Challenges of Broadband PLC for Medium Voltage Smart Grid Applications

Stephen Dominiak
Lucerne University of Applied Sciences and Arts
Horw, Switzerland

Lars Andersson, Mikko Maurer
CURRENT Technologies International GmbH
Mägenwil, Switzerland

Alberto Sendin, Iñigo Berganza
Iberdrola
Bilbao, Spain

Abstract—**This paper gives a brief overview of system level aspects related to the deployment of Broadband Power Line Communication (BPL) networks for smart grid applications within the Medium Voltage (MV) distribution network.**

I. INTRODUCTION

Distribution networks at Medium Voltage (MV) levels (i.e. 1 - 36 kV) comprise mainly underground cables, overhead lines and related infrastructure, including secondary substations (SS). SSs are the natural locations in which Smart Grid services are concentrated. One of the main challenges for the Smart Grid is to connect all relevant SSs with central utility systems. Applications can include the transmission of bi-directional aggregated Advanced Metering Infrastructure (AMI) or sensor data between the Low Voltage (LV) network and the utility as well as Distribution Automation (DA) such as the extension of IEC 61850 applications between the SSs [1]. The use of Broadband Power Line Communications (BPL) technology within the MV distribution network can provide a number of advantages compared to competing communication technologies [2]. Advantages provided by BPL include the fact that the communication network remains largely in control of the utility, the number of necessary backbone connections to the utility through the Wide Area Network (WAN) may be significantly reduced as well as supporting Ethernet/IP-based real-time and multicast applications. The current requirement for existing Smart Grid applications in the MV network is the ability to transmit a minimum of 100 kbps of real-time simultaneous bidirectional application throughput for all deployed SSs. The design of the telecommunications network must cope with this performance, and must be guaranteed ex-ante at the design and planning phase with little or no previous on field assessment. Next to the performance requirements, there is also a need to provide a solution based on an international standardized BPL technology (e.g. IEEE P1901 or ITU G.hn) in order to ensure equipment availability and reduce the investment risk for the utility. Furthermore, especially considering DA applications, the BPL network must provide high availability and quick recovery even in the presence of network disruptions. While the use of BPL in the MV network has been investigated since the days when last-mile Internet distribution was driving the market [3], it has received relatively little attention compared to LV-indoor and LV-access applications. Much of the existing academic work has focused on the modeling of the MV BPL communications channel or providing optimizations at the link level. However, in order to provide a large-scale deployment of BPL in a MV network, there are several system level and practical aspects which must be considered. Therefore, this paper will focus on describing some of the system level challenges in deploying BPL for MV smart grid applications.

II. MV NETWORK CHARACTERISTICS

The MV network mainly differs from the LV access and indoor network in terms of the physical topology, cable/wire types and link distances. A broad range of SSs can be found depending upon the area (urban, suburban or rural) and consumption levels. Big utilities may operate hundreds of thousands of SSs. Such a heterogeneous set of SSs, however, presents a fundamental common infrastructure: MV lines which interconnect SSs among themselves and to Primary Substations (PS). The underlying topology of this interconnection can be considered as a meshed ring topology in which a certain amount of redundancy is provided between SSs and PSs (see Fig. 1 for an example). Links between SSs are usually very heterogeneous with several different cable types as well as a combination of overhead lines and underground cables being found in a single geographical area. While underground cables represent point-to-point links with relatively stable loads and impedances, overhead MV lines, on the contrary, may present taps in a tree-like topology [4]. As links are repaired or the network is modernized, multiple cable segments spliced together may be found across a single link. Splices are a rather common occurrence and, depending upon the types of the spliced segments, may result in almost no transmission loss or a rather high loss (>10dB). Another rather common characteristic of underground MV networks is that multiple cables may be buried together in a common duct for a certain distance. Depending upon the length of the parallel runs as well as the cable types, the crosstalk attenuation between parallel cables may be rather low which will have an impact on the channel between SSs with cables in a common duct. This can lead to the introduction of connections or a change in the quality of the communications channels between SSs which are located multiple physical "hops" apart from each other in the electrical topology.

One typical misconception regarding the use of BPL in MV networks is that link distances are too long to support any reliable communications. Attenuation is a very important factor and will increase with distance and frequency, and as a consequence, longer MV links have to use frequencies in lower bands to guarantee a minimum performance. While it is true that BPL cannot achieve 100% coverage of all links in a typical MV network (especially in rural areas), measurements have shown that raw data rates of several 10's of Mbps are possible for links up to 500 m [5]. A general rule-of-thumb is that older Paper Insulated Lead Covered (PILC) and newer polyethylene (PE) insulated cables will support sufficient throughput on cables lengths up to 450 and 900 meters, respectively. Measurements on overhead lines are currently being performed with initial results showing that longer link distances compared to underground cables can be supported. An analysis of urban MV networks in Spain as reported in [6] show that roughly 90-95% of the links will generally support BPL, i.e. provide sufficient throughput to meet application requirements. It should be noted that the inability to provide 100% coverage will be no different than any other telecommunications technology.

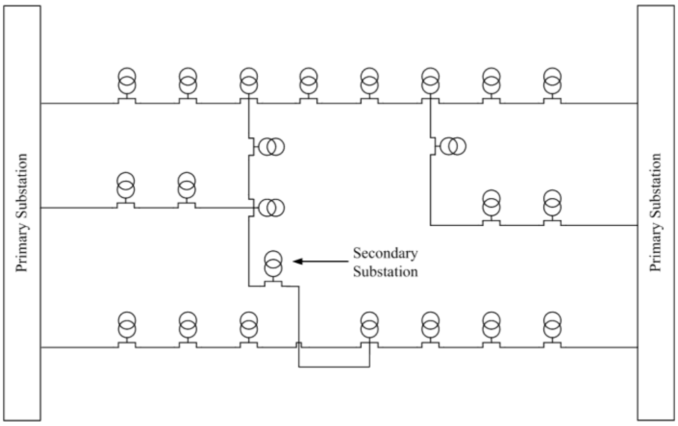

Figure 1: Simplified example of a ringed-mesh topology

III. BROADCAST DOMAIN AND REDUNDANCY

As previously mentioned, the topology of a MV network can be described as a ringed mesh topology in which SSs may have redundant paths to a single or multiple PSs. This means that SSs will have anywhere from one MV feeder (endpoint) to several feeders per station. For the case of multiple feeders, individual phases (3-phase system) are connected across a common bus bar. Feeder lines are switched within the electrical network such that a connected tree structure without loops is achieved. Load management and fault isolation can lead to manual or automated switching being performed in the network. In order to achieve independence from the underlying electrical network topology, but also to provide increased reliability through redundancy (redundant paths) coupling is generally performed on the feeder side of the switch (opposite the bus bar). This ensures that the logical PLC network topology remains independent of the MV network's current switched state. Complete independence of the switch state, however, cannot be achieved as the coupler loss will be dependent upon the state of the switch due to fact the impedance seen by the coupler will change during switching. Inductive coupling will generally function better in a closed switch state (low-impedance) and capacitive coupling in an open switch state (high-impedance). Therefore, changes in the switch state can instantaneously introduce a change in signal attenuation of ±20dB or higher. Unfortunately, for fault isolation applications, it is exactly in this time that reliable real-time communications between SSs are necessary. Meaning that a quick recovery time at the network level is required, which can be very challenging.

The selection of a coupling method is influenced by the cable/wire type as well as the characteristics of the transformer and switch. However, coupler selection may also be influenced by practical limitations such as confined space, safety distance requirements or other installation constraints. Safety regulations will generally require that couplers be installed on non-energized lines. In order to ensure that no power outages occur (as they could affect a very large area); this requires the preparation of a detailed network switching plan for the temporary re-routing of the MV distribution. Any such switching, of course, brings with it an inherent risk and must be carefully planned. In some cases, the installation of couplers may require the approval of the local or national regulations body. This means that close support from the utility is required not only for the planning, but also the installation phase. This additional risk and planning effort is one of the reasons that channel measurements in MV-networks have not been made on the scale as is found in similar LV networks as the access is limited and the costs of coupler planning and installation can be very high.

The potential presence of multiple feeders connected across a common bus bar means that a PLC signal injected at one SS may propagate in multiple directions (across each feeder), but also over multiple hops (across the bus bar of neighboring SSs), thereby creating a broadcast channel. On the one hand, the broadcast nature of the PLC signal in a MV network provides the potential for increased redundancy both through multiple paths (feeders) as well as across multiple hops along a single feeder. If a cable fault occurs, data may be routed across an alternative path or if a node failure occurs an intermediate node may be used as a relay. This is a very important aspect for Smart Grid communications in order to increase the network reliability against node and link failures. On the other hand, the interference domain of a SS may be rather large which can reduce the potential for resource reuse in the network. This problem is further complicated by the previously mentioned parallel cables in a common duct which leads to the fact that SSs located a large number of “hops” from each other may still exist in each other’s interference domain. The size of the broadcast domain for each node may change dynamically over time as the channel conditions and network switch state changes. With the standardized BPL technology there is currently no practical method available for limiting the interference domain size other than reducing the transmission power spectral density. Coupling to alternating phases on neighboring links has been investigated, however has been found to only provide minimal signal attenuation.

IV. NETWORK ARCHITECTURES

The presence of relatively large broadcast domains as well as the necessity to support multi-hop relaying in the MV network makes investigating MV-BPL at the network level so important. Medium Access Control (MAC) and relay selection (routing) techniques as well as the proper selection of network architectures become critical. Achieving application performance and high availability requirements with the limited available resources requires a high level of network wide resource reuse combined with techniques which can take advantage of the available redundancy within the network. Current BPL deployments in Spain are performed according to a centralized Time Division Multiple Access (TDMA) strategy. TDMA domains are defined which use a certain frequency band, allowing them to coexist with adjacent TDMA domains in a different band. Each TDMA domain consists of a central master device regulating the resource allocation and a number of cascaded repeaters forming a hierarchical topology. Bands can be reused at geographically separated locations if provisions for guard distance over MV cables are considered to avoid interference. Due to practical reasons only two bands are currently available for network planning which potentially leads to a sub-optimal coverage of the whole network in order to avoid interference.

The multi-band TDMA concept has been optimized and validated through initial pilot deployments [5]. However, the centralized nature of the TDMA domain has some disadvantages when trying to meet high availability requirements especially in the presence of dynamic network conditions (e.g. network switching, system faults or time-variance in the communication channel). For this purpose a distributed “adhoc” network architecture providing a self-organizing and self-healing network may be better suited [7]. Such architectures have been extensively investigated for wireless adhoc networks [8] and it is believed that they can be applied to MV-BPL networks. On the other hand, adhoc networks are known for their performance deficiencies especially in dense networks and it will be a challenge to demonstrate that the real-time traffic delivery requirements can be met. Network nodes must be able to regulate channel access and perform relay selection using distributed protocols. A challenging aspect will be to realize a distributed architecture within the framework of standardized BPL technology which will limit the available design space.

V. CONCLUSION

A brief overview of system level aspects related to the deployment of BPL networks within the MV distribution network has been provided. These topics are currently being investigated in a Swiss federally funded research project by the Lucerne University of Applied Science and Arts together with their industry partner CURRENT Technologies International (CTI) and is supported by the Spanish utility Iberdrola. The goal of this project is to develop concepts for a more distributed BPL-MV architecture and communication protocols which are better suited for large MV networks, but are still based on standardized BPL technology. Such concepts will reduce the necessary network planning and installation process providing a more “plug-n-play” solution, but also provide increased reliability through redundancy as well as enabling peer-to-peer communications for real-time DA applications.

REFERENCES

[1] Mohagheghi, S.; Tournier, J.-C.; Stoupis, J.; Guise, L.; Coste, T.; Andersen, C.A.; Dall, J.; , "Applications of IEC 61850 in distribution automation," Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES , vol., no., pp.1-9, 20-23 March 2011.

[2] For the Grid and Through the Grid: The Role of Power Line Communications in the Smart Grid, Galli, S.; Scaglione, A.; Wang, Z., Proceedings of the IEEE , vol.99, no.6, pp.998-1027, June 2011.

[3] PLC Commercial Deployment of Iberdrola, Alberto Sendin Escalona, ISPLC 2004.

[4] Ferreira, H. C.; Lampe, L.; Newbury, J.; Swart, T. G.;, “Introduction, in Power Line Communications: Theory and Applications for Narrowband and Broadband Communications over Power Lines (eds H. C. Ferreira, L. Lampe, J. Newbury and T. G. Swart),” John Wiley & Sons, Ltd, Chichester, UK.

[5] Andersson, L.; Sendin, A.; Berganza, I;, “Field Experience with Medium Voltage Broadband Powerline Carrier in Smart Metering and Smart Grid Deployments,”, Protection Automation & Control World Conference 2012, Budapest, Hungary, June 2012.

[6] Opera-IST project Deliverable 44, “Report presenting the architecture of PLC system, the electricity network topologies, the operating modes and the equipment over which PLC access system will be installed”, www.ist-opera.org \ Enter Opera 1 \ Document No 44.

[7] Bumiller, G.; Lampe, L.; Hrasnica, H.;, "Power line communication networks for large-scale control and automation systems," Communications Magazine, IEEE , vol.48, no.4, pp.106-113, April 2010.

[8] C. Siva Ram Murthy and B. Manoj, “Ad Hoc Wireless Networks: Architectures and Protocols”, Prentice Hall, 2004.