Statistical Model Study for Narrowband Power Line Communication Noises

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Abstract

Noise is one of the main problems for the Power Line Communication (PLC) system. Noise parameters vary from country to country. They depend on time, place, load types, power line topology and mains voltages. This is annoying issue for researches who try to make a mathematical model to understand noise characteristics. Therefore a lot of measurement campaigns should be done before setting up a mathematical model and also model has to include statistical studies. The subject of this paper is the development of a statistical noise model for Narrowband PLC in the low voltage network. Noise model parameters were derived from measurements of the mains voltages in using Data Acquisition card (DAQ) and a digital signal processing program. Results of this model obtained very akin to present situations. Contribution of this study is that it helps the researcher to work independent of power line voltage and frequency.

1. Introduction

It is known that PLC is based on electrical signals, carrying information, propagating over the power line. Its main attractive feature is that it is used the same power line network. There is no need for another communication infrastructure to be built separately and there is no any other bill to be paid for communication services. However, like other communication systems, PLC systems are also at risk of noise, attenuation and multipath effects. They restrict the channel performance [1].

PLC is classified according to its frequency bandwidth. It may be either broadband or narrowband system. The Narrowband PLC is used for low-data rate applications, like remote control and monitoring, data acquisition, street light control, home automation, and Automatic Meter Reading (AMR). The European PLC regulation norm CENELEC50065-1 defines the allowed frequency ranges. According to mentioned standard the frequency range subdivided into five sub-bands [2]. 3-9 kHz band range is the first one. Band A covers interval between 9 to 95 kHz. Band B covers interval from 95 kHz to 125 kHz. Band C covers interval between 125 and 140 kHz. Band D covers interval between 140 kHz and 148.5 kHz.

Narrowband PLC noise classification studies are given in [3-6]. These arrangements can be summarized taken into consideration noise duration and noise frequency. Basically noise is divided in three main categories. These are named as Continuous, Impulsive and Narrowband Noises.

There are also two sub-categories of the Continuous Noise such as Background Noise and Time Variant Continuous Noise. If noise's envelope exhibits a constant form at least more than a few cycles of mains it is named Background Noise. It includes summation of harmonics of mains cycle and different low power noise sources present in PLC system. The Power Spectral Density (PSD) of this noise type is found to be a decreasing function of the frequency. Time Variant Continuous Noise occurs if its envelope changes synchronously to the mains absolute voltage. The frequency of the periodic features of the noise is the same or twice the mains frequency. In Narrowband PLC systems this feature can be seen as a trouble because of the symbol duration and thus packet length tend to be long because of the relatively narrow bandwidth.

Broadcasting and wireless communication systems may contaminate PLC channels. Narrowband Noise comes out in power line network according to length of the power cables.

Impulsive Noise is generated by electrical appliances when users are turned on or turned off them. It has three sub categories. Periodic Impulsive Noise Synchronous with the AC Cycle waveforms composed of a train of impulses with the frequency of AC mains or two fold. It is caused by the silicon controlled rectifier or thyristor based appliances. Periodic Impulsive Noise Asynchronous with the AC Cycle is generated by switched-mode power supplies and AC/DC power converters. That kind of noise waveforms composed of a train of impulses with a frequency much higher than that of mains AC. Aperiodic Impulsive Noise is caused by switching transients. It is composed of impulses that occur random timing, often more than two seconds intervals. Amplitude of Impulsive Noise can reach out of the allowed maximum noise levels. Impulsive Noise is dominant and causes the greater problem to a communication system. Therefore, there is a lot of noise characteristic analysis for various electrical devices in literature [7-9]. In these studies impulsive noise is parameterized in time domain according to amplitude, width and interval time.

The purposes of this paper are analyzing noises and according to results of these analyses building a new enhanced narrowband power line statistical noise model that can be used for advanced studies as an offline noise generator. In the literature there is a gap about noise generators which work in time domain and base on statistical models for Narrowband PLC. For example, statistical study in [10] is based on frequency domain analysis and that covers frequencies ranging from 1 MHz to 30 MHz. It takes into consideration generating noise density spectrums statistically. Our model includes time domain results frequencies ranging from 3 kHz to 148.5 kHz. Time domain analyses are obtained using bandpass filter. Noise peak amplitude values are used in this modeling effort. Phase angle values are also taken into account when it is built.

The rest of the paper is arranged as follows. Section 2 describes the measurement setup, whereas in Section 3 the statistical noise model technique is illustrated. The proposed noise model and measured outputs are analyzed in Section 4. Conclusions and Further Research are drawn in Section 5.

2. Measurement Setup

Measurement campaigns were carried out for different type loads in both university laboratory and in a home. Authors especially focused on Narrowband PLC noise measurement up to 148.5 kHz and analysis of obtained data. The measurement setup that was used schematically looks as it is shown in Fig. 1.

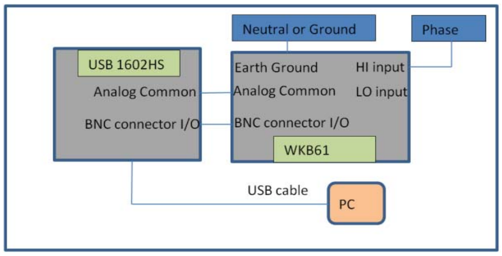

Fig. 1. Schematic representation of the measurement setup.

The main measurement component is USB-1602HS Data Acquisition (DAQ) card. It has USB-based high speed analog input and digital input/output (I/O) module. It has 16 bits resolution and 2 MS/s speed. It was connected to the low voltage network by means of WBK61 coupling circuit, which is basically a 200:1 probe that used for preventing the mains signal from entering the DAQ card. A digital signal processing software was used to record and evaluate the collected data.

3. Statistical Noise Model

Time domain analysis for Statistical Noise Model was carried out using a 5th order Butterworth type bandpass filter. Lower and upper cut off frequencies are changed for investigated bands. Frequency range from 3 kHz (f_{start}) to 150 kHz (f_{stop}) is divided into 147 frequency intervals (I) with the same length 1 kHz. Time domain output signals related to 3 - 4 kHz band are shown in Fig. 2 and Fig. 3.

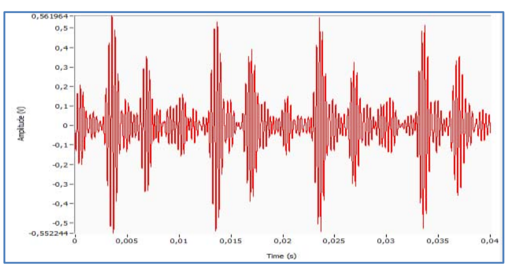

Fig. 2. Noise amplitude in time domain (3 kHz- 4 kHz).

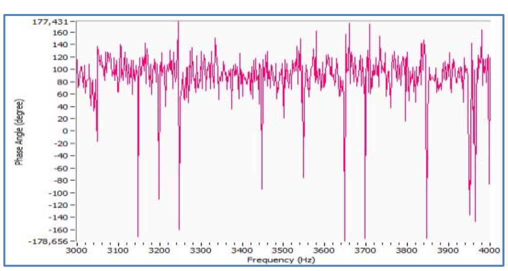

Fig. 3. Noise phase angle in time domain (3 kHz- 4 kHz).

It is assumed that the noise amplitudes in the I frequency intervals are statistically independent of one another. Each frequency interval i ($i \in [1, 147]$) contains 40000 measured samples of the noise's Amplitude value as Volt.

ξ_i ($\xi_i \in [x_{min}, x_{max}]$) is the peak value of the noise samples in the interval i on the measurement location at a given point in time. The values of ξ_i were arranged in a histogram length of the x axis (it represents amplitude or phase angle values) is 100. In such a way that all values of ξ_i are categorized into classes c of the same length (Δx) *is 1*. It is shown in Fig. 4 and Fig. 5 for 3 - 4 kHz band.

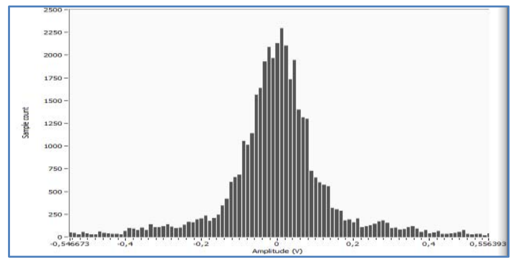

Fig. 4. Noise Amplitude Histogram (3 kHz- 4 kHz).

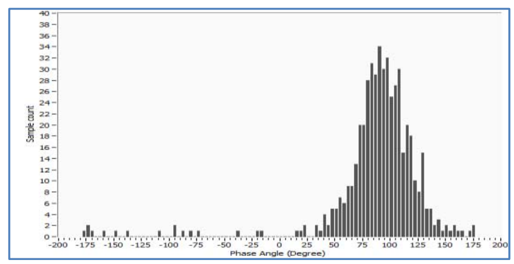

Fig. 5. Noise Phase Angle Histogram (3 kHz- 4 kHz).

For each class the number of values in this class (N_C) was determined. N_C divided by the total number of measurements (N_M) defines the relative frequency [10]

$$H(\xi_i \in c) = \frac{N_c}{N_M} \quad (1)$$

For $N_M \to \infty$, the relative frequency in equation (1) tends to the probability $P(\xi_i \in c)$ with the probability 1. The probability that the peak noise level in i is the the class c could be approximated by:

$$P[x<\xi_i \leq x+\Delta x] \approx \frac{N_c}{N_M} \text{ with: } x \in [x_{min}, x_{max}],\ \Delta x>0 \quad (2)$$

For the probability density function (pdf) $f_{\xi_i}^i(x)$ in the frequency interval i it follows that

$$\int_x^{x+\Delta x} f_{\xi_i}^i(x)\, dx = P[x<\xi_i \leq x+\Delta x] \quad (3)$$

$$f_{\xi_i}^i(x) = \lim_{\Delta x \to 0} \frac{P[x<\xi_i \leq x+\Delta x]}{\Delta x} \quad (4)$$

As equations 4 shows, the accuracy of the approximation of the pdf with the equivalent probability $P[x<\xi_i \leq x+\Delta x]$ depends on the length of the class Δx. Its pdf's can be seen in Fig. 6 and Fig. 7 for frequency range from 3 kHz to 4 kHz.

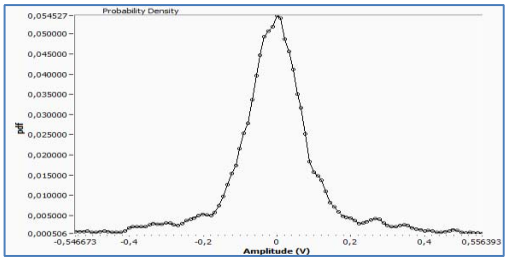

Fig. 6. Probability Density Function (pdf) for Noise Amplitude

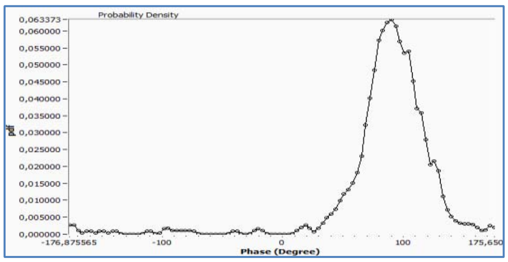

Fig. 7. Probability Density Function (pdf) for Phase Angle

The distribution of the random variable ξ_i is calculated using the following equation (5).

$$F_{\xi_i}(x) = P(\xi_i \leq x) = \int_{-\infty}^{x} f_{\xi_i}^{i}(t)\,dt \quad (5)$$

In the offline simulation of the background noise, the noise level in every frequency interval *I* is selected according to the pdf $f_{\xi_i}^{i}(x)$ by a random process. A random generator of a PC only generates values for the uniformly distributed 100 random variable η in the interval [0, 1]. For the implementation of the noise simulation on a PC, the uniformly distributed variable η has to be mapped to the variable ξ_i with the pdf $f_{\xi_i}^{i}(x)$. The random variable η could be transformed into a steadily distributed random variable ξ_i by the equations (5):

$$f_{\xi_i}^{i}(x)\,dx = \mp f_{\eta}(y)dy \quad (6)$$

$$F_{\xi_i}(x) = F_{\eta}(y) \quad (7)$$

Cumulative Distribution Function (CDF) $F_{\xi_i}(x)$ is shown in Fig. 8 and Fig. 9. The distribution function of a uniform random variable is determined by

$$F_{\eta}(y) = \int_{-\infty}^{y} f_{\eta}(u)du = y \text{ for } y \in [0,1] \quad (8)$$

From 7 and 8 it follows that

$$F_{\xi_i}(x) = F_{\eta}(y) = y \quad (9)$$

$$x = F_{\xi_i}^{-1}(y) = g_{\xi_i}(y) \quad (10)$$

$g_{\xi_i}(x)$ is the mapping function of a uniformly distributed random variable to the pdf of the random variable ξ_i.

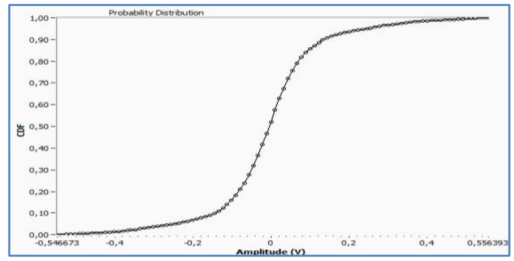

Fig. 8. CDF for Noise Amplitude (3 kHz- 4 kHz).

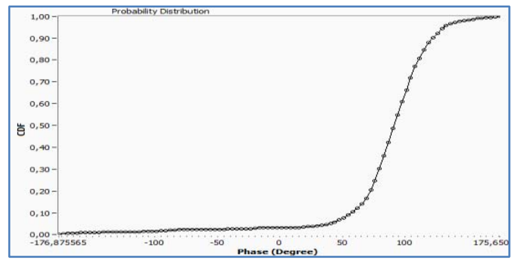

Fig. 9. CDF for Phase Angle (3 kHz- 4 kHz).

Finally, CDFs, amplitude and phase angle values were obtained via digital signal processing program and they were saved as MS Excel format. In MATLAB environment noise waveforms were created by means of the script. The amplitudes of waveforms were also calculated for the simulation period.

4. Results

The results of the measurements made in home are shown in Fig. 10. In this figure, best or worst noise scenario levels can be seen. These levels can be used to estimate capacity of power line. The Background Noise is decreasing with increasing frequency.

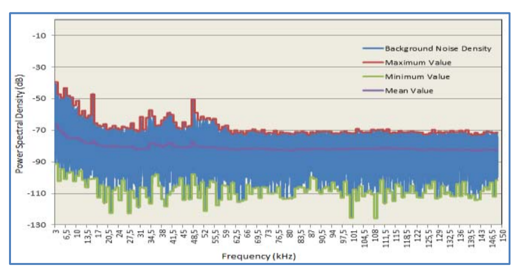

Fig. 10. PSD for residential environment (3 kHz- 150 kHz).

The largest minimum value : -91.26 dB,
The smallest minimum value : -125.8 dB
The largest maximum value : -39.6 dB
The smallest maximum value : -73.04 dB

The mean value of Background Noise ($PSD_{residential}$) as well as the curves of minimum and maximum Background Noise has decreasing amplitudes with increasing frequency, f (Hz). It can be described by (11). Model noise form can be seen in Fig. 11.

$$PSD_{residential} = -2.5972\ Ln\ (f) - 52{,}323\ \text{dB} \quad (11)$$

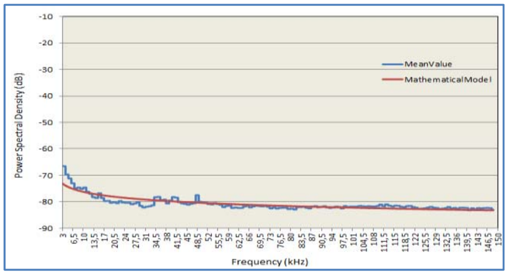

Fig. 11. Residential PSD Model (3 kHz- 150 kHz).

The results for the signals measured in the laboratory are shown in Fig. 12. In this figure best or worst noise scenario levels can be seen. The Background Noise is decreasing with increasing frequency.

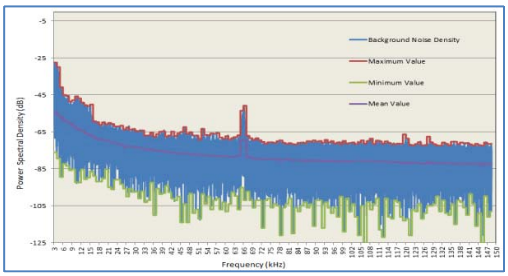

Fig. 12. PSD for laboratory environment (3 kHz- 150 kHz).

The largest minimum value	: -76	dB
The smallest minimum value	: -125	dB
The largest maximum value	: -27.4	dB
The smallest maximum value	: -72.4	dB

The mean value of Background Noise ($PSD_{laboratory}$) can be described by (12) frequencies between 3 - 95 kHz. It is described by (13) for 95-148.5 kHz band. Model noise form can be seen in Fig. 13.

$$PSD_{laboratory3-95kHz} = -\ 8.8569\ Ln\ (f) + 18{,}516\ \text{dB} \quad (12)$$

$$PSD_{laboratory95-148.5kHz} = -\ 3{,}8796\ Ln\ (f) - 36{,}21\ \text{dB} \quad (13)$$

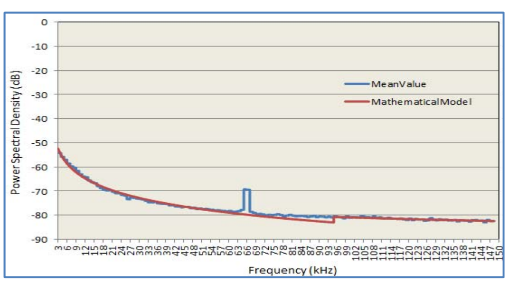

Fig. 13. Residential PSD Model (3 kHz- 150 kHz).

An example of Narrowband Noises for a residential environment is depicted in Fig. 14. This only consists of background noise with disturbances by low and middle frequency-radio signals in. Narrowband Noise amplitudes will be higher as long as power line modems closer to transmitter source. It is given in Fig. 15.

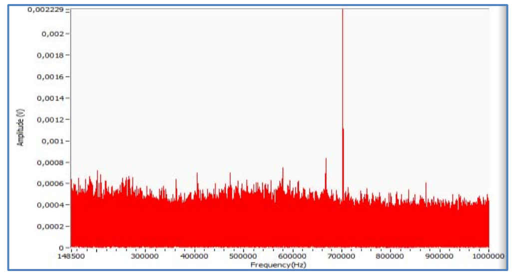

Fig. 14. Residential environment Background Noise with LF and MF radio - based Narrowband Noises

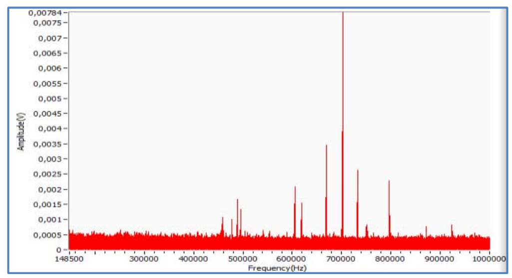

Fig. 15. Laboratory environment Background Noise with LF and MF radio - based Narrowband Noises

Periodic Impulsive Noise Asynchronous with the AC Cycle was generated by solar power inverter in laboratory. Its noise distribution in the frequency domain can be seen in Fig. 16. Its operating frequency is 75 kHz. In these figures red and blue lines represent off and on states of the device peak amplitude values as volt respectively.

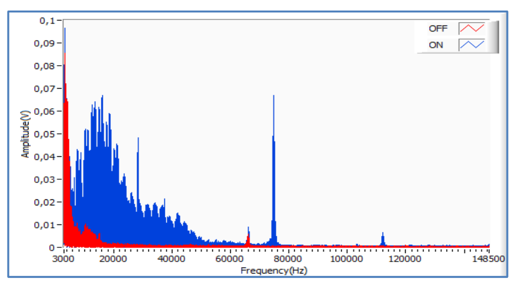

Fig. 16. Impulsive Noise contamination

Impulsive Noises are taken a place as if they are parallel channels. Amplitude of this noises can be higher than the allowed maximum noise levels. Each of theirs amplitude changes randomly in the studied whole frequency range. However maximum amplitude is observed vicinity of operating frequency and its harmonics. Harmonics can be seen in Fig. 17.

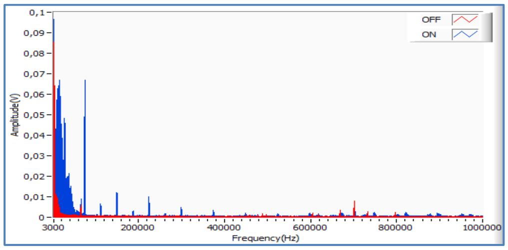

Fig. 17. Impulsive Noise and its harmonics

When the method explained in Section 3 are used we can generate these noises in time domain. It is very useful tool to work offline simulation desire. Graphical outputs of the created model are presented below. Generated noise from this model which is seen in Fig. 18 belongs to 3-4 kHz band. Its actual form is given in Fig. 2. In Fig. 19 and 20 depicts actual and generated noise waveforms. They can be compared with each other.

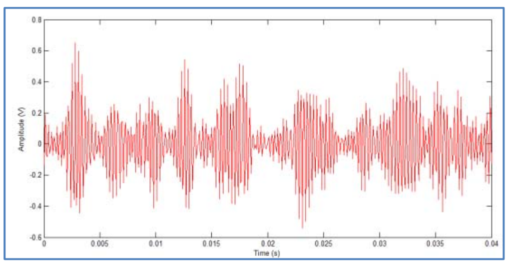

Fig. 18. Generated Noise form in time domain (3 kHz- 4 kHz).

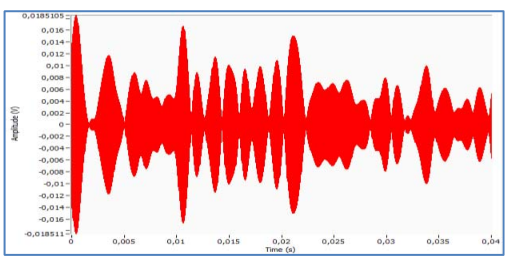

Fig. 19. Noise waveform in time domain (25 kHz- 26 kHz).

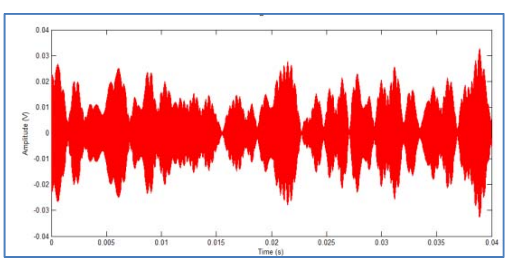

Fig. 20. Generated Noise waveform in time domain (25 kHz- 26 kHz).

5. Conclusions and Further Research

In this paper Narrowband PLC noises are measured and analyzed. Statistical approaching based power line channel noise model is proposed. It is based entirely on measurements in time and frequency domain. The model is in fact a family of parallel models in the time domain for selected frequency band. The frequency distance between two model is 1 kHz. The narrower the frequency distance is, the more accurate the power line model can be. The results verify already known characteristics and provide substantive information on the power line channel.

These measurements were carried out only in two different locations. Number of places can be increased to improve this model. Future work will cover modeling of adaptive filter design to cancellation of noise base on this study.

6. Acknowledgements

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7. References

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