Characterization of HV Lines for Digital Power Line Carrier Operation

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Abstract-Introduction or upgrades of digital Power Line Carrier (PLC) communication networks often require a new assessment of relevant power line features. This paper outlines an effective approach for measurement of the most important parameters in a PLC channel, which exploits advances in digital oscilloscope technology and software post-processing of acquired test data. Experimental results obtained on a 132 kV distribution line are presented to support the theoretical discussion.

I. Introduction

Power Line Carrier (PLC) is a widespread, reliable and cost-effective transmission system for operations and maintenance in electricity power utilities: in its digital form, this technology can provide facilities such as telephony (operation, maintenance and administration speech circuits), telegraphy, telecontrol, load frequency control, teleprotection and data transmission [1]. Current digital PLC (DPLC) equipment fulfils channelling requirements according to IEC60663 and IEC60495 and operates in a frequency range between 24 kHz and 500 kHz. Within that range a number of 4 kHz channels are aggregated and allocated to form a single link according to capacity requirements (i.e., total bandwidth per link equals 4 kHz, 8 kHz, ..., etc.), assuring compatibility and coexistence with other analogue and digital PLC.

A very schematic representation of a PLC system is given in Fig. 1. A power line is known to represent a rather difficult channel, particularly for broadband communications [2], [3]. To achieve a successful communication several factors should be taken into account during link analysis and design: in first place, the characteristics and behaviour of the electrical power line including the surrounding environment; after that, DPLC equipment and all the coupling devices that lie between the two ends of a link.

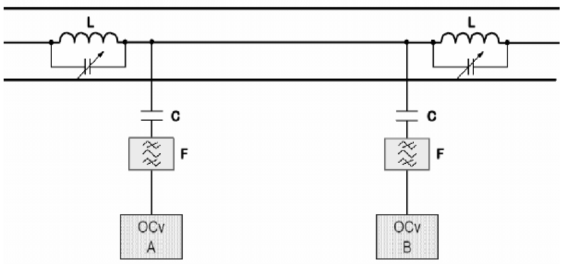


Figure 1. A PLC system (L = line trap; C = coupling capacitor; F = line tuning filter; OCvA, OCvB = tx/rx terminals).

DPLC broadens the old concept of narrow-band analogue PLC (based on single-sideband modulation and 4 kHz voice channels), requiring more frequency resources to assure the desired throughput (i.e., 8+8 kHz for a good quality 64 kb/s link) and reach, at the same time, the predefined availability objective. In this case, one of the main issues concerns the choice of a proper channel that complies with the frequency plan and ensures the desired target quality will be achieved. Therefore, it is important to fully characterize a line before the final configuration of a PLC system is decided upon [4].

This paper reports on the work, carried out jointly by ENEL Distribuzione S.p.A. and the Department of Information Engineering, Università di Padova, to determine an effective procedure for the test of 132 kV power distribution lines, preliminary to deployment of enhanced PLC devices. The aims of the tests are the determination of the frequency response and the characteristic impedance of the power line under test, the measurement of background noise to assess the level of interference affecting different PLC channels, the collection of statistical data on impulse noise.

ENEL Distribuzione formerly operated an array of specialised instruments for similar test purposes, including a spectrum analyser and a selective voltmeter; however, these are ill-suited for the tasks. A new test procedure has been designed, taking into account the need to have a reduced impact on the normal operation of the network in terms of personnel, time and logistic requirements. Main issues in these respects are: fast and simple execution, accuracy and reliability, electrical safety and limited instrumentation cost. The goal of the work was to implement the whole test procedure by using a single measuring instrument, complemented by a suitable set of signal processing and post-processing software procedures.

II. Power line characterisation

The comparatively narrow frequency range under consideration suggests the possibility to employ a digital oscilloscope for all measurements. From an accuracy view point, the main limitation of this choice is the amplitude resolution of the acquisition system. Assuming a typical 8-b analogue to digital converter, in any practical signal analysis application signal-to-noise ratio (SNR) is upper bounded to about 50 dB by the converter non-linearities. However, the resulting measurement accuracy is still good enough for the tests described in this work.

The most important requirements turned out to be the memory depth of the acquisition system (a few megasamples at least) and its computing power, enough for fast signal processing operations such as Fourier transform computations. This oriented the choice towards high-end oscilloscopes; a feature found in a number of them is the use of a Windows operating system, which in this application proves useful to simplify the management of procedures and the storage of test data by maintenance personnel. A digitally synthesized signal generator was selected to provide the test inputs.

A. Measurement set-up

Although standard instruments have been employed in this work, the measurement set-up had to be complemented by the introduction of specific devices, whose purposes are:

- overvoltage protection;
- power line impedance matching;
- reduction of noise and aliasing effects.

The use of transient suppressors is essential to protect the sensitive instrumentation ports. Specifically, surges have been found to occur, causing measured peak voltages in excess of 900 V at the coaxial cable ends. For this purpose, silicon Transient Voltage Suppressors (TVS) were employed, these allowing to withstand peak currents of 200 A for a maximum time of 10 ms. The rather high parasitic capacitance of a TVS (of the order of 10 nF) requires compensation, which is obtained by connecting low-capacitance Schottky diodes in series, so that total capacitance drops to about 30 pF.

Impedance matching is also necessary, since the reference line impedance of the PLC system under test is 75 Ω. Therefore, a 25 Ω anti-inductive resistor was connected in series to the 50 Ω instrument inputs. This helps reduce mismatches, but does not actually eliminate them entirely, as noted in the next subsection. Numerical corrections have been introduced in the measurements, to account for the impedance matching network.

Finally, an active low-pass filter has been designed and is placed in front of the oscilloscope input. In fact, the oscilloscope internal band-limiting filter has a 20 MHz cut-off frequency, while the maximum sampling rate employed for most of the measurements discussed below is just 5 MHz. Since the frequencies of interest do not exceed a few hundred kHz, the additional external filter has the purpose of reducing both aliasing and noise.

The device is a fourth-order Butterworth filter with a cut-off frequency of 525 kHz, and has been realised by cascading two second-order Sallen-Key active cells. Very high-speed, low-noise operational amplifiers were employed in the design. The filter response is flat to within 0.2 dB in the frequency range from 40 to 400 kHz, while the falloff beyond the cut-off frequency is -80 dB/decade. A unity-gain buffer amplifier input stage ensures a sufficiently high input impedance.

B. Frequency response measurement

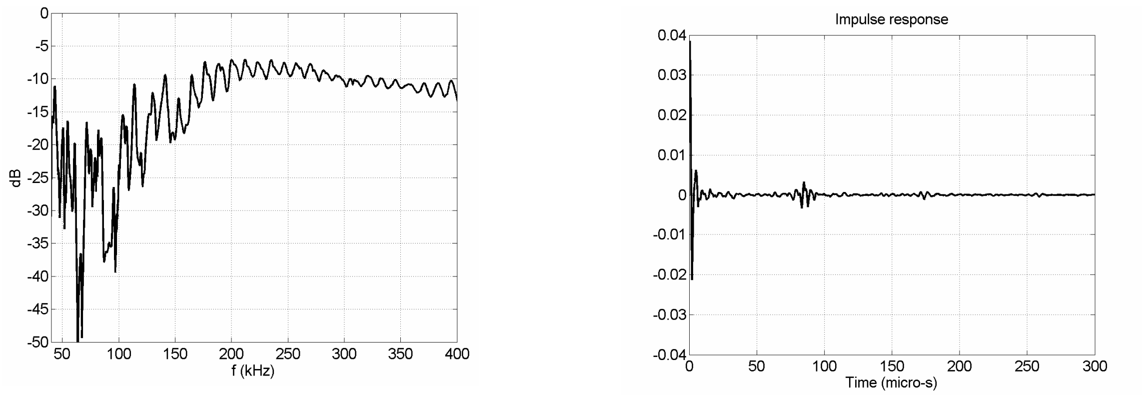
Determination of frequency response requires a typical input-output measurement which, in this case, is compounded by the fact that the two PLC ends of the power line may be some tens of km apart. This makes synchronization of the input and output signals difficult. Therefore a different approach was selected, which entails generating a periodical, swept-frequency sinewave of constant amplitude (a chirp) and acquiring the corresponding output at the opposite end of the power line. The resulting data record is processed by calculation of a fast Fourier transform, that yields the desired measurement. This approach may sound rather brutal, but proves to be effective for a number of reasons:

- no accurate triggering is required: it is just necessary that the generator sweep time coincides with the acquisition time given by the time-per division setting of the oscilloscope.
- multiple measurements spanning the whole frequency range can be obtained by a single sweep in a short time.

It should be reminded that, since the acquisition time is set to correspond to an integer number of sweep periods, theoretically no windowing is required. In practice, deviations from nominal occur both in the generator and in the digital oscilloscope clocks. However, typical mismatches between the time references of the two instruments can be expected to be not greater than 100 ppm in relative terms; their cumulative effects are negligible in comparison with the bounds due to the limited amplitude resolution of the oscilloscope acquisition system, small enough to dispense with corrections.

Lack of an accurate trigger means that phase information is lost: the measurement only provides the modulus of the carrier line frequency response. This is actually the required information, since PLC channels are rather narrow and the main purpose of this measurement is to support decisions on channel allocation.

An additional concern regards phase continuity: to generate the required periodic chirp the sinewave generator must be frequency-modulated by a signal that varies linearly with time. However, a periodic sawtooth would not fit the purpose well enough, as its sharp discontinuities cause spurious frequencies to appear. To modulate frequency a triangle waveform was used instead, producing a very clean and constant amplitude spectrum in the desired frequency range.



a) b)

Figure 2. Measured frequency response (a) and calculated impulse response (b) of a 132 kV power line.

Measurement of the frequency response of a HV line in the range 40-400 kHz is presented in Fig. 2.a. This measurement is obtained by computing first the Fourier transforms of records of samples acquired with a 5 MHz sampling frequency. Each record spans a 500 ms observation interval, which gives a frequency granularity of 2 Hz. Spectral averaging has then been employed to enhance the result by reducing the effects of broad-band noise. Fluctuations are caused by reflections due to impedance mismatches, inherent in the line-to-ground transmission mode of the measured link. Application of time-domain techniques, as usually employed in network analysers, showed that far-end reflection contributes a response whose delay is approximately 85 μs, as shown in Fig. 2.b. The effect is confirmed by the corresponding estimated line length of 12.75 km, which agrees (to less than 5%) with design data giving the power line length as 13.2 km. Consideration may be given to the use of time-windowing techniques to improve the frequency response measurement by eliminating the contribution of reflections.

C. Characteristic impedance

This quantity is determined as the geometric mean of two values of the line impedance measured at the input, respectively with a shorted and with an open termination. The generator set-up is the same as in the previous case and produces a swept 40-400 kHz signal. A suitably selected sweep time allows the digital oscilloscope to operate in continuous, untriggered acquisition. The measurement produces a plot of impedance versus frequency, as in Fig. 3.

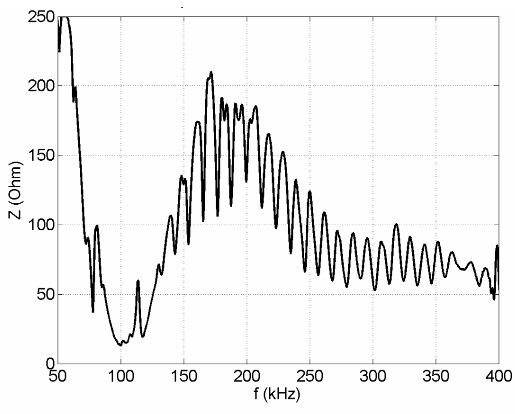


Figure 3. Characteristic impedance of a 132 kV power line.

III. Analysis of noise

Noise analysis is essential to determine the suitability of PLC channels to support communications at the desired capacity. All PLC receiver specifications, in fact, indicate the minimum signal SNR at which the design bit rate can be guaranteed. This value depends on the available transmitter power, the adopted modulation scheme and the noise level in the power line. Whereas measuring the background noise allows the estimation of the achievable signal-to-noise ratio and, consequently, of the sustainable data rate, the analysis of impulsive noise is relevant to assess the availability of the PLC channel.

A. Background noise

In this measurement the oscilloscope, plus its frequency analysis software functions, is employed as a spectrum analyser (with a dynamic range limited by the 50 dB SNR bound mentioned above). One end of the power line is closed on a matching 75 Ω load, while the oscilloscope is connected at the opposite end, behind the external low-pass filter that limits the analysis bandwidth to 525 kHz. In this case windowing is required to compensate for leakage effects: either Hanning or Blackman windows were employed in the tests. An example is given in Fig. 4, where a minimum frequency step of 50 Hz has been achieved by selecting the time-per-division setting of 2 ms/div. Unfortunately, at the sampling rate of 100 MHz this also yields a rather large record size of 2,000,000 samples, making the computation of the spectrum rather slow. However, this setting still provides the best trade-off between frequency resolution, noise reduction and computational complexity.

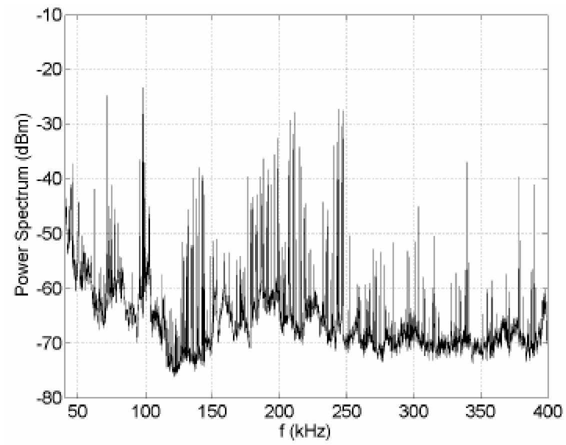


Figure 4. Measured power spectrum of background noise in the range 40-400 kHz.

Spectral averaging can be employed to enhance the estimation of interfering signals and of broad band background noise. Continuous monitoring is also possible, but is should be reminded that frequency analysis of such a large data record is time consuming. An example of this kind of measurement is provided by the waterfall diagram of Fig. 5, which results from the acquisition of data over 20 ms observation windows, spaced 10 minutes apart. Total observation time is nearly 19 hours and result show that background noise remains fairly stationary.

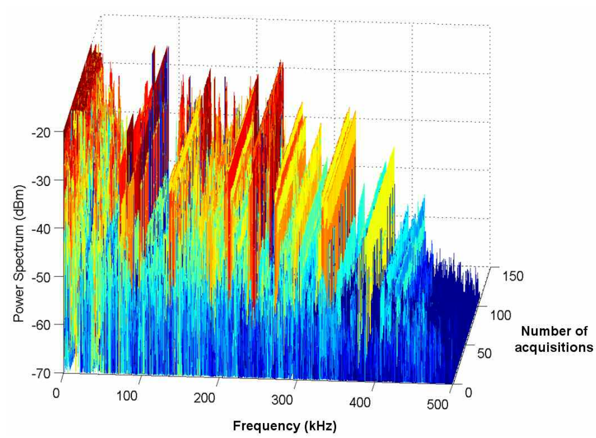


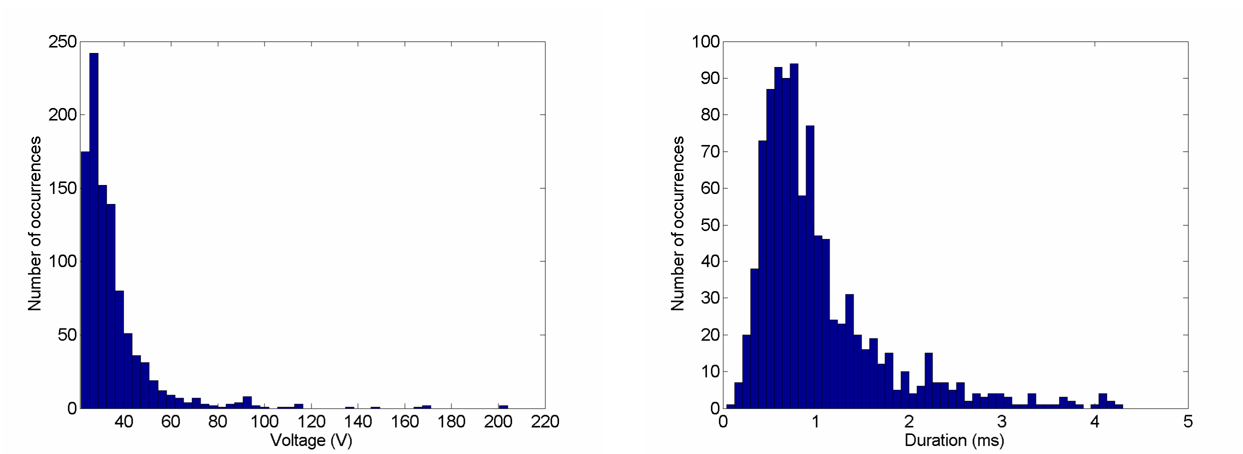
Figure 5. Continuous monitoring of background noise power spectrum in the range 40-400 kHz.

Noise monitoring might be coupled with bit error ratio (BER) measurements to allow diagnosis of possible impairments causing BER degradation in DPLC. In this case, however, it might be preferable to monitor shorter noise bursts. This function has been obtained by implementing in digital form the equivalent of a traditional spectrum analyser "max-hold" function. In fact, total computation time is 2 s per spectrum trace so that, assuming the same 10-minute spacing, each generated "max-hold" trace would result from the computation, at each frequency point, of the maximum value among about 300 computed spectra.

B. Impulsive noise

Impulsive noise on power lines is composed of narrow pulses, or pulse trains, whose peak values are well beyond the average background noise level. It can be caused by discharges due to atmospheric phenomena, line faults, the operation of circuit breakers and protection relays, arcs to ground, short circuits, etc. Statistic characterization of

impulsive noise is mainly aimed at predicting possible link downtimes and measurements may include the identification of aperiodic and periodic pulses, their peak amplitude, duration, interarrival time.
This task is made easier by exploiting a facility provided by most digital oscilloscopes having deep memories, i.e., memory segmentation. The acquisition memory is divided into smaller segments, each containing the number of samples that are to be filled when a single event occurs. Then, with the instrument set up in “single acquisition” mode, a number of independent “events” can be acquired, all triggered by the same conditions at different times. The instrument stops when the whole memory has been filled with a group of comparable events.
Preliminary analyses showed that, for the environment under test, impulsive noise had no significant spectral components above 300 kHz, therefore a 5 MHz sampling frequency was chosen; segment size was set to 10 ms, which is long enough to capture even the slowest occurrences of impulse noise. With memory segmentation, inter-segment hold-off time is quite short, allowing the correct acquisition of pulse trains. The acquisition time is recorded together with each segment, so that interarrival times can be easily analysed.
Statistical analysis is necessarily performed *a posteriori* and is concerned with the distributions of the amplitudes, durations and interarrival times of impulses. These information allow the characterisation of impulsive noise as a stochastic process and enable an assessment of the reliability of a DPLC link, based on classic parameters such as availability, mean time between failures, downtime, etc.
An instance of what can be obtained with this kind of measurements is presented in Fig. 6.a, which shows a histogram of peak impulse voltage. Trigger level in this case was set to 15 V; accordingly, the histogram lower bound is 20 V and bin size is 4 V. It can be seen that the number of occurrences decreases exponentially with the amplitude, but it should be remembered that, during repeated tests, peak voltages up to 924 V have been measured.



a) b)

Figure 6. Measured histogram of impulsive noise peak amplitudes (a) and durations (b).

A corresponding histogram of impulse lengths is shown in Fig. 6.b and confirms that using a 10 ms size for oscilloscope memory segmentation is correct and leaves a sufficient margin.
The use of a single histogram for the analysis of interarrival times is more difficult, since impulsive noise can be characterized by bursts, in addition to single events. Therefore, results are presented in Fig. 7 by a set of histograms; each refers to a different range of interarrival time values.

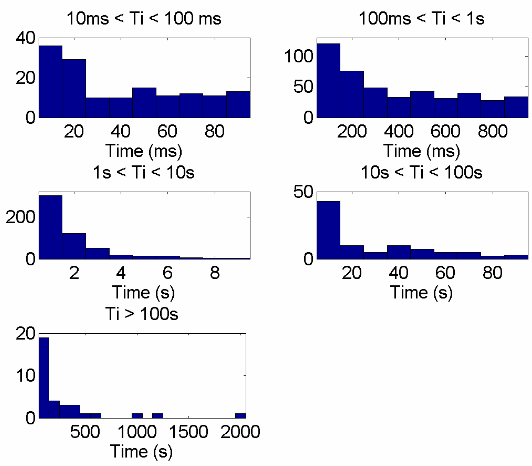


Figure 7. Measured histograms of interarrival times: 10ms<T<100ms; 100ms<T<1s; 1s<T<10s; 10s<T<100s; T>100s.

It should be remarked that the value of 10 ms corresponds to the memory segment size. Therefore, it is the minimum separation the instrument can detect. The mean interarrival time is of the order of 10 s, but this information is of little relevance, since the corresponding standard deviation can easily be more than an order of magnitude larger. In fact, measured interarrival times range from 10 ms up to over 30,000 s, spanning six orders of magnitude; this explains why each histogram in Fig. 7 has been referred to a single decade. This use of different time scales allows to differentiate between bursts, that are accounted for by the two topmost histograms, and single events. It can be seen that single impulses are often separated in time by several seconds, but bursts account for a significant number of occurrences.

IV. Conclusions

Tests carried out over a number of real HV distribution lines showed that the proposed approach can form the basis of a methodology for the systematic collection of information about relevant transmission parameters, needed to improve and optimise DPLC modem design. The same procedure could be effectively applied to quickly and accurately characterize a HV line, selecting the best channel to be used for DPLC link implementation. The definition of a standard test procedure, based on the approach and equipment described in this work, is under consideration.

One of the main advantages of the proposed approach is the reduced complexity of equipment. In fact, high-end digital oscilloscopes have been shown to possess the flexibility required to implement all the necessary measurements, at a good performance level. Once the many features of this class of instruments have been understood and mastered, efforts can be concentrated on the development of appropriate software procedures for application-specific analyses of measured data, allowing very efficient measurement procedures to be realised.

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