Broadband over Power-Line Networks for control and automation systems in Smart Grids

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***Abstract*— This paper presents a review of Broadband over Power Line Communication technology as a mean of communication for the detection, control and automation of an electrical network. Some of the applications in which this type of technology can be used are sending information from power quality meters, energy management and automation systems, demand management, among others. A review and an analysis about the communication system requirements based on BPLC is presented, particular emphasis is paid to the currently installed network conditions required to allow the utilization of this technology**

Keywords; *Power Line Communication (PLC), Broadband over Power-Line (BPLC), Advanced Metering Infraestructure (AMI), Smart Gri, Micro Grid, Power Quality monitoring, distribution automation.*

I. Introduction

Smart Grid, refers to an operation mode of the electrical system using communications, power electronics, and storage technologies for balancing production and consumption, achieving reliability, security, and efficiency improvements. Such benefits are expected to be experienced by all the agents involved in the electricity production like the energy customers, utilities and generating facilities [1][2]. Along with the growth of smart grids worldwide a discussion about the most suitable communication options has been carried out. Among the more commonly employed technologies for this kind of network, Broadband over Power Line Communication offers several attractive options by means of the usage of higher frequencies, a wider frequency range and high speed.

PLC is a technology capable of handling data and voice transmission through already installed electric networks. The PLC technology comprises a group of elements and transmission systems, so that other services are offered to customers like internet, telephone, television, remote data reading, control, etc., besides electricity.

PLC is also known as Power-Line Telecommunications (PLT), Power Band and Power-Line Networking (PLN), Broadband over Power-Lines (BPLC), also known as Power Line Internet, is a method of power line communication that allows relatively high-speed digital data transmission over the public electric power distribution wiring. The broadband access is the goal of various technologies deployed worldwide. However, the implementation has been limited by the existing infrastructure in each country.

Thanks to the electric network and the BPLC, it is possible to provide internet service to further places where electric network is available but no communication networks exists. In addition, measurements like power consumption and power quality can be performed, recording information useful for the customers and the utilities.

The transmission of data using BPLC permits to offer several new services, particularly in low-voltage networks. Among other services, BPLC enables the ability to remotely turn on or off a customer, electricity revenue metering, detecting a service outage, detecting any unauthorized use of electricity, improving asset management and streamline the operation of the overall network, active demand management, fault location and additional services as TV and Internet [3], as it has been stated before. BPLC is an attractive option because it uses existing infrastructure.

In order to integrate the electricity and the BPL communication systems at low voltage electric systems, it is necessary to analyze the network's capabilities and characteristics for BPLC transmission [4]. The network's topology, frequency response and bandwidth lead to the determination of the communication capabilities of the network, which depend strongly on the manner it has been constructed. In Colombia, all networks are built according to the Colombian Technical Standard NTC 2050, based mainly on the National Electric Code NEC or NFPA 70 [5].

In this paper, the place for the integration of the electric and the communication systems is proposed to be the distribution transformer, nearby the customers or at the distribution substations. At this location, the coupling is done between the electric networks with complementary devices. Such devices will receive and send information, turning the transformer or the substation into a local control center, where measurements and information can be analyzed.

Using low voltage lines for data transmission, either outdoor or indoor, there are a wide number of users connected to a transformer, in which impedance levels should be adjusted because the transmission signal gets disturbed and experiences attenuation.

This paper studies the technical characteristics and the low voltage network's electric model established in the standard NTC 2050 and the Technical Regulations for Electrical

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Installations RETIE, determining the possibilities and limitations for data transmission.

II. Communication Scenarios

With the development of the Smart Grid, many international and national organizations currently working in the development of standards. According to the NIST (National Institute of Standards and Technology), was structured a conceptual model that defines communication scenarios power lines as the power level [6]. These scenarios are defined as follows:

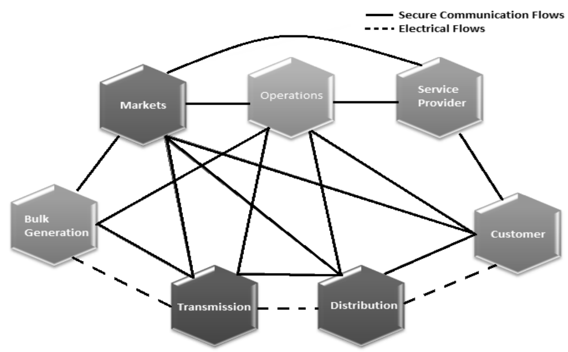

Fig.1. Interaction of actors in different Smart Grid Domains through Secure Communication Flows and Electrical Flows. Source: National Institute of Standards and Technology (NIST) and U.S. Department of Commerce

Extra High Voltage (EHV) and High Voltage (HV) lines are used for transmission systems throughout the entire country or even for international power transfer. At this voltage level this technology is not widely used because transmission lines are usually quite long, causing significant signal attenuation. Additionally, transmission system's communications are carried out by means of optical fiber.

Medium Voltage (MV) distribution lines are connected to transmission systems through primary transformer substations. They are used for distribution within the cities, towns and industrial customers. At this voltage lower structures are used. In addition, Intelligent Electronic Devices (IEDs), such as reclosers, switches, capacitor banks and the phasor measurement units, can be directly connected. This voltage level requires relatively low data rates and BPLC can provide economically competitive communication solutions.

Low Voltage (LV) distribution lines are derived from the distribution transformers' secondary circuits. A communication signal can pass through the secondary of the transformer to the low voltage line with a strong attenuation in the order of 55 dB to 75 dB. This problem is easily solved by using signal couplers (capacitive or inductive, as shown in Figure 2 and Figure 3) that avoid going through the transformer. Thus communication is sent directly from medium voltage to low voltage. A Master Gateway is connected to each transformer, depending on the analysis of the system's topology. This Master Gateway will operate as data concentrator, receiving information from customers fed by the transformer. A Gateway employed at low voltage can control up to 1000 users, approximately. Each customer is defined by a two-way smart meter with a MAC ID for supervision, control, monitoring, and in real time functions.

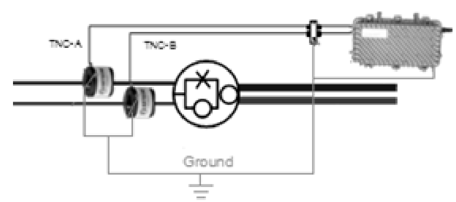

Fig. 2. Underground Coupler. Source: Smart Grid Connectivity Corinex

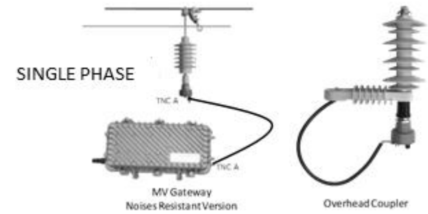

Fig. 3. Coupling the signal in to a single phase MV line using a single medium-voltage coupler. Source: Smart Grid Connectivity Corinex.

By integrating BPLC, the National Electric System can provide internet service and meet other needs, besides those already mentioned through existing networks. Such a system involves one of the most widespread infrastructures the country, the transmission network. BPLC may be a last mile solution to offer Internet service to rural people, without the installation of additional infrastructure. The proposed scheme requires an Internet Service Provider (ISP) that supplies data to a terminal carrier wave, located at a power substation and connected to the networks.

III. Control and Automation in Smart Grids

At present the most technologies applied to electrical networks is in transmission. These technologies convert conventional grids into smart grids. Some of the technologies used in these new networks are:

- FACTS Devices (Flexible Alternating Current Transmission System) that allow transmission lines to provide maximum power and help stabilize the network with an exact power controlled. FACTS encompass all systems based on power electronics used for power transmission [7].
- Control Systems Wide Area (WAMS) is a distributed measurement system in power system phasor measurements involving (PMU) capable of rapidly analyzing anomalies in electricity quality in large geographical areas to prevent the development of dangerous instability in the network [8].
- Phasor Measurement Unit (PMU) or Synchrophasor, is a device used to observe accurately the dynamic state of the electrical system. The PMU data obtained secondary windings of power transformers and current are then processed to obtain the voltage and current phasors and then be sent to the hub receives data that organizes and distributes [9].
- Data Acquisition Systems and Supervisory Control (SCADA) analyze the electrical network conditions in real time, providing data for fast power settings [10].
- A High-Voltage, Direct Current (HVDC), can deliver power over long distances with low losses on land and underwater, and connect asynchronous networks. For

underwater power cables, HVDC avoids the heavy currents required to charge and discharge the cable capacitance each cycle [11].

A. *Smart Grid Benefits*

BPLC technology provides a solution for real-time communication for automating electrical systems, improving service reliability. Intelligent electronic devices (IEDs) and systems that protect receive sensor data and can issue control commands, if they detect abnormal voltage, current or frequency, voltage raised or decreased levels in order to maintain the desired voltage quality. Some of the benefits obtained with the automation of power grids are listed below:

- Reduced O&M Expenditures. Using IEDs to monitor power factor in real-time will save on generation and reduce generation emissions.
- Reliability. Detection fault location, fault insulation and service restoration functionality.
- Flexibility in network topology. Controlling bidirectional energy flows that occur with the inclusion of new sources of power generation to the grid, for example photo voltaic cells, electric cars, wind turbines, among others.
- Efficiency. One of the improvements of intelligent network is to improve the efficiency of energy use, particularly with the use of a smart power management in order to obtain homogeneity in the load curve, for example turning off air conditioners during short-term spikes in electricity price. The intelligent use of technology to improve the efficiency of electrical networks and manage the balance between supply and demand reduces the need for emergency generators. In addition, demand management and the creation of better storage allow the flexibility to manage the intermittency of renewable energy sources.
- Sustainability. The flexibility of Smart Grids allows the penetration of new renewable energy sources to electricity generation and thus has a variety of ability to meet demand.
- Market. Bidirectional communication between consumers and energy suppliers, allowing greater flexibility in their operating strategies.
- Reliability and Quality of Service.
- Monitoring and measurement of energy quality in real time.
- Increased Availability: The Micro-Grids can be switched based on network's condition or fee. Reconnect consumer choice.
- Energy Storage. Energy storage has implicit time dependence: a node may inject or extract energy depending on weather and operating conditions.
- Demand response. Allows generators and loads to interact automatically in real time, coordinating demand to flatten spikes. Eliminating the fraction of demand that occurs in these spikes, demand management eliminates the cost of adding reserve generators, cuts wear and extends the equipment's lifespan. Demand management allows users to reduce their energy bills down saying devices priority to use energy only when it is cheaper too [12].

IV. Low Voltage Line characterization and modeling

Because the electrical networks were not initially designed to carry a communication channel, they have several disadvantages such as a wide range of noise, signal attenuation, coupling difficulties, etc. Additionally, electrical networks have different topological configurations, voltage levels and transmission media: aerial or underground. Thus, BPLC usage over electrical networks becomes a challenge when it is used for telecommunications purposes [13].

As the distribution networks contain an undetermined number of customers, determined by the network's rated capacity, the analysis of the communication signal's propagation is a quite complex task.

The data transmission is sensitive to the electric losses and waveform distortion, which itself depends on the load and the demanded reactive power at each part of the system. Devices like capacitor banks can severely prejudice the intensity of the signal.

For the characterization and modeling of the communication channel, the inductance, resistance, capacitance and conductance must be determined and analyzed (Figure 4). These parameters are determined by the properties of the channel used for data transmission. Some of these parameters vary with frequency as resistance; however, the inductance and capacitance values are practically independent of frequency.

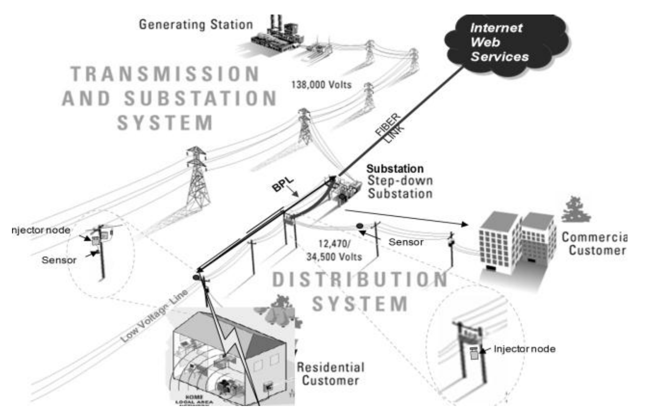

Fig. 4. Low voltage line characterization and modeling. Source: Smart Grid Connectivity Corinex.

The electrical network impedance is strongly determined by the load current, which is not constant and is determined by the variation of the loads.

Besides there are other parameters, known as secondary: characteristic impedance Z_L and the propagation constant γ both parameters depending on the frequency and the primary parameters.

The characteristic impedance can be calculated by the following equation,

$$Z_L = \sqrt{\frac{R + j\omega L}{G + jwC}} = \sqrt{\frac{R + j2\pi f L}{G + j2\pi f C}} \quad (1)$$

And the propagation constant is expressed by

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (2)$$

R represents resistance per unit length
G is the leakage conductance per unit length
L inductance per unit length
C capacitance per unit length

Where α is called attenuation constant and β phase constant, calculated by the following equation:

$$\alpha = \frac{R}{2Z_L} + \frac{GZ_L}{2} \ \text{[Nepers]} \quad (3)$$

$$and\ \beta \approx \omega\sqrt{(LC)} \ \text{[radians per unit Length]} \quad (4)$$

As it was previously mentioned, there are a variety of conductors used in the distribution low voltage networks, which implies that attenuation values and characteristic impedances will be highly disperse. In developing this work, some of the typical topologies commonly used in Colombia were employed. Three-phase-conductor configuration with external concentric neutral used in underground installations and for indoor cables gauges 6, 8, 10, 12 and 14 AWG both phase to neutral, normally installed throughout a half an inch (½ in) diameter PVC pipeline, in accordance with Colombian Technical Standard NTC 2050 [5].

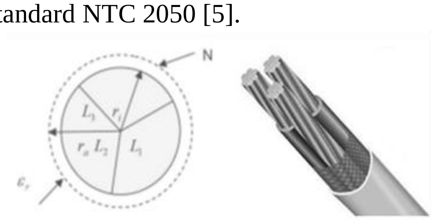

Fig. 5. Three-phase-conductor configuration with external concentric neutral used in underground installations.

For this type of cables, the electric field has a radial symmetry, and it is assumed that the minimum space between conductors is compared with r_a and r_i. radios. Due to the similarity of this type of cables to coaxial cables, capacitance and inductance can be calculated with the equations inherent to this. Thus the capacitance and inductance of a coaxial cylinder is given by:

$$C = \frac{2\pi\varepsilon_0\varepsilon_r}{ln\frac{r_a}{r_i}} \quad (5)$$

$$L = \frac{\mu_0}{2\pi} ln\frac{r_a}{r_i} \quad (6)$$

The resistance per unit length is then given by

$$R = \frac{1}{\sigma a}\left(\frac{1}{2\pi r_a} + \frac{1}{2\pi r_i}\right); \ R = \frac{1}{2}\sqrt{\frac{f\mu_0}{k\pi}}\left(\frac{1}{r_a} + \frac{1}{r_i}\right) \quad (7)$$

A high frequency, resistance per unit length R, is determined by a phenomenon called “skin effect” where the current density is higher near the surface of the conductor, and decreases with depth in the conductor. Electric current flows mainly in the "skin" of the conductor, between the outer surface and a level called the skin depth. A 60 Hz in copper, the skin depth is about 8.5 mm. At high frequencies the skin depth is less. The penetration depth "a" is given by the following equation and as mentioned above depends on the frequency and conductivity of the wires "σ".

$$a = \frac{1}{\sqrt{\pi f \mu_0}} \quad (8)$$

Conductance losses per unit length of a line can be calculated if the losses are multiplied by the factor capacitance $\tan\delta$:

$$G = 2\,\pi f C * \tan\delta \quad (9)$$

For insulation materials such as PVC missed factor is $\tan\delta \ll 1$, and for high frequencies it is possible to assume that $G \ll wC$ and $R \ll wL$ that R increases proportionally with the square root of the frequency f. Typical values of the airlines of low voltage networks per unit length are:

Inductance	$0{,}9 - 1{,}57\ mH/Km$
Capacitance	$(7 - 13) * 10^{-3} uF/km$
Characteristic impedance	$5{,}6 - 6{,}4\Omega$

The dielectric constant ε_r depends on the frequency but is not large variation and the loss factor $\tan\delta$ in PVC behaved in a nearly linear on the axis on a logarithmic scale.

The attenuation $L\,(f,l)$ can be calculated from the attenuation factor (f), depending on the length l in dB:

$$L\,(f,l)\text{dB} = 20 * log_{10}\left(e^{\alpha(f)l}\right) = 8.686\alpha(f)l \quad (10)$$

In the following graph shows the resultant curve of the characteristic impedance attenuation for a length L = 1 km, and for frequencies between 1 and 20 MHz.

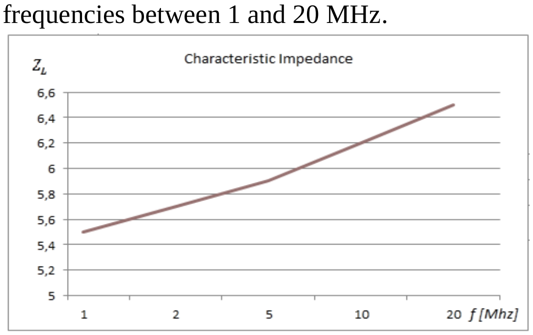

Fig. 6. Characteristic impedance as a function of frequency.

Fig. 7. Attenuation per unit length as a function of frequency

In residential electric installations the wires used are: 6, 8, 10, 12 and 14 AWG. The most common wire gauge is 14 AWG both phase to neutral, and installed along a PVC pipe half inch in diameter. Because the spacing between wires is less than ten times the radius conductors models will be taken to *cosh* equations:

$$C = \frac{\pi \varepsilon_0 \varepsilon_r}{cosh^{-1} \frac{D}{2r}} \qquad (11)$$

$$L = \frac{D}{2r} * cosh^{-1} \frac{D}{2r} \qquad (12)$$

$$R = \frac{1}{\pi r \sigma_c a} \qquad (13)$$

For a 14-AWG gauge conductor, corresponding to a 0.8-mm radius, and also assuming distance D = (1.25x 2r), and considering that copper is the most common conductor for indoor installations, the graphs of characteristic impedance and attenuation are:

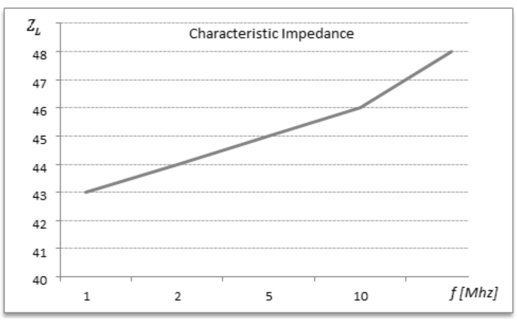

Fig. 8. Characteristic impedance as a function of frequency

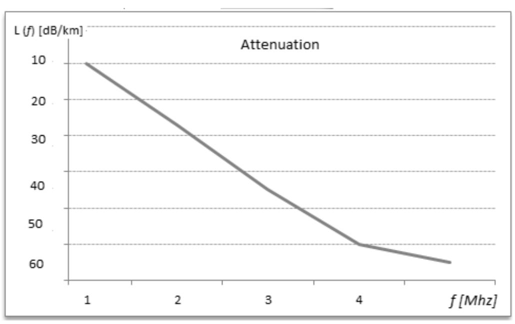

Fig. 9. Attenuation per unit length as a function of frequency

V. THE BPLC SMART GRID NETWORK

The proposed implementation of the smart grid developed in the city of Bogota, capital of Colombia, on a low voltage network.

A. *Objetives*

The objectives of the intelligent network implementation were:

- Implement a smart grid in a small low voltage electrical network, including communications, renewable energy, automation, control, real-time measurement and power quality monitoring.
- Evaluate the use of technology in the network communication for control, automation, measurement and monitoring.
- Implement the use of renewable energy to meet household consumption. Using solar photovoltaic panels on an isolated network with substitution of the existing power grid.
- Control, automate, measuring and monitoring of equipment investment DC / AC using technology BPLC.
- Measure and analyze power quality in the network according to EN 50160. Report real-time alarms and events using technology BPLC
- Measure real time environmental parameters such as wind speed, irradiance, temperature, plus battery bank monitor and monitor the electrical parameters of the network using BPLC.

B. *Description and the Network Topology*

The smart grid project supports two main states: the conventional network with investors including synchronized to the grid and the grid where the distribution network or some other type of generator is used to give substitution, in this case the investor is the solely responsible for the supply of this network. If the grid is connected to the power grid, the grid is supplied from the conventional network. The voltage and frequency of the grid are the same as those of the conventional network.

In a grid system, it is possible to integrate a generator as well as the public, as a second backup system, to improve the reliability of the network as mentioned above. This is useful in case of network failures for a long time, when the size of the battery after a certain time is no longer enough to provide electricity during cutting.

The usual solution in these cases is to use a transfer switch, available in manual or automatic. Using a switch of this kind, in the inverter connection (which normally connects the public) will connect a diesel generator.

For the development of this project we used the grid concept with substitution of the distribution network. After designing the system to supply the rated load and ensure the electrical parameters, we proceeded to dimension the investors that were required. According to the design used two inverters Sunny Island and Sunny Boy 3300. In the following picture you can see an overview of the project. In developing the project utilized wind speed sensors, irradiance and temperature, such measurements are sent as shown in the diagram via the RS485 communication to the inverter Sunny Boy, as shown in Figure 10.

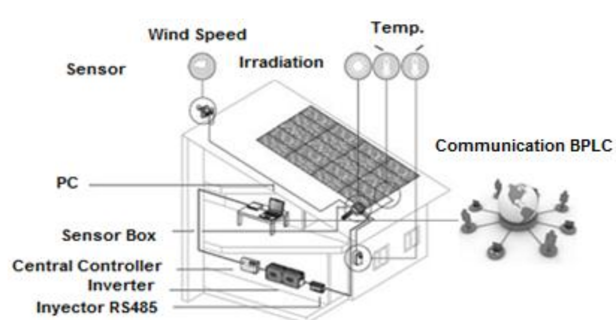

Fig. 10. Overview of the proposed implementation of photovoltaic solar energy, measurement of environmental parameters and smart grid communication. Source SMA Solar

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Figure 11 is the wiring diagram of investors to WebBox for sending data to a router through BPLC technology. Then these data can be displayed on the Web site.

of the National University of Colombia in Bogotá to use grids installed for communication, as well as some buildings that can be installed properly some other power plants.

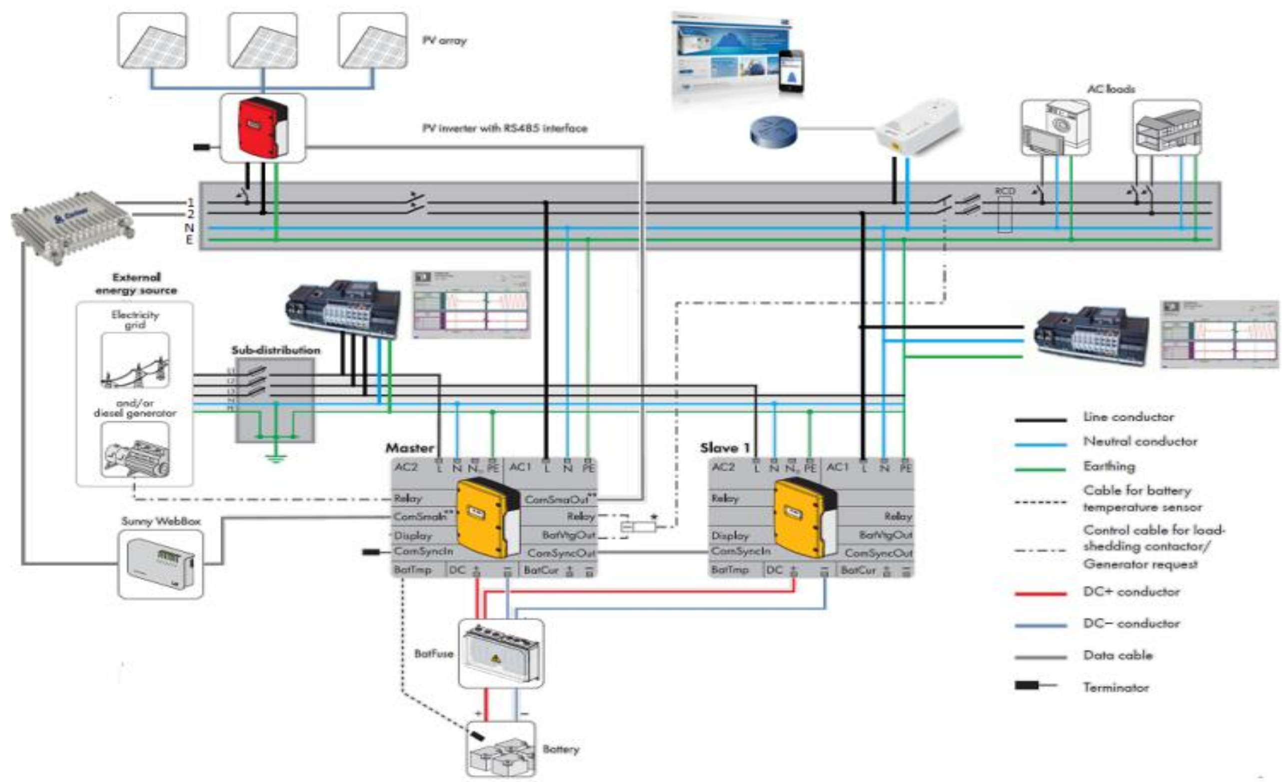

Fig 11. General Scheme of intelligent network connection. Source: SMA Solar Technology AG, Power Standars Lab and Corinex Smart Grid.

VI. Network Functionality

After implementation of the Smart Grid an overview of the situation before and after the network is summarized in the following Table I.

Functionality	Conventio-nal Grid	Smart Grid
Advanced Metering Infrastructure (AMI)	No	Yes
Remote Load Management	No	Yes
Fault Recognition and Identification	No	Yes
Power Quality Measurements	No	Yes
Voltage, current and Power Measurements	No	Yes
Real time outage detection	No	Yes
Reliability and Quality of Service	No	Yes
Wind speed, irradiance, temperature readings	No	Yes
Surveillance and Physical Security	No	Yes
Security	No	Yes
Scalability	No	Yes

Table I. Smart Grid Network functionality

VII. Next Steps

Within the next steps in the development of the smart grid are the expansion of photovoltaic generators currently installed and the inclusion of new customers to the network. Is expected to have for the following projects with the facilities

Another task to develop is to find more benefits from this smart grid and that can be evaluated using performance indices. Also evaluate the use of technology BPLC over other technologies in the communications of the smart grid.

On the communications side, it plans to include IED´s on the network and test the use of technology BPLC for communication with protocols IEC61850. Capacity time synchronization with external GPS clock.

Evaluate some power quality indices, such as number and duration of interruptions and measure the reduction of energy consumed in the distribution network, and the availability and reliability of smart grid and reducing non-technical losses. Detection and targeting of failures with the use of the software. Apply computational intelligence techniques for data analysis and decision support in SCADA systems.

Finally we hope to use all intelligent networking concepts and include them in new projects.

VIII. Conclusion

In this paper we have presented a detailed walk-through to the small Smart Grid project in Bogota city, deployed using a BPL technology. The challenges faced during design and the lessons learnt during implementation are discussed and analyzed. Low voltage line characterization and modeling and network functionality.

Finally, next steps towards enhancing the performance of BPLC networks are also presented.

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