deviation values from the SNRs for 5, 10, 15, and 20 MHz frequencies in the 20 ms cycle are gathered in Table 4.1. Standard deviation \( s \) is calculated with

\[
 s = \left( \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right)^{1/2}, \tag{4.2}
\]

where \( n \) is number of samples, \( x_i \) sample \((\text{SNR}_i(f))\), and \( \bar{x} \) mean value of the samples as

\[
 \bar{x} = \frac{1}{n} \sum_{i=1}^{n} x_i. \tag{4.3}
\]

Table 4.1: Statistical data gathered from the estimated SNRs for certain frequency bands in 20 ms cycle in the LVDC laboratory setup and the LVDC field grid.

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Field grid</th>
<th>Min (dB) (5/10/15/20 MHz)</th>
<th>Max (dB) (5/10/15/20 MHz)</th>
<th>Mean (dB) (5/10/15/20 MHz)</th>
<th>Std. dev. (dB) (5/10/15/20 MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AXMK NN</td>
<td></td>
<td>1.9/17/3.6/5.3</td>
<td>62/53/55/49</td>
<td>20/10.7/24/18</td>
<td>10/14.7/7/1.59</td>
</tr>
<tr>
<td>AXMK LN</td>
<td></td>
<td>-10/-22/-14/-19</td>
<td>42/55/56/35</td>
<td>7.4/4.4/9.1/0.4</td>
<td>10/15/12.5/9.8</td>
</tr>
<tr>
<td>AMCMK LN</td>
<td></td>
<td>-32/-50/-55/-68</td>
<td>29/13/2.6/-16</td>
<td>-10.5/-26/-32/-31</td>
<td>10/12/11.4/7.9</td>
</tr>
<tr>
<td>CCC-CEI1</td>
<td></td>
<td>-15/-3/-15/-26</td>
<td>53/45/35/22</td>
<td>9.6/13.6/9/-8.9</td>
<td>7.6/5.9/6.6/5.9</td>
</tr>
<tr>
<td>CCC-CEI2</td>
<td></td>
<td>9/16/12/-1.8</td>
<td>57/58/58/47</td>
<td>23/28/27/12.5</td>
<td>5.7/5.6/5.7/5.4</td>
</tr>
<tr>
<td>CCC-CEI3</td>
<td></td>
<td>-21/-17/-22/-42</td>
<td>29/30/35/3.9</td>
<td>-2.2/-0.7/-3.8/-25</td>
<td>7.9/6.6/7.6/6.4</td>
</tr>
<tr>
<td>CE1-rectifier</td>
<td></td>
<td>-25/-46/-51/-87</td>
<td>25/-10/8/-38</td>
<td>-6.6/-33/-39/-77</td>
<td>6.1/5.5/5.4/5.4</td>
</tr>
</tbody>
</table>
As shown by Figures 4.10–4.13, and Table 4.1, the SNRs decrease as the communication frequency applied, the communication range, and the noise PSD power in the receiver are increased. The standard deviation values of the SNRs are higher in the LVDC laboratory setup than in the LVDC field grid; between 5.4–7.9 dB and 7.1–15 dB in the LVDC grid and the laboratory setup, respectively. Based on the analysis, the communication between the CEI1 and the rectifier within the 815 m cable segment seems to be impossible. The situation is even worse when the receiver is at the CEI1; according to the measurement results, the noise power is stronger in the CEI even in the idle mode, compared with the case when the rectifier is in the normal load mode. Furthermore, when the results of this analysis are compared with the estimations obtained from the SNR analysis in the LVDC laboratory grid, the communication in the 420 m cable segment looks more promising, when compared with the estimation of the 500 m AMCMK cable segment in the laboratory grid. This is explained by the higher noise amplitudes and thereby higher noise PSD levels than in the LVDC field grid, and consequently, the standard deviation values of the SNRs are higher in the laboratory grid. The CEIs in the loaded condition seem to have a major effect on the PLC channel performance.

4.4 Theoretical information capacity

In addition to the estimation of the signaling range by the SNR analysis, the theoretical throughput with HomePlug 1.0 modems in the frequency band from 4.49 to 20.7 MHz as a function of SNR for different cable segment lengths is observed by the Shannon Theorem. The Hartley-Shannon law is given by

$$C_{ch} = B \log_2 \left(1 + \frac{S}{N} \right),$$

where $C_{ch}$ is the channel capacity in bps and $B$ is the bandwidth used. $S$ and $N$ are the signal and noise PSD at the receiver end, respectively. Based on the measurements carried out for the PLC channel in the LVDC laboratory system, the frequency-dependent signal attenuation in the low-voltage power cables, the channel gain, and the noise PSD, an analysis of the theoretical channel capacity can be made. According to (Kosonen and Ahola, 2010), the Hartley-Shannon theorem is not suitable as such for frequency-dependent PLC channels; the assumption in the Hartley-Shannon law is that the communication channel is an AWGN channel. In addition, and as shown by the noise analysis, the noise in such PLC channels is time varying in practice, and the majority of the noise is impulsive because of the switched-mode power electronics in the channel ends. However, the Shannon theorem can be applied to frequency-selective channels to obtain a directional estimate of the channel capacity. Based on the estimated transmission and noise PSDs, the theoretical data transmission capacity derived from the Hartley-Shannon theorem is calculated by
4.4 Theoretical information capacity

\[ C_{ch} = \int_{f_h}^{f_l} \log_2 \left[ 1 + \left( \frac{P_s(f)}{P_n(f)} \right) \right] df, \quad (4.5) \]

where \( P_s(f) \) and \( P_n(f) \) are the estimated signal and noise PSDs in different load conditions in the receiver. The boundaries \( f_h \) and \( f_l \) of the integral are the highest and lowest frequency in the observed band (Kosonen and Ahola, 2010). The both directions of data transmission from the rectifier to the inverter and vice versa are covered. The noise in the analysis is calculated with the Welch PSD estimate of the total noise sample of 20 ms. Thus, the average noise PSD level is used. This represents only the averaged stationary part of the noise without the contribution of the impulsive noise variation during the mains cycle. Thus, an overestimated channel capacity is given.

4.4.1 Case: LVDC laboratory setup

The channel capacities are first calculated for the PLC channel in the LVDC laboratory system by (4.5). Channel capacities are calculated for the measured channel lengths of 198 m with the AXMK cable and for 122 m with the AMCMK cable in the maximum load conditions with the data direction from the rectifier to the inverter, which presents the worst case scenario. In addition, the channel capacities are calculated for the 500 m cable segments for both cable cases. The channel capacities are listed in Table 4.2. Based on the theoretical channel capacity results (Table 4.2), the NN and LN coupling in the AXMK cable gives much higher capacities, and all the subcarriers are used even with the 500 m cable segment compared with the AMCMK cable. The results with the AMCMK cable are not that promising; the data transmission does not work with the longest cable segment of 500 m.

Table 4.2: Theoretical throughput and the available subcarriers in the PLC channel in the LVDC laboratory system for the measured channels and estimated for 500 m for both the AXMK and AMCMK cables and the couplings NN and LN.

<table>
<thead>
<tr>
<th>AXMK cable</th>
<th>Load (kW)</th>
<th>Coupling</th>
<th>Number of subcarriers</th>
<th>Theoretical channel capacity (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>198 m</td>
<td>18</td>
<td>NN/LN</td>
<td>84/84</td>
<td>174/104</td>
</tr>
<tr>
<td>500 m</td>
<td>18</td>
<td>NN/LN</td>
<td>84/84</td>
<td>124/48</td>
</tr>
<tr>
<td>AMCMK cable</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>122/500 m</td>
<td>18/18</td>
<td>LN/LN</td>
<td>84/0</td>
<td>93/0</td>
</tr>
</tbody>
</table>

These results correspond with the SNR analysis; the communication in the 500 m AMCMK cable segment in the laboratory noise conditions seems to be impossible or very challenging. This is because of the stronger signal attenuation in the AMCMK cable compared with the AXMK cable.
4.4.2 Case: LVDC field installation grid

The channel capacities are calculated similarly for the LVDC field installation grid. The channel capacities are calculated with the channel gain estimations for each field grid cable segment between the rectifier and the CEIs. The channel gains in the field installation system in individual cable segments are estimated based on the channel gain and cable input impedance measurements in the laboratory, and with the modeled channel gains in the AMCMK cable.

The channel capacities are calculated for the channel lengths of 180 m, 320 m, 420 m, and 815 m between the CCC and the CEIs, the CEI1 and the rectifier, respectively, in different load conditions recorded in the field installation. The loads vary randomly in time, and the loads are unsymmetrical between phases unlike in the laboratory system, where the loads can be set symmetrical between phases. This was also the case in the channel capacity analysis above. The channel capacities are listed in Table 4.3. Based on the results in Table 4.3 compared with the ones in Table 4.2, it can be seen that the noise has a major effect on the PLC channel capacity. Even if the cable segment length increases, the data communication is still possible in the LVDC filed system, while in the laboratory, the data transmission seems to be impossible with the 500 m cable. The channel capacity presented for the 815 m cable in Table 4.3 is estimated when the data direction is from the CEI to the rectifier. In the opposite direction in this case, the channel capacity and the number of subcarriers was equal.

<table>
<thead>
<tr>
<th>AMCMK cable</th>
<th>Load at CEI (W)</th>
<th>Number of subcarriers</th>
<th>Theoretical channel capacity (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>180 m</td>
<td>60</td>
<td>84</td>
<td>167</td>
</tr>
<tr>
<td>320 m</td>
<td>800</td>
<td>81</td>
<td>60.6</td>
</tr>
<tr>
<td>420 m</td>
<td>1700</td>
<td>28</td>
<td>9.5</td>
</tr>
<tr>
<td>815 m</td>
<td>800</td>
<td>2</td>
<td>0.47</td>
</tr>
</tbody>
</table>

4.5 Latency and data transmission tests

Latency and data transmission tests were performed between the HomePlug 1.0 compliant modems modified for the application. Besides the HomePlug 1.0 circuitry, the PLC modems include a small-signal diode over-voltage protection circuit as presented in Publication IV. The data transmission tests were carried out for the PLC channel in the LVDC laboratory setup and the LVDC field installation grid. The data transmission test setup comprises PLC modems connected with inductive couplers differentially between the two DC conductors of the AXMK and AMCMK cable in the laboratory setup, the AMCMK cable and the Ethernet switch in the grid branch in the
4.5 Latency and data transmission tests

field system, and two PCs connected between the modems. The data transmission tests were performed with Iperf software (Gates et al., 2003), which gives the data rates in the TCP/IP layer from the server to the client over the channel (PLC modems work as bridges in the channel). The latency tests between the modems were carried out with the ping functions. The data transmission results in the laboratory and the field pilot installation grid are presented in Table 4.4 (Publication VI). The C-R and R-C in the table refer to the direction from the CEI to the rectifier and vice versa. LN1 in the LVDC laboratory setup is the LN coupling case in the AMCMK cable.

Table 4.4: Data transmission rates between two PCs via HomePlug 1.0 compliant PLC modems with the inductive coupling interfaces in different load conditions, between CEI and rectifier (C-R), and vice versa, respectively in the LVDC laboratory setup, and in different intervals in the LVDC field grid.

<table>
<thead>
<tr>
<th>LVDC Laboratory grid</th>
<th>LVDC field grid</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEI load</td>
<td>Data rate (Mbps)</td>
</tr>
<tr>
<td>No load</td>
<td>C-R: 5.83 / 5.27 / 5.35</td>
</tr>
<tr>
<td>R-C: 5.83 / 5.27 / 5.34</td>
<td>CCC-CEI3: 5.91, -/ 60 W</td>
</tr>
<tr>
<td>6kVA</td>
<td>C-R: 5.37 / 2.92 / 2.53</td>
</tr>
<tr>
<td>R-C: 5.08 / 2.50 / 0.47</td>
<td>CEI1-CEI3: 1.38, 60 W / 2 kW</td>
</tr>
<tr>
<td>12 kVA</td>
<td>C-R: 5.09 / 2.47 / 2.19</td>
</tr>
<tr>
<td>R-C: 4.72 / 2.22 / 0.28</td>
<td>CEI3-CEI1: 0.1, 1 / 7 kW</td>
</tr>
<tr>
<td>18 kVA</td>
<td>C-R: 4.67 / 2.39 / 2.06</td>
</tr>
<tr>
<td>R-C: 4.20 / 2.09 / 0.36</td>
<td></td>
</tr>
</tbody>
</table>

Based on the data transmission results in Publication VI, the data transmission in the LVDC field installation worked every time, when the communication was performed between the PLC modems connected next to the CEIs and/or the cable connection cabinet, where the PLC signal was relayed and repeated. The ping between the modems was < 10ms every time when communication was carried out directly between modems. When the communication between the modems was relayed through the Ethernet switch in the CCC, the latency was slightly increased, but the ping was below 15 ms. However, the load supplied by the CEIs has a major effect on the PLC performance, shown as dramatically decreased data rates when loads are connected. The communication between the rectifier and the CEI1 was not successful. This is because the signal is attenuated strongly in the 815 m grid segment. Based on these results, the concept is applicable to the LVDC system, if the communication signal is repeated at 500 m as proposed. The latency requirement is met for the present smart grid applications. Some applications may require even lower latencies (<10 ms) as in (ABB, 2010; Bose, 2010). To respond to these, lighter protocols than TCP/IP should be used. For example UDP packets do not use an acknowledgment (ACK) function, that is, confirmation from the receiver to the transmitter that the packet has been correctly received. This would decrease the latency to half. In addition, a novel 6LowPAN protocol is a lightweight version of TCP/IP; it applies a shorter packet structure than the one used in Ethernet.
5 Conclusion

In this doctoral thesis, an HF band PLC-based data transmission concept based on a commonly used IP protocol and commercially available PLC modems for an LVDC electricity distribution system was introduced and studied. The LVDC system is considered an example implementation of novel smart grids. The modern distribution grids provide smart applications, such as remote metering, customer load control signals as part of demand side management operated by power grid vendors, and grid protection carried out by communications between the IEDs in the grid. Thus, besides remote network connection between the low-voltage network and the grid operators, also a local network for the system is required. The LVDC distribution network differs significantly from the traditional low-voltage AC grids, because the parts of the medium-voltage AC grid, the public distribution MV/LV transformer, and the low-voltage AC grid are replaced with a rectifier, a DC grid, and customer-end inverters in the other ends of the network. Switched-mode power-electronic devices in the ends of the network generate voltage and current harmonics and impulses with a certain frequency and duration to the DC line, and thus, the channel contains impulsive noise up to HF frequencies. Therefore, to avoid the most adverse effects of the noise generated by the rectifier and the CEIs, the HF band is considered more suitable over low frequencies, and is thereby applied to the PLC. Furthermore, the LVDC grid architecture and structure between the rectifier and the CEIs provide an opportunity to apply the HF band in the PLC; signal repeaters are implemented in the grid branches for the purpose. By this, the communication network is divided into network segments, which makes it simpler to control and manage.

First, one of the most popular topics globally today, smart grids, was outlined. The most common applications that make the grids smart were covered, starting from the remote meter reading, which was first introduced in the late 19th century and carried out with PLC. The smart grid concept platform for an LVDC electricity distribution network was presented with its main features. After the introductory chapter, the PLC concept for the LVDC system was addressed, and the frequency band for the PLC was chosen based on the assumptions of the channel characteristics and noise in the channel. This was partly based on studies carried out in a similar environment as presented in Publications I and II. In the next chapter, the LVDC PLC channel was studied in detail by an analysis of channel characteristics. The underground low-voltage cables typically used in the low-voltage distribution networks as a communication channel in the frequency band of 100 kHz–30 MHz were studied. The signal attenuation in the cables is one of the most essential factors when the HF band PLC is applied. It defines the maximum signaling range when the network topology, signaling power, and noise characteristics in the channel are known. Thus, the frequency band of 100 kHz–30 MHz covering the band typically used for PLC was analyzed. Furthermore, a two-port channel modeling approach was selected for modeling the cables, and a lumped model with its parameters for the cables was formed. The two-port modeling method is justified, because the PLC modems are coupled differentially between two cable conductors, which are connected
between the neutral and the other DC pole at the rectifier and the CEIs. Consequently, each component in the LVDC PLC channel was represented by a two-port input impedance model. The channel component models in the PLC channel were formed, parameterized, and verified by measurements. The channel model was constructed with a circuit simulator by connecting all channel components together according to the LVDC PLC channel topology. The channel model was verified by channel gain measurements.

Noise samples in the PLC channel ends were measured to study the effects of noise, which is mainly impulsive and generated by the rectifier and the CEIs to the DC grid where the PLC modems are installed. Based on the noise measurements, signal attenuation in the cable, channel gain measurements, and the channel modeling, the signaling range was analyzed with the SNR estimation. In addition, a theoretical channel information capacity analysis was carried out. To support the analysis, practical data transmission tests in the LVDC laboratory setup and in the LVDC field grid were performed. The studied aspects were throughput, reliability, and latency, which are defined as the most critical factors when smart grid applications and functionalities are considered. The analysis shows that the HF band PLC and HomePlug 1.0 modems are applicable to the LVDC system if the PLC signal is repeated in the grid branches.

**Suggestions for future work**

In the course of study, the author has identified the following subjects, which should be investigated further. In this doctoral thesis, the communication method was based on the HomePlug 1.0 specifications, and commercial HomePlug 1.0 compliant modems were applied to the LVDC PLC concept. To optimize the performance of the communication system, also the novel HomePlug Green PHY compliant modems designed especially for smart grids should be studied. The coupling interface used in the system can also be adopted to other HF band techniques without any modifications. The application of the circuit simulator should be considered further. It also provides simulation profiles in the time domain, and thus, impulsive noise generation in the rectifier and the CEIs could be modeled and its effects on different types of PLC techniques and modulation schemes simulated. Furthermore, the low-voltage cables studied in this doctoral thesis are four-conductor cables. Consequently, to improve the cable model, and thereby the channel model, four conductor cable models could be designed. Moreover, the LVDC PLC channel model should be completed by designing and constructing models for branched channel with noise sources. However, the circuit simulator for channel modeling is rather heavy and very sensitive to parameter changes in the model. Therefore, the channel model is planned to be implemented in a MatLab Simulink environment as single filters. By doing this, channels with different types of topologies could be simpler and faster to model.

In this study, only the HF PLC was considered. Therefore, new high-speed NB-PLC modems, such as G3-PLC should be tested to consider their performance in such a channel.
References


EN 50 065-1 (1991), *Signalling on low voltage electrical installations in the frequency range 3 kHz to 148.5 kHz*, CENELEC, Brussels, Belgium, 1991.


References


Appendix A: Measurement setups

Input impedance measurements for low-voltage cables and each channel components were carried out with an HP4194A impedance analyser and an HP41941A impedance probe kit. The measurement setup is presented in Figure A.1.

Measurements for the channel gain and phase were carried out with an HP4194A impedance analyser with its gain-phase measurement, and S-parameter measurements with an Agilent 4395A network analyzer with an S-parameter test set device Agilent 87511A for the LVDC PLC channel. The measurement setups are presented in Figures A.2 and A.3.
Figure A.3: Measurement setup for the S-parameter $S_{21}$ insertion loss of the PLC channel with a network analyzer. $S_{12}$, $S_{11}$, and $S_{22}$ can be measured accordingly.
Appendix B: Measurement data

Figure B.1: Input impedances of all switching states of the CEI IGBTs.

Figure B.2: Input impedance of the IGBT module, when all switches are open in the frequency band of 100 kHz–30 MHz. The parameters applied to the model are: $C_{\text{IGBT}} = 12.2 \text{ nF}$, $L_{\text{IGBT}} = 531.2 \text{ nH}$, and $R_{\text{IGBT}} = 0.468 \Omega$. The correlation between the modeled and measured impedances is 0.9981.
Appendix B: Measurement data

Figure B.3: Measured and modeled input impedance and phase of a fuse and a DC/DC power supply module, and of a fuse and a current sensor in the frequency band of 100 kHz–30 MHz. The parameters applied to the models are: $L_{F, PS} = 221.2$ nH, $R_{F, PS} = 0.05154$ $\Omega$, and $C_{F, CS} = 229.7$ nF, and $L_{F, CS} = 1.033$ mH and $R_{F, CS} = 0.6119$ $\Omega$. The correlation between the modeled and measured impedances for the fuse and the current sensor, and for the fuse and the power supply are 0.9995 and 0.7780, respectively.

Figure B.4: Measured and modeled input impedance and phase of a small-signal diode bridge in the frequency band of 100 kHz–30 MHz, when open circuited. The parameters applied to the models are: $L_{P,D} = 339$ nH, $R_{P,D} = 3.825$ $\Omega$, and $C_{P,D} = 111.4$ nF, and $L_{S,D} = 99.56$ nH. The correlation between the modeled and measured impedances is 0.999.

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