COMPLETE MV-BPL COMMUNICATIONS SOLUTION FOR LARGE AMI AND GRID AUTOMATION DEPLOYMENTS

Jon AGUIRRE VALPARIS
Ormazabal - Spain
jna@ormazabal.com

Aitor AMEZUA
Ormazabal - Spain
ama@ormazabal.com

Juan Antonio SANCHEZ
Ormazabal - Spain
jsr@ormazabal.com

Alberto SENDIN
Iberdrola – Spain
asendin@iberdrola.es

Javier SIMON
Iberdrola – Spain
fjavier.simon@iberdrola.es

Stephen DOMINIAK
HSLU - Switzerland
stephen.dominiak@hslu.ch

ABSTRACT

This paper presents a comprehensive solution for broadband backbone communications systems over the medium voltage power lines (MV-BPL) for large AMI and grid automation deployments. Roll out experience, materials, monitoring and control systems will be outlined together with the on-going research activities.

INTRODUCTION

All over the world, regulators are pushing for improved power quality and supply continuity (SAIDI, SAIFI) and the implementation of energy efficiency measures. The electricity distribution network is undergoing a deep transformation towards its digitalisation, where secondary transformer substations are affected by many of these innovations.

Today, medium voltage grid is responsible for almost 85% of supply continuity problems suffered by end customers [1]. Therefore, investments in medium voltage grid automation equipment are defined as strategical to help improving power quality and supply continuity. The use of accurate medium voltage measurements (V, I, P, Q, E) has allowed to improve grid state estimation together with the reliability of fault detector indicators enabling control systems ready for automatic grid recovery [2]. These functionalities have increased dramatically the number of data collected per installation, demanding more and better communication services to Remote Terminal Units.

Contrary to the medium voltage equipment, where the evolution of the systems has been progressive, in the low voltage side the irruption of SmartMeters has produced a disruptive change in the design and implementation of new infrastructures related to measurement and billing of energy consumers, so called Advanced Metering Infrastructure or AMI. These changes have influenced deeply the communication technologies and especially those that provide the capillarity the electricity network demands. Backbone connection from the consumers to the head end systems [3] is critical to support all the services.

Many technologies are available in the market and not a single one does comply with all technical and economical requirements. Best solution is the combination of a variety of technologies (MV-BPL, 2G/3G/4G mobile, fibre optics, digital radio…) which enable the larger number of services and cover practically all the distribution network with a proper balance between private and commercial solutions.

Two key aspects must be borne in mind when selecting the communications technology to be deployed:

- Ensure proper operation: the applications demand many services (IP communications, cybersecurity protocols, support distribution protocols, communication network management services, devices' firmware upgrades…) and large amount data (meter readings data for millions of clients, monitoring data for tens of thousands of substations…) to be exchanged between the head end systems and the devices in the field, with high reliability and availability standards.
- Seamless deployment: network planning, system engineering, procurement, installation, commissioning operation and maintenance must be as simple as possible to keep overhead cost, CAPEX and OPEX low.

Compared to other mature technologies Medium Voltage Broadband PowerLine communications (MV-BPL) is a technology which has been developed to provide broadband and low latency IP connectivity between transformer substations by means of the MV cables and lines [4].

For the deployment to be successful, it is important to observe a minimum set of rules that will be defined in the paper. The materials needed for a complete working solution will also be described, from the BPL modem to the MV couplers to inject the signal in GIS and AIS substations. The need of a Network Management System (NMS) to monitor, control, operate and maintain large quantity of devices will also be pointed out, along with troubleshooting of real cases and good practice guidelines.

The result of the proposed system is a private network that is fully owned and operated by the DSO/DNO. At present, the system is being rolled out and successfully operating in 10,000+ transformer substations in 24kV and 36kV underground networks.

Finally, on-going research activities will be presented. With the aim of being able to deploy the technology in any medium voltage grid, scenarios containing overhead lines are being evaluated. A successful proof of concept project has been completed and first pilot installations will be installed in locations where a favourable regulation exists.

MV-BPL TECHNOLOGY

This broadband communication solution, offers the possibility to extend an access point (or more than one for high availability features [5]) to a number of secondary transformer substations through PLC technology over the Medium Voltage network.

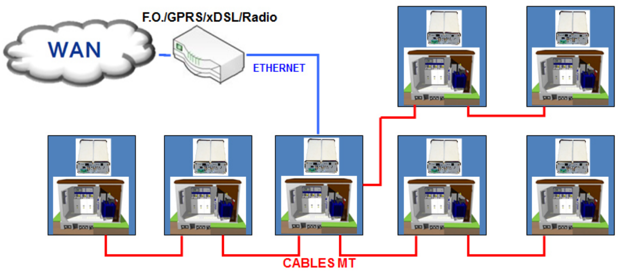

Figure 1: MV-BPL cluster example

For this purpose, PLC communication equipment shall be installed in various neighbouring secondary substations.

The group of installations will result in an IP based communication network where an access point should be provided (2G/3G/4G, Fiber Optics, xDSL …) to connect the created Local Area Network or cluster to the backbone communications network.

Architecture and deployment rules

With more than 10.000 MV-BPL communication devices deployed, the following architecture and conservative deployment rules are defined to ensure a successful communication service in large deployments, avoiding previous onsite assessment.

The architecture of the medium voltage installations connected can support daisy chained or star topologies, but it is not recommended to install clusters with more than 15 nodes in a row or 20 in total.

The cluster is managed by a device defined as Master, being the rest of the devices named Repeaters. The backbone or access point could be installed in any of the nodes, but it is recommended to place it in the the Master.

Technically, the technology allows to use a bandwidth from 2 to 34MHz with a bit rate of 200 Mbps. Experience has shown that as Medium Voltage cables were not conceived as a communication channel, the attenuation of the cables does not allow the use of high frequencies for reasonable cable lengths, i.e. communication distances.

During the development of PLC products for Medium Voltage networks, intensive field tests were performed to achieve the deployment rules for massive roll-outs (conservative enough to guarantee the operation) and search the limits of the technology. Reaching to an optimal point where 2 frequency bands are used: 2-7MHz and 8-18MHz.

To understand this conclusion, it has to be taken into account that the higher the frequency, the greater the attenuation in the cable. On the contrary, the lower the frequency the more complicated is to guarantee the proper coupling of the signal to the medium voltage as a bigger capacitive coupler is required to obtain lower insertion losses for low frequencies. These constraints and the necessity to have more than one frequency mode of operation to allow the installation of adjacent clusters, results in the selected 2 frequency modes of operation.

In addition to frequency band or cable distances, cable types also need to be taken into consideration. The following table summarizes the deployment conditions:

	MODE: 2-7MHz	MODE: 8-18MHz
Lead-Oil cable	500m	350m
PE cable	1.000m	700m

Table 1: Distance between two adjacent nodes

These are the deployment rules for a single cluster, when a second cluster wants to be deployed, the second frequency mode should be used to avoid interferences.

If a third cluster has to be deployed in the vicinity, one of the frequency modes has to be repeated, as a consequence, a guard distance has to be kept.

	MODE: 2-7MHz	MODE: 8-18MHz
Lead-Oil cable	1.300m	900m
PE cable	2.000m	1.500m

Table 2: Distance between same frequency clusters

Underline that these are conservative distances that ensure operation in large roll-outs. For links with longer distances, link viability should be validated, which negatively affects flexibility and roll out speed when deploying the solution.

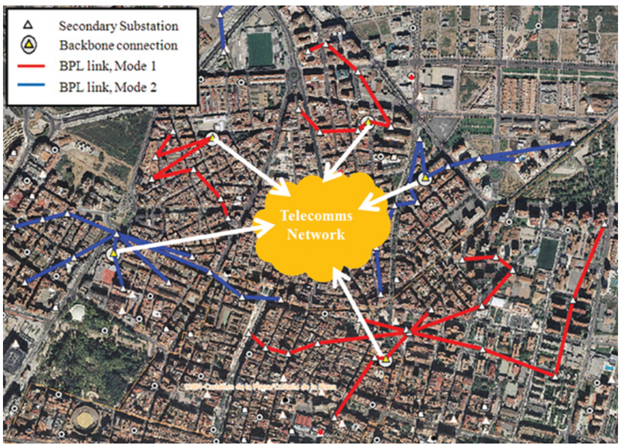

Figure 2: Deployed clusters example

MV-BPL solution

There are various technologies available to inject MHz signals into the medium voltage, mainly capacitive or inductive couplers. In order to be independent of the status of the switchgear to provide a permanent communication infrastructure, PLC couplers are installed before the switchgear (cable side)

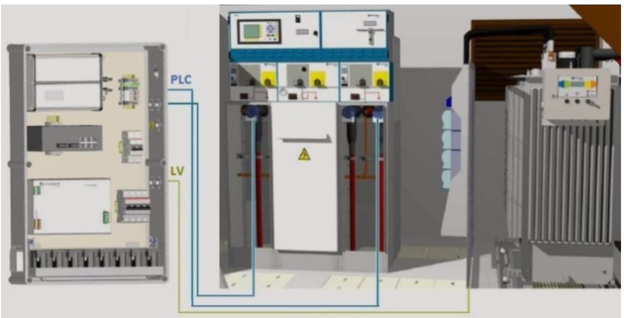

Figure 3: Secondary Substation with MV-BPL solution

Experience has shown that even if inductive couplers have the benefit of an easy installation, minimum performance is not assured with open switches. Therefore, the communication solution presented in this paper only shows the use of capacitive couplers, which is considered a robust element of predictable behaviour.

It should be taken into account that the coupler will be installed mainly in secondary substations with very limited space. Thus, for SF_6 insulated cabinets, T connectors (type C) are used for EN-50181 or ANSI/IEEE 386 bushings.

Additionally, the couplers can be combined with MV voltage sensors in the same device what gives a higher value to the solution, provided that grid automation IEDs also use of these compact electronic sensors due to its comparable accuracy with conventional voltage transformers. This medium voltage measurement is being used to send voltage, power and energy measurement information to the DMS and OMS. Fault indicators are also using these sensors to implement especially directional fault detection methods.

About technical requirements, couplers must be certified according to the insulation tests defined for the electrical sector, being IEC-60044-7 the reference for partial discharges, power frequency and lightning impulse tests. Additionally, it must be guaranteed that signal insertion losses to the medium voltage will be below 4dB for all frequencies (2-34MHz).

Resolved the signal injection to the medium voltage, the device in charge of generating the signal and managing the communication infrastructure is the MV-BPL Modem to be installed in every connected secondary substation. The characteristics of the Modem can be divided into those strictly related to PLC functionality and those related to access, configuration and associated services.

The Modem uses OFDM modulation with up to 1.536 carriers in configurable frequencies from 2 to 34 MHz with a maximum output power of 24dBm. As it has been stated in the deployment section, the main modes of use are 2-7 MHz and 8-18 MHz, so the Modem has integrated analogue filters to select the band in use. The PLC communication will be managed by a Modem defined as Master who will control the access to the medium of all the devices in the cluster. In addition to PLC features, the device is able to manage VLANs for network segregation, RSTP for redundant link management and QoS for traffic prioritization.

Regarding device access characteristics, cybersecurity is a mandatory feature for communication devices, granting device access through TACACS+, secure web page communications with HTTPS, remote login secured with SSH and file transfer with FTPS. The following chapter will deal with deployed device management software using SNMPv3 protocol.

The last to take into account for large-scale deployments is the cabinet where the devices will be housed, which will include the power supply and battery charger to ensure the communication of the PLC cluster even in cases of voltage outages, Figure 3.

Device monitoring through Network Management Systems

When the number of deployed devices is very high, it is not very practical to monitor each of them separately, so for the monitoring of communication equipment, management software called NMS (Network Management System) are used to discover deployed devices and work on Fault, Configuration, Accounting, Performance and Security (FCAPS).

The management software is web based, with a central server which facilitates the simultaneous access from several locations and users. The data collected of the communication network will be available in real time and also stored in a database to be accessible in a later stage.

At a more detailed level, given the peculiarity of a BPL cluster, an NMS has been developed to handle this particular feature and live information of the cluster could be accessed such as: secondary substation name, MAC address, PLC link quality, upload/download speeds …

Figure 4: BPL cluster example

MV-BPL ROLL OUT EXPERIENCE

Deployment good practices

The following sequence is the installation process of a BPL link between two secondary substations:

- De-energization of the MV cable: depending on the coupling method and the switch gear type, the installation could be done without de-energization, but normally it is necessary to do so for safety reasons.
- Phase identification: establish a method to identify that both ends of the MV line in which the couplers are installed, correspond with the same cable.
- Installation of couplers and BPL communication devices, following the installation recommendations of the manufacturers.
- Connection between BPL device and the coupler through RG58 coaxial cable. It is important to test that the coaxial cable is properly done.
- Perform first connectivity verification of the BPL link. A conservative recommendation should be to obtain at least minimum physical speed of 10Mbps Tx and Rx in all positions of the MV circuit breaker (normally equivalent to SNR >15dB in both directions).

Following the deployment rules and if the installation is properly done, the BPL link should show good performance.

Operation and maintenance

After commissioning of a new BPL cluster in the network, the NMS will help to supervise the BPL devices in its life-cycle in the network. But the grid is not static, and the boundary conditions could change over time. This might suppose that an operating BPL link becomes non-operating. This is due to new factors originally non present during installation phase:

- BPL device becomes unavailable due to miscellaneous hardware or software factors (such us high temperature, component degradation, misconfiguration, …). Certainly in BPL equipment this means a very low percentage of problems compared to other types of telecommunication technologies that are installed in the secondary substations. This is due to the fact that in a native way and by design, the BPL equipment was conceived to be installed in electrical environments.
- Unexpected noise source or BPL interference (producing low SNR): most common noises in real deployments were produced by other electronic devices installed in secondary substations such as battery chargers, RTUs, relays or metering devices. This can be solved by simply replacing the damaged components or applying filtering methods.
- BPL Link degradation/fault due to: increase of attenuation (new splice), medium voltage cable cut-off, coupler unit fault or degradation, coaxial cabling or connectors degradation due to miscellaneous factors (humidity, ..) leading to impedance mismatch. This might imply revision and optimization of the cabling and the coupler installation.
- For new secondary substation created in the electrical grid that affects the BPL topology, review of BPL planning would be needed.

Troubleshooting strategies

Despite planning efforts, a few BPL links considered feasible in theory, might show throughput values below expected thresholds. The most common cases found and the typical solutions are shown in the following table [6]:

Category	Symptoms	Solution
Impedance mismatch	• Low received power levels (OFDM carriers) • Asymmetrical (both ends) received power levels (OFDM carriers)	• Cabling (connectors) problem solving • Coupling unit installation improvement (cable distance shortening)
Saturation	• Short MV cables distance • Low performance (throughput) • Reception automatic gain control, 0	• Attenuation by software • Attenuation using external hardware
High Attenuation	• High MV cables distance • Low performance (throughput) • Low SNR • Reception automatic gain control, maximum	• Cabling and coupling units connection improvement • MV cable phase change
Noise	• Low performance (throughput) • Low SNR • Reception automatic gain control, maximum • Abnormal BPL received signal spectrum	• Cabling and coupling units connection improvement • Noise filtering (e.g., mains)

Table 3: Typical situations in BPL links to troubleshoot

ON-GOING RESEARCH TOPICS

In addition to continued cybersecurity developments to ensure secure communications when managing remotely the devices and high availability solutions to provide a set of mechanisms intended to solve the different fault cases that might occur, the main on-going research topic deals with overhead lines.

MV-BPL through overhead lines

The paper has presented MV-BPL communication solution as a mature technology for deployments on underground cables, where a set of rules is defined that ensures a communication service with no previous onsite assessment.

However, in order to enable a more widespread deployment of the BPL technology also for sub-urban and rural environments, it will be necessary to apply the technology to overhead wires. Within an initial pilot project, extensive point to point measurements, channel/noise modelling and a pilot installation test have been performed to validate the analysis.

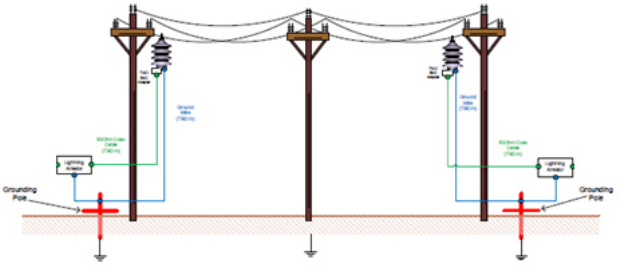

Figure 5: Overhead point to point measurements

Up to 65 point to point channel, noise and throughput (Mbit/s) measurements have been performed on a mixed medium voltage network which included underground cables and overhead wires as well as underground to overhead transitions. Throughput results can be summarized in Figure 6 and channel and noise measurements have been mathematically modelled to calculate recommended maximum distances.

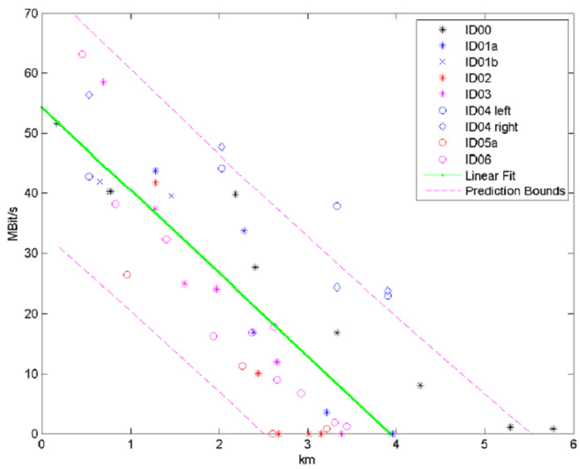

Figure 6: Throughput Vs Distance

A very summarized analysis of the 65 measurements compiled in Figure 6, would be that in the best scenario communication was possible up to about 6 km and in the worst case around 2.5 km. As we are targeting the definition of conservative deployment rules without any prior assessment, it is not realistic to think and promote that the technology reaches up to 6 km but to conclude that we are able to cope with overhead links up to 2km no matter the amount of branches on the overhead line. A further important result is that the transition point from underground to overhead provides very little additional attenuation of the BPL signal.

As channel attenuation and noise were also measured and modelled mathematically, a model of the Signal to Noise Ratio (SNR) versus distance and frequency could also be developed. The SNR model was then used together with a model of the underlying BPL technology in order to determine the maximum theoretical achievable distances given the following assumptions:

1. Desired minimum PHY data rate: 10 Mbps
2. Transmit Modem PSD: -50 dBm/Hz

The results of the analysis for the different BPL channels are shown in Table 4. As can be seen the results are very similar to the results of the throughput measurements shown above.

Maximum distance for mode 2-7MHz	2.3 km
Maximum distance for mode 8-18MHz	2.3 km

Table 4: Maximum theoretical distances

These assumptions were validated in a field trial with a complete BPL cluster and it is expected to keep installing devices according to these deployment rules.

CONCLUSION

A communications infrastructure has been presented that brings together information from several neighboring secondary substations, showing the conditions and necessary elements that have facilitated the deployment of thousands of installations for AMI and grid automation in underground networks.

In order to cover all types of electrical networks, the feasibility of using MV-BPL technology has been demonstrated for future deployments that may include mixed and overhead networks.

REFERENCES

[1] H. BAROJA, J. A. SANCHEZ, I. MARTIN, “Nuevos conceptos para automatización de centros de transformación MT/BT. Soluciones: Funciones y productos”, *CLADE 2012*.

[2] J. MARTI, C. RICHTER, E. GABRIEL, “Automatic Grid Recovery (AGR/ARA), the virtual operator”, CIRED2015.

[3] G. AMANN, L. ANDERSSON, A. AMEZUA, “Resultados experimentales de tecnologías de comunicaciones para Smart Grid”, *CIDEL 2014*.

[4] A. AMEZUA, M. MAURER, L. ANDERSON, A. SENDIN, J. SIMON, M. SOLAZ, “MVBPL – Reliable, future proof and cost efficient”, *CIRED 2015*.

[5] M. SOLAZ, J. SIMON, A. SENDIN, L ANDERSSON, M. MAURER, "High Availability Solution for MV-BPL Communication Networks",*IEEE ISPLC 2014*.

[6] A. SENDIN, M. SANCHEZ-FORNIE, I BERGANZA, J. SIMON, I. URRUTIA, "Telecommunication Networks for the Smart Grid ", Artech House, 2016.