ELVIS (Enel Low Voltage Identification System): Improving narrowband PLC communication performance by means of electrical characteristics measurement of distribution line.

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ABSTRACT

In a PLC based AMI system a crucial role on overall system performance and KPI fulfillment is played by the reliability of the communication on distribution line.
Typical PLC communication architecture is based on concentrators, normally installed into secondary substations, and PLC nodes spread over the distribution network, normally near the customer premises. Capability of a PLC node to setup a connection with its concentrator is conventionally named reachability.
Reachability of a node on distribution line strongly depends on electrical parameters that are not easy to measure such as cables attenuation, loads impedance, narrow band/wide band noise and, often, unknown network topology, which, in addition, are not stable across the hours, days, weeks and seasons.
Aim of this paper is to detail ELVIS, an integrated hand-held device able to perform all the needed measurement as well as to act as a PLC node in order to allow performing many PLC communication diagnostic functions in a simple, guided and safe way due to its integrated wireless communication capabilities and APP based MMI.

INTRODUCTION

Electrical characterizations of the PLC communication are typically carried out with not-dedicated instruments requiring ad hoc setup, often made of a mix of expensive, bulky and fragile instruments [1], [2]. A typical setup is based on a de-coupling filter, to filter out the low-frequency (50/60Hz) line voltage, and an oscilloscope or spectrum analyzer, both being quite expensive devices that require well trained staff for the connection and initial setup and are most suited for a laboratory environment than for a real field activity.
Some PLC silicon vendors provide customized hardware for "in band" PLC signal level measurement but still we're talking about devices more suited to a laboratory environment and with limited diagnostic capabilities.
PLC diagnostic measurement are fundamentally field activities to be performed often outdoor, in places where dedicated sockets to connect to AC voltage are not available, no protections (like RCDs switches) for the operators are provided and furthermore no comfortable places (like desks and so) are available to correctly position expensive measurement equipment.
As a result of this a PLC diagnostic device must:
- Be quite small and hand-held.
- Be provided with safe and easy connection to the low voltage network.
- Have an high environmental protection degree to allow it operating outdoor.
- Have an high electrical insulation class to allow safe operation without exposing diagnostic operators to undesired electrical risks.
- Have wireless interfaces to allow remote control by the operator(s).
- Integrate in a single instrument all the needed diagnostic\measurement features.

The design of ELVIS was done following the requirements above, aiming to a compact device with power line impedance measurement capability, signal measurement, PLC isolated coupling circuit with BNC connection and 2 PLC modems to support all the three modulation schemes (2 BPSK and 1 FSK) used by ENEL within its massively deployed AMI systems. The instrument includes a simple LCD display to allow a very basic local interface, a simple push button to allow navigating in the menu tree, some diagnostic LEDs and a LED bar to be used as a very direct signal level monitor.
The instrument is then completed with a Bluetooth Low Energy interface (to operate it from a smartphone or tablet running a dedicated APP) and a Wi-Fi interface, allowing both access point and client connections.

ELVIS USE CASES

Network assessment

One of the major issues when approaching a new DSO grid, is to be able to characterize the communication network in relation to specific grid equipments or specific layout of the grid.
In such cases the scope is to be able to ensure that the grid is suitable for PLC communication. ENEL experience is that the major causes of PLC communication issues are related at first to the noise level along the lines (generated by loads connected to the grid), secondly to the attenuation of the signal level injected by the transmitting node and received by the receiving node due to low impedance of specific loads or to line attenuation.

Communication troubleshooting

Another condition in which it is very important to perform field measures is in case of reachability issues; from ENEL experience most of the PLC communication problems in field are due to network topology uncertainty (i.e. meters associated to a wrong concentrator).

Noise level measurement

This kind of analysis is performed in absence of communications: no transmitter is connected to the grid and one ELVIS device is attached in different positions of the grid and signal is measured (In normal conditions the sampling points can be 200-300 meters far from each other, but depending on the network conditions wider or narrower sampling areas can be adopted). In addition it can be important to understand if noise is narrow band (sometimes narrow band noise can be bypassed selecting a different PLC carrier frequency) or wide band. Noise level can be recorded at fixed frequency over time or over a user-defined frequency range (noise spectrum).

Impendence level measurement

A very low PLC impedance (< 2-3 Ohm) can strongly impact on the tx-rx level, reducing the capability of a PLC modem to communicate over the power line. Impedance level can be recorded at fixed frequency over time or over a frequency range (impedance spectroscopy).

Point to point pinging

Since the signal can also be affected while transmitted along the line, it is very useful to evaluate the real line transmission capability: this task can be conveniently performed by the use of two or more ELVIS devices placed along the lines and communicating to each other.

S/N estimation

One ELVIS can be configured as a master transmitter: in such mode it continuously performs a lookup process; another ELVIS can then be placed in the position where we want to estimate the S/N: in this way it will be able to measure the background noise while the Master is not transmitting and the received signal level when the master is sending lookup packets.

Line attenuation

Line attenuation can be measured as well by placing an ELVIS device set to TX mode at the beginning of the line to be evaluated and moving a second device across the network to evaluate the dB/meter attenuation.

Line detection

While working in point to point mode ELVIS is capable to diagnose, in case of three phase distribution, which line is the signal coming from. This is very useful because in typical cases the crosstalk between the lines, although it can temporarily guarantee reachability between two nodes, it is typically subject to significant variations across the day due to changes in loads connected to the network. So, in principle, having PLC communication through crosstalk is not the best option or at least it must be evaluated carefully.

DEVICE ARCHITECTURE

From the hardware point of view, the device is divided into two main blocks: an “Extension” board and a CPU board (Fig. 1).
The extension board hosts the power supply unit, a three-phase PLC coupling circuit, the two PLC modems, all the analog front-end and A/D conversion circuitry needed for the S/N and impedance measurement as well as the micro-controller, that manages all the “low-level” tasks related to modems management, communication and measurement tasks.
The CPU board manages all the “high-level” applications related to the functionalities of the device, the peripherals, and connectivity to the external device.
In the next sections all the relevant blocks are discussed in details.

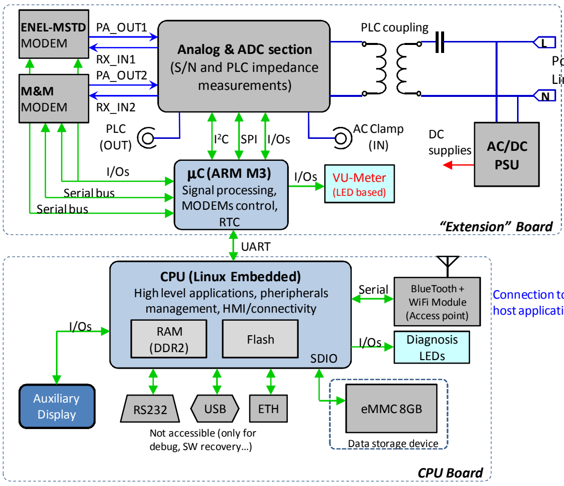

Fig. 1: general architecture.

PLC modems

The device is equipped with two power-line modems, one managing the “Meters&More” standard [http://www.metersandmore.com/] operating in Spain and in many worldwide pilots, the other one managing the two standards operating in Italy. All the three technologies are based on narrow-band modulation techniques with A-band carrier frequencies as per Cenelec standard [3].
The receiver inputs of the modems are coupled to the power-line through three separate coupling circuits in a way that either one single phase or any combination of the three phases can be accessed at the same time. The power outputs are connected to a single PLC TX coupler which can be switched to one phase at a time.

Signal/Noise measurement

Signal/Noise measurement is based on the swept-tuned topology typically used in spectrum analyzers (Fig. 2).

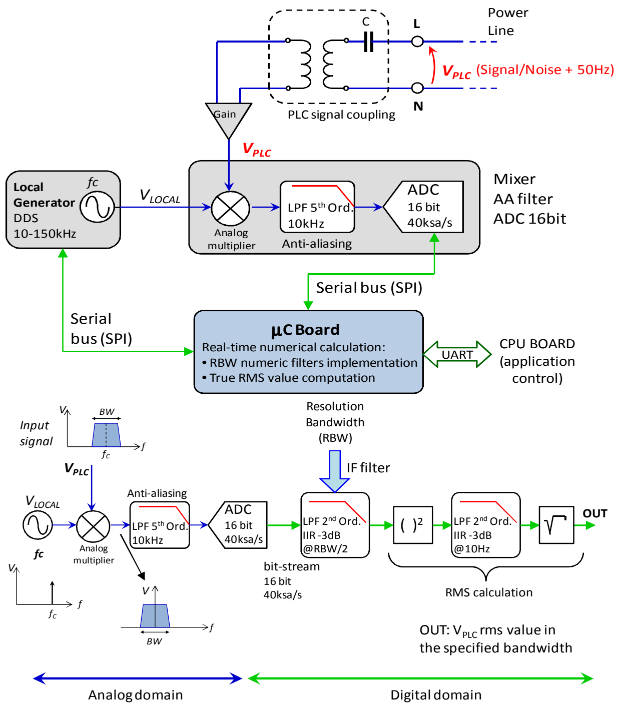

Fig. 2: block diagram and working principle of the S/N measurement.

The PLC signal is extracted from the power line through the PLC coupler, pre-amplified and mixed with the signal from the local oscillator (*Vlocal*) which sets the central frequency for the measurement. The signal is then low-pass filtered (anti-aliasing) and converted by the ADC into a real-time bit stream (16bit/sample @ 40Ksample/s). In the digital domain, the signal passes through a low-pass filter which sets the resolution bandwidth for the final rms calculation.
The advantage of this solution is that the ADC has to sample the down-converted signal in its base-band, which is much lower than the central frequency. This introduces advantages in terms of cost of the hardware and computational effort of the micro-controller.

Impedance measurement

The basic principle for the impedance measurement is quite simple: a sinusoidal signal at the test frequency (*fc*) is applied to the power line (*Vplc*), and the corresponding injected current is measured (*Iplc*). A simple ratio rms(*Vplc)*/rms*(Iplc)* gives the magnitude of the power-line impedance at *fc*. The problem of this approach is that in a noisy environment, which is the case of a power line, the measure is strongly affected by the noise which is summed to the applied voltage and to the injected current. A very selective band-pass filter around *fc* should be used to reject the noise. Beside this, in order to correctly calculate the rms value of *Vplc* and *Iplc* a sampling rate greater than 2 times the test frequency is needed (in practice, a sampling rate much higher than *fc* is needed).
A popular approach for precise measurement of impedance in presence of strong noise is based on the "lock-in" technique, or "synchronous detection" which allows to determine the (complex) value of *Vplc* and *Iplc* with a strong rejection of the noise out of the test frequency [4], [5].
Block diagram and working principle are shown in Fig. 3.

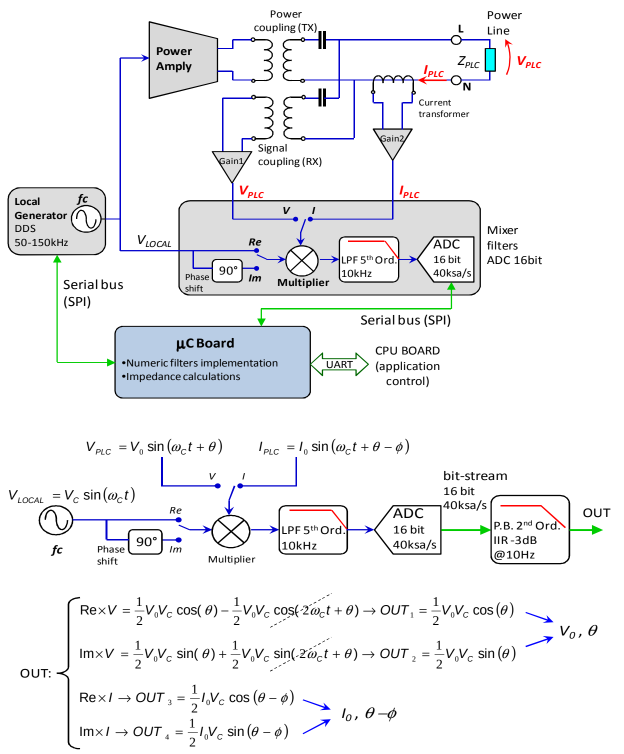

Fig. 3: block diagram and working principle of the impedance measurement.

The test signal (*Vlocal*) is coupled to the power line through the "TX" coupler. The actual voltage applied to the power line is then acquired through a second coupler ("RX"), while the injected current is collected through a wideband current transformer. At this point, *Vplc* and *Iplc* are mixed (multiplied) with *Vlocal* and with the same signal in quadrature (90° shift), so that a total of four measurements are carried out. After the mixer, the resulting signals are low-pass filtered so that only the DC component of the multiplication is retained and converted by the ADC, while the component at $2\omega_C$ is cut. It is easy to demonstrate the results summarized in fig 3: the four operations allow the extraction of both the *Real* and *Imaginary* parts of *Vplc* and *Iplc* (with respect to *Vlocal* which is the reference phasor). Once the phasor of *Vplc* and *Iplc* are known, the calculation of the complex Zplc is straightforward.
In the digital domain, the signals are further low-pass filtered. Noise rejection is directly related to the cutoff frequency of such filter: the lower the cutoff frequency, the higher the SNR [4].
Another advantage of this technique is that, since only the DC component of the mixed signals is relevant, the ADC

sampling rate can be much lower than the test frequency (providing that the low-pass filter cuts effectively the components at $2\omega_c$ resulting from the multiplication).

CPU and interfaces

The CPU board is equipped with an ARM9 microprocessor which runs on an STLinux Ver. 2.6 distribution Operating System, supporting also web services to access ELVIS features with a normal browser. Besides the DDRII RAM and the FLASH memory which hosts the OS, the board is equipped with an eMMC memory (8 GBytes) which acts as solid state mass memory (for data storage).
As already discussed, for safety reasons, the only interfaces accessible by the user are wireless: the board is equipped with a *Bluetooth 4.0* module and a *WiFi* module which can both work as client or access point.

Mechanical design

The boards are housed in a UL-V0 plastic box with a protection degree of IP44 making it suitable for outdoor operation. The external dimension are: 157mm (width), 254mm (height), 65mm (thickness), resulting in an ergonomic handheld device (Fig. 4).

Fig. 4: 3D rendering of the device.

CASE STUDIES

The first ELVIS prototype has been used in various real field applications, some of them being summarized in this chapter.

Analysis of PLC reachability

In a portion of a residential distribution network (ENEL distribution network, Italy) poor reachability of the meters were reported. The PLC technology used in such portion of the network is based on FSK modulation at 72kHz carrier frequency.
The noise spectrum measured on a street junction box is shown in Fig. 5. The noise measured at 72kHz in the bandwidth of the PLC signal (5kHz, blue curve) shows a value of 85dBuV. This is a quite high value which can explain the reachability problems reported.

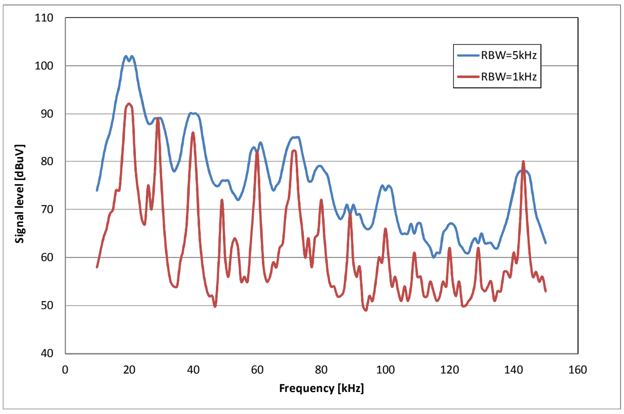

Fig. 5: noise spectrum measured at the street junction box.

Looking at the spectrum taken with a narrower resolution bandwidth (1kHz, red curve) we can recognize a quite regular pattern of peaks evenly spaced by about 10 kHz. This is the fingerprint of a disturbing device with a fundamental working frequency of 10 kHz whose harmonics are injected into the power line. Later on, a photovoltaic inverter has been identified as the source of the noise.
The power line impedance measured on the same junction box is shown in figure 6. The magnitude at 72kHz is 3.9 Ohm which is quite low and it can contribute to the poor PLC performances in that area.

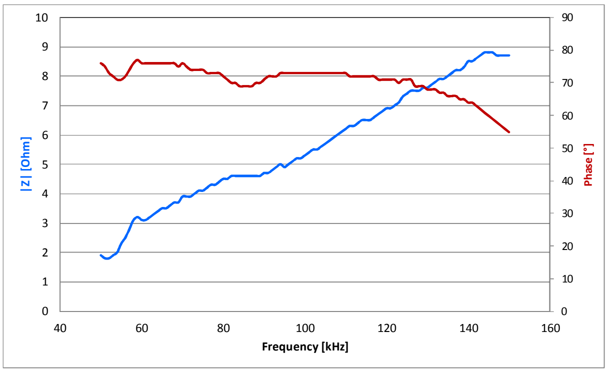

Fig. 6: impedance spectroscopy (magnitude, blue curve, and phase, red curve).

PLC performances characterization

PLC characterization has been carried out in a portion of the network operated by a DSO part of ENEL group located in Colombia. In that area a field trial with the installation of smart meters provided with “Meters&More” PLC technology has been rolled out.
As relevant example, we can report the result shown in figure 7, where the noise spectrum taken at the data concentrator (located in the secondary substation) has been collected for the three separate phases. As it can be noticed, the noise on L3 at the carrier frequency (86kHz) is several dB higher than the noise on the other two

phases, which shows some correlation with the poorer reachability of the meters connected to that phase.

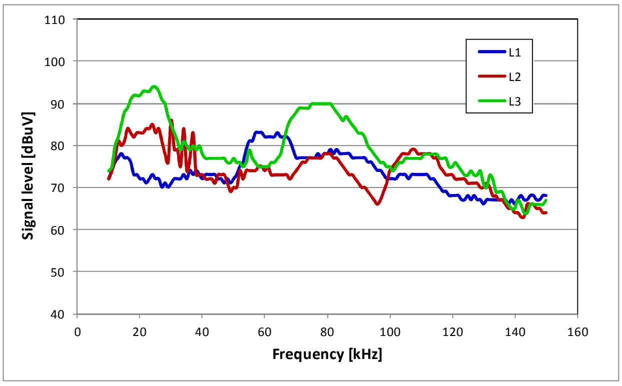

Fig. 7: noise spectrum of the three phases at the secondary substation.

Noise in proximity of meters that could not be reached by PLC communication were recorded as well, one example being shown in figure 8 (3 phase meter) which shows a very high level of noise (97-106 dBuV) at the carrier frequency.

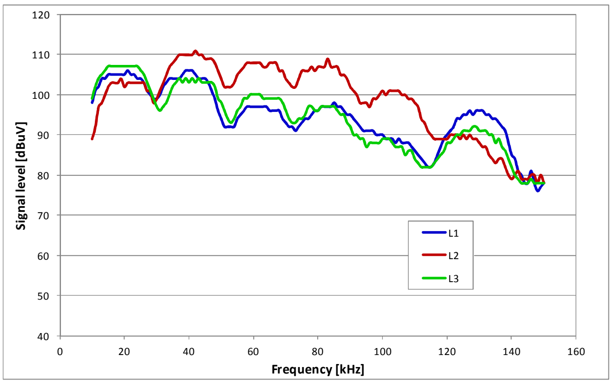

Fig. 8: noise spectrum taken in proximity of a three phase meter not accessible by PLC communication.

Being the noise level on phase L3 (the phase used by three phase meter for PLC communication) around 90 dBuV it is evident that the poor reachability is due to high noise on the network. In this case, having a chain of repeaters that allows a PLC signal higher than 90 dBuV (S/N of the modem is 6 dB) to reach the meter helped us solving the reachability problem.

S/N and line attenuation estimation

As in the previous example, a similar analysis has been carried out to characterize a portion of network located in Czech Republic (PLC technology: B-PSK @ 86kHz). In this case, a couple of device has been used in master/slave mode with the master connected at the secondary substation, and the slave moved in different locations along the network.

For each different position the noise floor and the received signal amplitude were recorded, and the corresponding estimation of the S/N and line attenuation were calculated. The following table summarizes a relevant subset of such measurements:

Location	Reachability	Signal	Noise	S/N	Attenuation
Substation	N/A	120 dBuV	70 dBuV	-	-
#1 (Slave)	0%	77 dBuV	75 dBuV	2 dB	43 dB
#2 (Slave)	0%	58 dBuV	47 dBuV	11 dB	62 dB
#3 (Slave)	50%	68 dBuV	53 dBuV	15 dB	52 dB

The S/N in location #1 is so low that no PLC communication is possible. The S/N is reduced due to a combination of the quite high line attenuation and to the quite high level of noise.

In the second location, the estimated S/N is not so low but the signal strength is very close to the intrinsic sensitivity threshold of the PLC modem, for this reason the reachability remains zero.

Finally, in the third location, the low level of noise helps to maintain a quite high S/N despite the high signal attenuation and the resulting reachability is 50%.

CONCLUSIONS

Getting the best out of a PLC based AMI system is strongly related to reachability from the concentrator of PLC nodes connected to the network. To improve reachability it is sometimes mandatory to perform field measurements of PLC communication influencing factor with cheap, easy to use, light weight equipment.

ENEL Distribuzione ELVIS, has been successfully used in both Italy and abroad to analyze many PLC communication cases and will support future massive AMI deployments.

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