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Analysis of Practical Parameters Required for Power Line Carrier (PLC) System Design

تحليل المعاملات العملية المطلوبة لتصميم منظومة خطوط القوى الحاملة

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ملخص البحث:

لقد أدى تزايد الطلب على الاتصالات فى العصر الحالى إلى تحول منظومات امداد الطاقة الكهربية من مجرد استخدام خطوط النقل فى نقل وتوزيع الطاقة الكهربية إلى وسيلة متعددة الأغراض يتم من خلالها نقل القدرة والصوت وخدمات نقل البيانات بأشكالها المختلفة وبالتالى يمكن فى هذه الحالة اعتبار خطوط النقل والتوزيع على أنها قنوات اتصال. ولتصميم المنظومة المناسبة للاتصالات يجب دراسة عدد من المعاملات العملية ذات الصلة ، وأهم هذه المعاملات الضرورية لاستخدام خط النقل كقناة اتصال تتمثل فى: خصائص الضوضاء المضافة وتقنيات الترميز وتوهين الإشارة عبر خط النقل.

هذا البحث يعرض دراسة تحليلية للمعاملات الرئيسية لمنظومة خطوط القوى الحاملة وقد تم بناء برنامج كمبيوتر باستخدام لغة الماتلاب لتحليل هذه المعاملات وبالتالى تصميم خطوط القوى كقنوات اتصال، وهذا البرنامج مفيد لمقارنة طرق التوهين المختلفة واختيار افضلها، ويمكن استخدامه لمحاكاة أنواع الضوضاء المؤثرة على الخط الحامل وبالتالى تصميم الفلتر المناسب لها.

ABSTRACT

The increased demands of communications make the power supply on a way to migrate from a pure power distribution system to a multipurpose medium delivering power, voice and various data services. Transmission and distribution lines are considered as communication channels.

A number of practical parameters have to be studied for appropriate design of any communications system. The main parameters of interest of the power lines as a data communications channel are: additive noise characteristics, modulation techniques and signal attenuation over the transmission line.

This paper presents an analytical study of the main parameters of PLC system. A Matlab computer program is developed to analyze these parameters and can be used for designing PLC channels. The developed computer program is helpful in comparing different modulation methods and can be used to simulate different additive noise affecting the PLC channel and consequently design the appropriate filter.

Keywords: Power line carrier, noise, modulation, attenuation, PLC transfer model

1- Introduction

The electric power grid is about to face an important renewal in which the information and communication technologies are of vital importance. Thus, it is important to have a solid communication infrastructure. During the last years PLC technologies have been widely developed mainly. Currently, PLC networks provide a proprietary solution and enough reliability and quality conditions [1]. Besides, the opening of the market, the need to integrate Distributed Energy Resources (DER) and the increase of the power supply demand create a new scenario in which the approach of the energy distribution system has to change.

When designing or analyzing a PLC network, the structure and components of it, as well as its topology have to be taken into account. For appropriate design of any

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communications system, we have to address a number of important design issues related to characterization of the power line channel constitutes some important parameters. The main parameters of interest of the power lines as a data communications channel are: additive noise characteristics, modulation techniques and signal attenuation over the transmission line [2].

In this paper the performance of power line channel has been investigated. A comprehensive analysis of the main parameters affecting the design of PLC in electrical power systems is presented.

2. Additive Noise Characteristics

Additive noise is the most crucial factor influencing digital communications over the power distribution networks. Noise is defined as unwanted electrical signals with broadband spectral content lower than 200 kHz superimposed upon the power system voltage or current in phase conductors or single lines [1].

There are many reasons of noise in high tension electrical power networks include corona discharges, lightening, power factor correction banks, and circuit breaker operations. On low voltage networks, much of this noise is filtered by medium/low voltage transformers [3]. Noise and disturbances on the power network include over voltages, under voltages, frequency variations and so on. However, the most harmful noise for PLC applications is that superimposed on a power line. Switching devices such as light dimmers, induction motors in many common appliances and high-frequency noise caused by computer monitors and televisions often causes such superimposed noise, which is not a white noise [4]. The CENELEC Standard 50090 [5] provides the details of networking at homes and buildings, with twisted pair wires, coaxial cables, fiber channels, power lines and RF medium as being the alternative communication channels. This section is concerned with modeling and study of noise in the PLC for electric networks.

2.1. Classification of Noise in PLC

The broad band frequencies or the carrier frequencies are in the frequency range of some hundreds of kilohertz up to 20MHz. They can be classified into narrow band, and wide band, according to the frequency standard regulations. According to the CENELEC Standards the carrier frequency ranges from 3 kHz to 148.5 kHz, is called the narrow band carrier frequencies. Some countries like Japan uses expanded band width up to 30MHz, which is called the wide band carrier frequency range [6].

The additive noise in broad band power line communication channels can be generally classified into three main classes: *background, narrowband, and impulsive noise* which is the most effective one although it takes a very short duration [7-9].

2.1.1 Background noise:

This kind of interference is of stochastic nature and can be described by a power spectral density (PSD) or power spectrum, and it is considered to be the sum of numerous low power noise sources [3].

Connection of electrical loads to the power line injects noise into the power line environment. During the high activity time a lot of electrical loads are switched on, while there are much lesser loads being switched on during the low activity time. Such usage of electrical loads causes a higher mean noise, about 10 dB-m in the high activity time period. Background noise, narrow band noise, and periodic asynchronous impulsive noise are usually stationary over periods of seconds and minutes or sometimes even hours, and can be regarded generally as background noise [3].

The background noise has an exponentially decaying shape, and can be generalized using decaying function [8]:

$$N(f) = N_0 + N_1^{*} e^{-kf} \qquad (1)$$

The noise level has a higher standard deviation in the high activity time than that in the low activity time. During the high activity time, more switching on and switching off of the loads occur. Throughout the whole frequency band of interest the standard deviation during the high activity time is higher by about 10 dB-m than that of the low activity time. The background noise signal in time domain $N_{Back}(t)$ can be syntheses by filtering a white noise source [4] .

2.1.2. Narrow band noise types:

The narrow band noise consists of continuous wave signals with amplitude modulation. Normally, narrow band noise experiences the highest amplitudes in the evening hours, when propagation conditions for short wave radios are pretty good, while it is much lower in day light [3]. The narrow band noise portion $N_{narrow}(t)$ is described as follows [4]:

$$N_{narrow}(t) = \sum_{i=1}^{N} A_i(t) * \sin(2\pi f_i t + \phi_i) \quad (2)$$

where:

f_i : The carrier frequency
$A_i(t)$: The amplitude
φ_i : The phase
N : Number of independent sinusoids

The narrow band interference is periodic and non-synchronous to the power system frequency, and it is usually generated by television sets and computer monitors [8]. Switch mode power supplies also cause such disturbances [8-9]. In equation (2) the phase of the carriers may be chosen arbitrary out of the interval [0, 2π] and is not depending on time. Neglecting the amplitude modulation, the received amplitudes of the narrow band interference change only slowly with time [4]. Then equation (2) can be approximated to:

$$N_{narrow}(t) = \sum_{i=1}^{N} \sin(2\pi f_i t + \phi_i) \quad (3)$$

2.1.3. Impulsive noise type

So far we have been discussing the stationary interference. However a large number of interferences observed in power supply networks have impulsive stochastic character. While background noise is generally stationary, impulsive noise caused by switching transients introduces significant time variance [3-4]. The impulsive noise is the most severe noise impairments encountered on the line, and can be of a variety of types in terms of amplitudes, widths and inter-arrival times of the noise pulses. There are two major sources of this type of noise. One single impulse associated with ON-OFF of domestic loads such as lamps, TVs, etc., which can cause 1V amplitude pulses lasting 1 ms or more. The second type is caused by those loads that themselves generate impulse trains like triac controlled fan regulator, light dimmers, thermostats etc., with 20V peaks lasting over tens of microseconds being common[9] .

The impulsive noise amplitudes can kill the data signals during its peak excursion, and cause numerous bit and burst errors [4], [9]. The disturbance effect of the impulsive noise affects the whole range of frequency band and its duration is very short [8]. Switching of inductive loads can produce impulses saturating any receiver for periods of tens or even hundreds of microseconds. These impulses may have very rapid rise times, and are virtually impossible to filter out completely. These impulses are capable of ringing the power line itself, because the network and its attached loads poses both inductance and capacitance, they may resonate at a frequency which depends on instantaneous loads, producing decaying ringing waveforms lasting several cycles at frequencies in the communication band [2].

2.2 Modeling of PLC Noise

The noise model described the statistics of instantaneous value of noise is necessary for designing PLC system for any utility application. To simulate the instantaneous noise power in different conditions, a PLC model is derived and a Matlab program is developed. A noise filter will be included with the model so that the program can be used to simulate the effect of the filter. The model is based on considering the noise as an additive white Gaussian noise [6], [10].

The dominant components of noise are:

1- Stationary continuous noise.
2- Cyclic impulsive noise synchronies to the mains.
3- Cyclic stationary continuous noise.

The mathematical model of the noise depends on the assumption of three noise components [6]. In this model, the noise function *n(t)* can easily be generated using a Gaussian function. The Gaussian function generates random noise variables changes with time and can also be used for modulation choice in the next section.

The variance of this noise wave form *n(t)* is presented by the noise mode [6]:

$$\sigma^2(t,f) = \sigma^2(t) * a(f) \qquad (4)$$

$$\sigma^2(t) = \sum_{i=1}^{3} A_i * \left|\sin\left(\frac{2\pi}{T_{AC}} * t + \theta_i\right)\right|^{n_i} \qquad (5)$$

$$a(f) = \frac{e^{-af}}{\int_{f_o}^{f_o+w} e^{-af}.df} \qquad (6)$$

The parameter that describes the power system frequency is T_{AC} which is the cycle duration of the mains AC source, typically 1/50 or 1/60 seconds. The function σ^2 represents the instantaneous power of noise. The function *a(f)* represents the power spectral density normalized by the total noise power in frequency range from f_0 to $f_0 + w$, where *w* is the frequency bandwidth. In this paper we will use the CENELEC Standards, 3-148.5 kHz. The instantaneous power of noise can be presented by a set of parameters:

- A_1, A_2, and A_3 for amplitudes.
- θ_1, θ_2, and θ_3 for phase angles.
- n_1, n_2 and n_3 for impulsiveness or power concentration in frequency domain.

The first term of equation (5) represents the stationary continuous noise, the second represents the stationary noise, and the third represents the cyclic impulsive noise synchronous to the mains. These parameters are given in Table (2) [6]:

Table (2) an example of noise parameters

Amplitude	Phase angle	Impulsivne
$A_1 = 0.13$	θ_1 = Arbitrary	$n_1 = 0$
$A_2 = 0.26$	$\theta_2 = 128$	$n_2 = 9.3$
$A_3 = 16$	$\theta_3 = 161$	$n_3 = 6.9*10^3$

2.3 Simulation of the Noise Model

A Matlab program is developed and simulated to represent the following effects.

i. Noise variance with and without considering the effect of frequency change.
ii. Time response of noise instantaneous power, at different frequencies.
iii. Effect of random noise in the power line carrier environment.
iv. Effect of the proposed filter

To explore the effect of frequency, the program is simulated at different frequencies. The output plot of the program for operating frequencies of 3, 10 and 100 kHz are shown in Figures 1, 2 and 3 respectively.

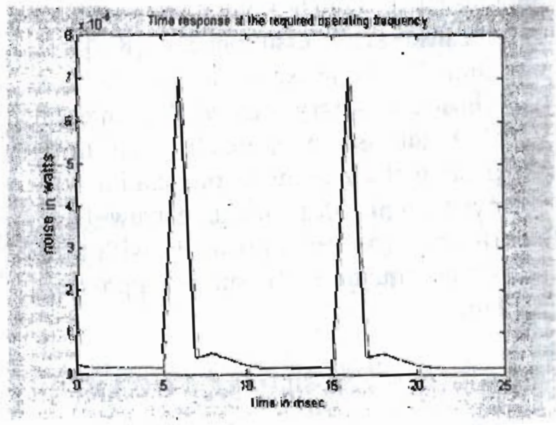

Figure 1: Noise power at an operating frequency of 3 kHz.

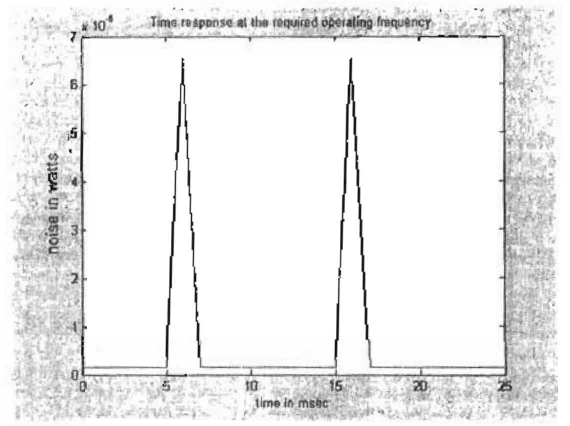

Figure 2: Noise power at an operating frequency of 10 kHz.

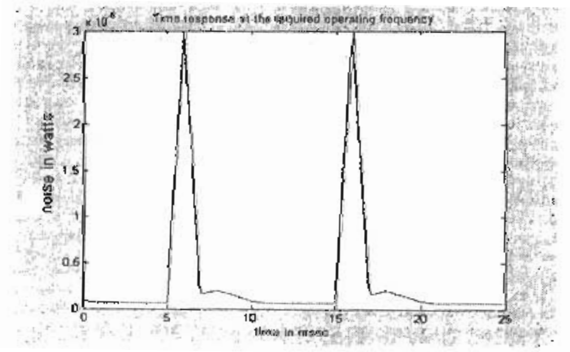

Figure 3: Noise power at an operating frequency of 100 kHz

From the preceding it can be observed that:

- The noise power is generally very small
- The amplitude of the impulsive noise power decreases, with increasing the frequency. It is $7*10^{-5}$ for a frequency of 3 kHz, it is $6.8*10^{-5}$ for a frequency of 10 kHz, and $3*10^{-5}$ for a frequency of 100 kHz.
- The increase of the operating frequency leads to a decrease of impulsive noise power, which is the most severe type.
- The change of noise power with frequency is plotted, in the bandwidth of the CENELEC standards; also the change of noise power with time is plotted. The output of the simulation program in this case is shown in Figure 4.

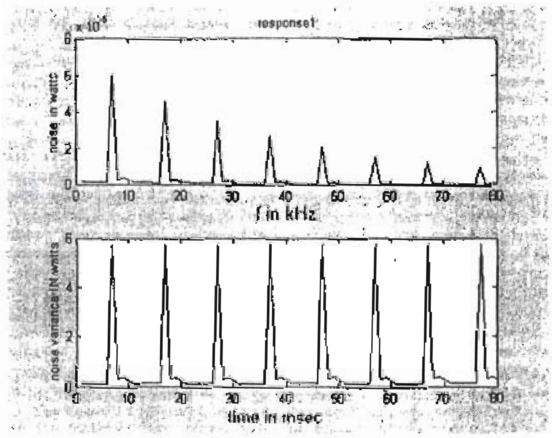

Figure 4: Noise power versus frequency and time.

Figure 4 shows that the increase of the operating frequency causes a decrease of impulsive noise power, which is the most severe type. Whereas, the impulsive noise power is constant with time without the effect of frequency (see the lower plot of Figure 8).

Finally, the simulation of random noise signal of florescent lamps was made based on measured data stored in a computer file in a digital storage oscilloscope.

The program simulated with and without including a noise filter, the noise signal, is passed through filter, then the filter reduces the amplitude of noise.

Figure 5 shows a comparison between the two cases, it can be observed that the noise amplitude is reduced in to less than 0.01V, which shows that the proposed filter is effective. This can be used as a software program for PLC noise filtering.

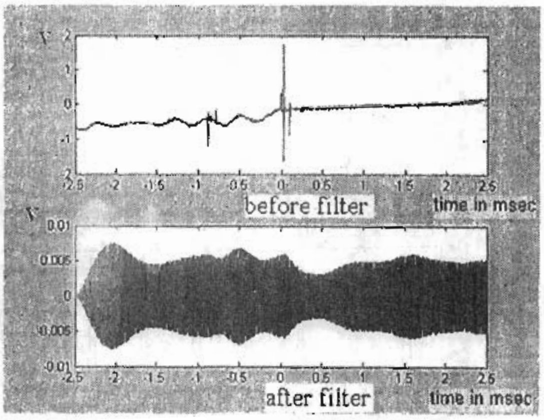

Figure 5: Simulation of proposed noise filter effect.

3. Modulation Techniques

The choice of the modulation technique for a given communications system strongly depends on the nature and the characteristics of the medium on which it has to operate. The powerline channel presents hostile properties for communications signal transmission, such as noise, multipath, strong channel selectivity. Besides the low realization costs, the modulation to be applied for a PLC system must also overcome these channel impairments. For example, the modulation, to be a candidate for implementation in PLC system, must be able to overcome the nonlinear channel characteristics. This channel nonlinearity would make the demodulator very complex and very expensive.Therefore, the PLC modulation must overcome this problem without the need for a highly complicated equalization [11]. Various choices of modulation methods are available for digital transmission, including digital Amplitude Modulation, Quadrature Amplitude Modulation, Phase Shift Keying and Frequency Shift Keying [12-13]. CENELEC standards generally recommend the narrow-band Modulation schemes [14], which are based on sinusoidal carrier signal. Such a carrier is characterized by three parameters-amplitude A, frequency f, and zero phase φ.

The following equation includes all basic possibilities of modulation [5]:

$$s(t) = A(t).\sin[2\pi.f(t).t + \varphi(t)] \quad (7)$$

3.1 Methods of narrow band modulation

The methods of narrow band modulation include: amplitude modulation (ASK), frequency modulation (FSK) and phase modulation (PSK) as explained by Figure 6.

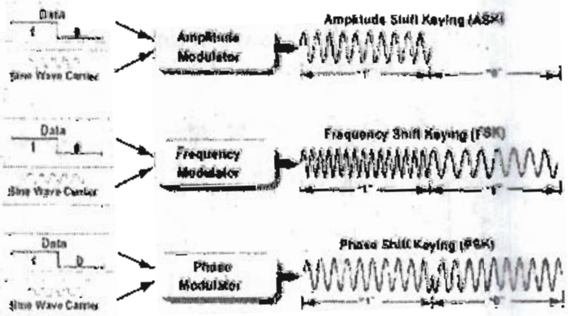

Figure 6: Methods of narrow band modulation

3.1.1 Amplitude modulation:

In the amplitude modulation (AM), a time dependent change for the carrier amplitude A(t) occurs according to the data signal. In the simplest case there are only two values zero and one for A(t), i.e., a zero bit disables the carrier, while a one data bit enables it. This method is called amplitude shift keying (ASK). This modulation method is a historical method for data transmission over powerlines [12], [5]. In general, however, (ASK) is not deemed suitable for low power data transmission over powerlines. This modulation system is nearly obsolete now [14].

3.1.2 Phase modulation

Phase-Modulation methods achieve much better results. One of these methods called phase shift keying (PSK), it is simple and efficient [5].

. In PSK modulation the phase of the carrier wave is varied by the binary input stream. The binary input stream modulates the zero-phase angle of the carrier in such a way that carrier phase is switched between zero and 180 degrees. With binary phase shift keying two output phases are possible, carrier frequency remaining constant. One output phase represents logic 1 and the other logic 0. As the digital input signal changes state, the phase of the output carrier shifts between two angles that are 180 degrees out of phase [12],[13],[5], such a waveform is shown in Figure 7.

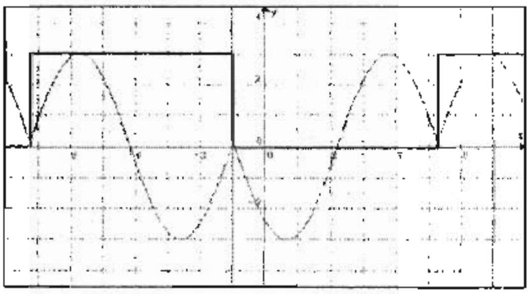

Figure 7: Diagram of PSK operation.

PSK is not particularly sensitive to amplitude or frequency influences, and it is the least sensitive to broadband noise among all narrowband modulation schemes discussed here. On the other hand, BPSK could be sensitively disturbed, if fast phase hops were to affect the modulated carrier on its way from the transmitter to the receiver in the mains. Unfortunately, although such effects are rather infrequent in usual interference scenarios, they cannot be totally excluded; PSK has hardly been used in simple systems that use the CENELEC EN-50065 range. One reason may be rather costly phase detection in the receiver [5]. Mathematically, phase shift keying is represented as:

$$s(t) = A.\sin[2\pi.f.t + d(t)\pi] \qquad (8)$$

where d(t) represents the change of the binary input stream between logic 1 and logic 0.

3.1.3 Frequency modulation

Nodaway most implementations prefer frequency shift keying (FSK) [5], and it is preferred for its relative robustness [14]. Frequency shift keying (FSK) modulation is a form of FM modulation where the frequency of the carrier wave is varied by the binary input stream. As the binary input signal changes from a logic 0 to a logic 1, and vice-versa, the FSK output shifts between two frequencies: a mark or logic 1 frequency and a space, or logic 0 frequency [12], [13]. Today, several transmission systems based on FSK with certain modifications, are used in large numbers, both for building automation and for energy related value added services offered by power supply utilities (PSUs) [5]. Equation (9) and the introduced data vector b_i can be used to describe an FSK signal, consisting of zeros and ones:

$$s_{FSK}(t) = A.\sum_{i=-\infty}^{\infty} rect(\frac{t - iT_b}{T_b}).[b_i.\sin(2\pi.f_1.t) + \bar{b}_i.\sin(2\pi.f_2.t)] \qquad (9)$$

given the data signal, i.e., at b_i=1, a carrier at frequency f_1 is sent during T_b , while frequency f_2 is sent while b_i=0.[5].

In general (FSK) is relatively robust transmission scheme, because corrupted frequencies on the transmission path are much less likely than corrupted amplitudes. Overlaid interference can not affect the frequency of a transmitted carrier, as long as certain threshold is not exceeded.

3.2 A Proposed Narrow-band Modulation Scheme

It is a difficult problem to determine which modulation scheme, FSK or PSK is more suitable to power line carrier applications. In deciding between the advantages and disadvantages of each scheme, the PLC designer must continuously keep in mind the hostile environment of PLC communications. To choose which scheme is best suited to PLC techniques, the author develop a Matlab computer program and applying both types of modulations. The program is implemented for a PLC channel in varying environments of noise and phase shift to compare the performance of PSK and FSK modulation schemes. The simulation was performed on a purely mathematical, analytical basis, using Monte-Carlo techniques [15].

The MATLAB code uses the fundamental equations that describe the behavior of FSK and PSK systems to simulate their performance. Random noise which affects the power line carrier environments is added to the "modulated" signal, using a subroutine program to generate random variables using a Gaussian function.

The input data to the modulation/demodulation system is compared to the output data. Using this technique, the probability of bit-error in the received output is determined.

The procedures of develop program is:

1- Specify Signal to Noise Ratio SNR of the communications channel and the number of Monte Carlo simulations to run.
2- Specify the time interval of simulation and the number of samples to be taken during time interval
3- Create a loop for the phase error at the receiver starts from 0 to1.
4- Calculate the phase shift of the receiver = phase error * π.
5- Calls subroutine functions, which perform Monte Carlo simulation of frequency shift keying and phase shift keying modulation schemes.

Performing comparison for N=1000 simulations, it takes a long time, but returns more accurate results. We focus on the best case and the worst case phase delay or phase error simulations to show the variation of the bit error probability versus (S/N), The best case for low phase error of 0.1* π and 0.2* π, is shown in Fig. 8, and the worst case of phase errors of 0.9* π and 1* π, is shown in Fig.9.

From the output simulation curves of (S/N) versus bit-error probability, we find:

- *For a low phase delay channel*, both systems have similar performance, phase shift keying being more slightly more reliable than frequency shift keying.
- *For a high-phase delay channel*, the phase shift keying becomes totally unreliable, with error probability approaching 100%.

Phase delay in the PLC channel is expected and unpredictable. The reliable performance of frequency shift keying modulation with any reasonable amount of phase delay makes it the modulation scheme of choice for PLC applications in low voltage distribution networks, although phase shift keying method has higher transmission rate than frequency shift keying method.

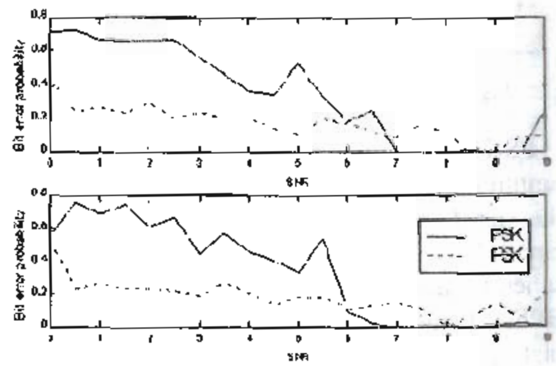

Figure 8 Simulation results of a channel with a low phase delay of the receiver.

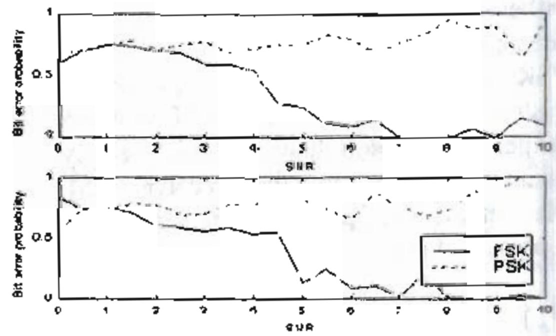

Figure 9 Simulation results of a channel with a high phase delay of the receiver.

4. Signal Attenuation in PLC Environment

The losses of the real cable cause attenuation dependent on cable length and frequency. It is necessary to have a detailed knowledge of the PLC transmission channel

4.1 PLC Transfer Model

Several approaches for modeling the transfer characteristics of a power distribution network were developed [16-19]. The main drawback of these approaches is the great number of parameters which cannot be determined with sufficient precision, so that it is impractical to use these approaches for complex PLC distribution networks.

M. Zimmerman and K. Dostert developed the approach called the echo-model, based on using black boxes to represent the parameters of the PLC distribution network [20].

The power line cables and connections are unmatched. Due to the topology and the structure of the distribution network, numerous reflections are caused. The signal propagation does not only take place along a quasi "line of sight" path between the transmitter and the receiver [2], [16-20]. Additional propagation paths (echoes) result in multi-path signal propagation which leads to frequency selective fading in the transfer function, this is shown in Fig.10.

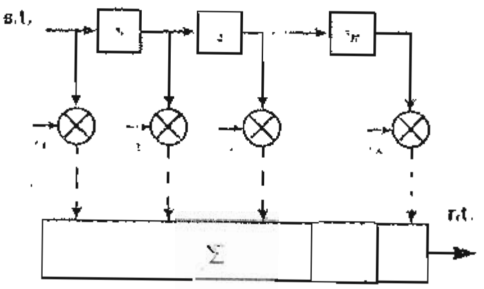

Figure 10 The multi-path signal propagation

The model described the transfer function $H(f)$ by a few number of characteristic parameters based on both topological and physical signal propagation effects in low voltage distribution networks, and the noise is modeled as an additive non-white Gaussian noise [2]. The echo model is shown in Fig.11.

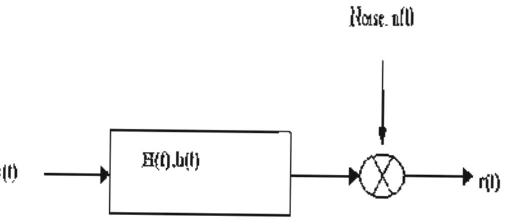

Figure 11 A channel model representing the echo model

A mathematical multi-path signal propagation model of the transfer function was presented in [20] as:

$$H(f) = \sum_{i=1}^{N} g_i \cdot A(f, l_i) . e^{-j2\pi f t_i} \quad (10)$$

It represents the basis of models describing the complex transfer function of typical power line channels [18]. The weighting factor (g_i) of the transfer function for complex networks can be calculated using an efficient method based on dividing the network into modules. By applying this model, all substantial effects of the transfer characteristics may be modeled using a set of parameters: attenuation factors (k, a_0 , a_1), weighting factor (g_i) and finally length of line l.

4.2. Classification of PLC channels

Characteristics of the PLC transmission channel are dependent on features of the power distribution line network and on the line type. The PLC channel can be classified according to an available voltage as follows:

- ***Channel with a very high voltage:***

This PLC channel has good transmission facilities thank to low noise levels and no-frequent failures on the line. Low noise levels are given mainly by a low number of connections that can cause reflections on the line due to imperfect matching of impedance. (Therefore, the multi-path effect can be neglected.) However, the very high voltage channel is not used as a data signal transmission line, only as a supporting line for bundles of optical fibers.

- *Channel with a high voltage (HV):*

This PLC channel is used for a data signal distribution in the point-to-point topology. The HV channel is not so good as the very high voltage channel, but its transmission facilities are almost maintained along the whole line length.

- *Channel with a low voltage (LV):*

This PLC channel is used for a data signal distribution in the point-to-multipoint topology. The LV channel is utilized for a power distribution in houses, flats, buildings, etc. In these locations, there are usually many points with imperfect matching of impedance. Therefore, the noise level can be increased and the information signal could be damaged. Also, the multi-path effect is self-evident.

Characteristics of the PLC transmission environment focused on the multi-path signal propagation, the signal attenuation, the noise scenario and the electromagnetic compatibility are introduced in [21]. In this study we use a parametric model for various PLC reference channels in a real topology of power distribution networks. The parametric model for the PLC channel is possible to adapt for any topology of the power distribution network. Parameters of this model with various coefficients were presented in [21].

The following set of reference channels for a practical utilization was established:

Reference channel 1 (RC1) – a channel between transformer stations with features of the HV channel. A distance between separate transformer stations is around 1000 m.

Reference channel 2 (RC2) – a channel from the transformer station up to the main circuit breaker, a distance is approximately 150 m.

Reference channel 3 (RC3) – a channel from the main circuit breaker up to the counting box of consumed energy in the house, a distance is maximum 250 m.

Reference channel 4 (RC4) – a home scenario.

For the presented parametric model, parameters for various PLC reference channels were assumed from the paper [4]. In spite of their simplification, it is still accurate enough for the PLC system performance analyses. The values of parameters required for the multi-path signal propagation in reference channels are given in the appendix [21].

The developed program is applied to the four standard channel models to analyze the transfer function. The channel response varies heavily with frequency as shown in Figures 12-15.

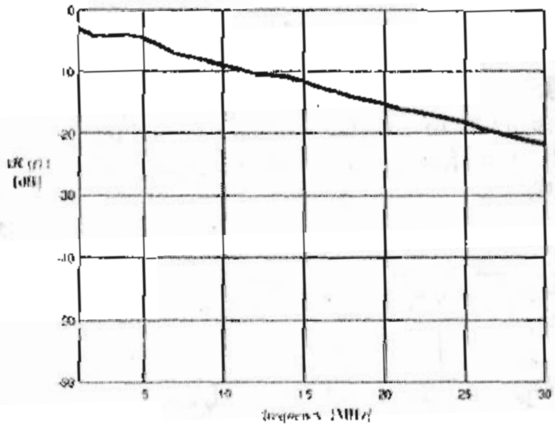

Figure 12 The frequency response of the RC1 channel

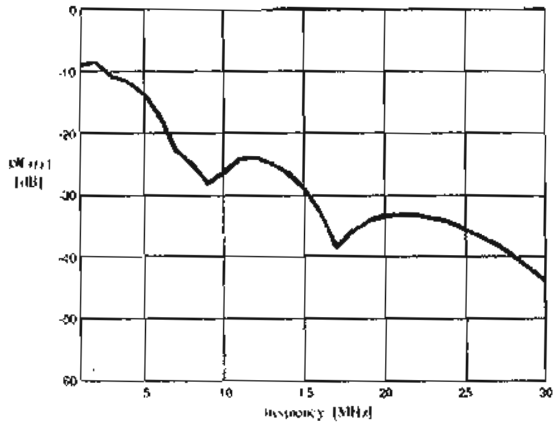

Figure 13 The frequency response of the RC2 channel

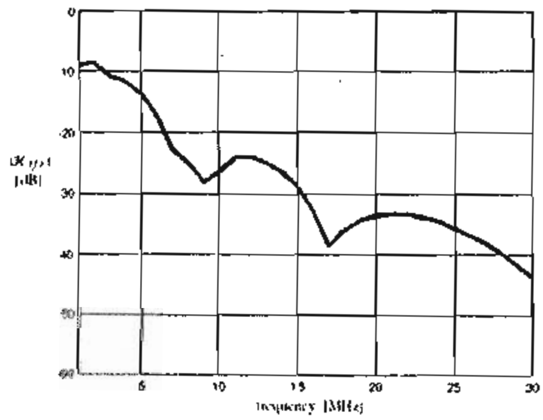

Figure 14 The frequency response of the RC3 channel

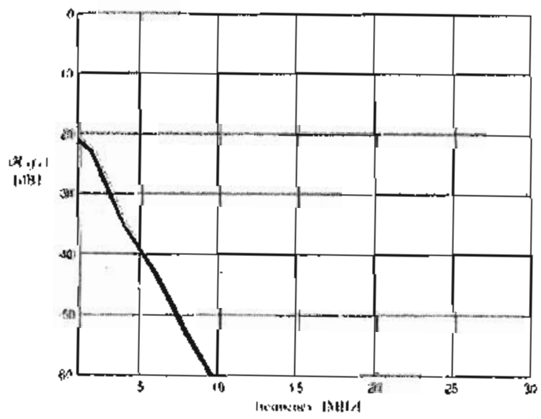

Figure 15 The frequency response of the RC4 channel

5- Conclusions

It is necessary to conclude the great importance of a correct location planning of the PLC communication networks according to obtain a better performance of the PLC data transmission system.

The development of a reliable PLC system requires: analyzing channel transfer characteristics, knowledge about channel noise, and a good choice of appropriate modulation technique.

A computer program is developed to analyze the PLC performance.

The developed computer program detects the appropriate narrow band modulation method, suited for PLC based on Monte-Carlo techniques. The program compared the performance of frequency shift keying and phase shift keying modulation methods

The developed program is applied to analyze the transfer characteristics of four standard PLC channels and detect the response of every channel with different frequencies. The transfer characteristics of each channel can be determined without detailed knowledge of channel dimensions.

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Appendix

Parameters of PLC Reference Channels

Table A.1
Parameters of the RC1 reference channel,
$k = 1,\ a_0 = 0,\ a_1 = 1.5 \times 10^{-9}\ (m/s)$

N	1	2	3	4	5
g_i	0.6	-0.08	0.08	-0.08	0.15
$l_i\ [m]$	100	130	160	190	300

Table A.2
Parameters of the RC2 reference channel,
$k = 1,\ a_0 = 0,\ a_1 = 2.5 \times 10^{-9}\ (m/s)$

N	g_i	$l_i\ [m]$
1	0.17	211.5
2	0.25	228
3	-0.1	243
4	-0.12	254
5	0.33	278
6	-0.37	306
7	0.18	330
8	-0.2	360
9	0.05	390
10	-0.15	420
11	0.15	540
12	0.15	740

Table A.3
Parameters of the RC3 reference channel,
$k = 1,\ a_0 = 0,\ a_1 = 4.5 \times 10^{-9}\ (m/s)$

N	g_i	l_i [m]
1	0.103	113.2
2	0.029	90.1
3	0.043	101.8
4	-0.058	143
5	-0.045	148
6	-0.04	200
7	0.038	260
8	-0.038	322
9	0.071	411
10	-0.035	490
11	0.065	567
12	-0.055	740
13	0.042	960
14	-0.059	1130
15	0.049	1250