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Cyclic Parameters of an Information Channel over the 220 V Power Line

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Abstract: *The electrical network is not a conventional communication medium. Moreover, in the traditional sense it is hostile. The modern sophistic methods of signals processing and communication enable its successful use as communication medium. The present paper investigates the features of the electrical power line – explicit non-coordinated loading and its modulation by the network voltage.*
The research is directed towards high-speed communication occupying a band up to 30 MHz. The relation of the system functions of the low-voltage supply line of 220 V and the parameters characterizing it as a medium of multi-path propagation is studied with respect to the main harmonic (50 Hz). Investigations of a real network are accomplished and the parameters introduced are defined.

Keywords: *time-varying channel; multi-path propagation; fading; Doppler's spread; frequency and time coherence.*

1. Introduction

During the last decade the interest towards the power supply network has increased considerably in connection with its application as the last unit in the communication systems for service delivery from the global networks up to the final user. Different standards and regulations have been adopted that divide the communications through the supply line (for the low-, average- or high voltage range) into two main types: wide-band – up to 30 MHz (still not standardized, but with some restrictions and requirements implied by some organizations, such as HomePlug [11], PLCforum [10]) and narrow-band – from 3 up to 148.5 kHz (specified by CENELEC EN 50065 European standard). The good knowledge of the fine (thin) characteristics of the medium enables the more complete use of the available resources and higher reliability of the systems working in the "last mile" of the telecommunication network of access.

The supply line may be regarded as time-varying linear channel (filter) TVLC(F), the features of which alter randomly in time. It is described by correlation and power spectral density functions (system functions)[1, 2, 3, 6]. The dependence of these parameters on the phase of the main harmonic of the supply voltage is studied.

The characteristics of TVLC(F) (random or determined), represented as system functions, are described analytically in general by Z a d e h [13]. He has introduced a time-varying transfer function and bi-frequency function that depict the TVLC(F) in the frequency domain and complete the time-varying impulse reaction (TVIR). Kailath [14] applies a single and two-fold Fourier transform for the pulse characteristic and shows that the variation can be determined by the frequencies of the filter input and output and that the changes themselves can be defined with the help of the filter variation rate. Generalizing the results of Zadeh and Kailath, Belo has proved in his work [1] that TVLC(F) may be dually presented in the time and frequency domain as time-frequency dual pairs. Belo's research is fundamental and widely cited in the developments and investigations on mobile radio communications [2, 3, 9]. The present study considers the communication channel along the electrical power line in terms of multi-path propagation of radio waves. This implies a more detail description of the separate parameters and their interpretation in the sense of the supply line used as communication medium.

The paper offered specifies some basic parameters: duration of the impulse response (IR), power centre, efficient duration of the PR, time and frequency selectivity of the channel, feasible time interval for struggle with the inter-symbol interferences, multi-path spread profile, Doppler's spread and shift, duration of the time and frequency coherence.

The subject matter is arranged as follows: Section 2 – formation of the problem discussed and presentation of the main relations; Part 3 – measurement equipment; the experimental results are shown in Section 4, and the conclusions – in Section 5.

2. Main relations and parameters

An electrical network (EN) is regarded as a time-varying channel through which information signals are spread with a carrying frequency of f_c. Its equivalent impulse response (IR) is:

$$c(\tau,t)=\alpha(\tau;t)e^{-j2\pi f_c\tau}, \tag{1}$$

where $c(\tau, t)$ is the impulse response of the channel at moment t, for an impulse applied at moment $t-\tau$; $\alpha(\tau, t)$– attenuation of the signal component with a delay τ at moment t; f_c – carrying frequency of the transmitted signal.

We assume the EN as a filter with a finite impulse response (FIR). One of the main parameters restricting the speed of data transfer and the techniques for channel equalization is the duration of the impulse reaction. In accordance with different requirements, different definitions are used for impulse response duration. The present paper uses the following algorithms: SEE (signal energy estimation), GAIC (generalized Akaike information criterion), GLRT (generalized likelihood ratio test), mGLRT (modified GLRT) [7].

At known IR, the middle (power centre) and its efficient duration are determined by the expressions:

(2) $$\mu = \left(\sum_{n=1}^{M} nc^2(n)\right) \Big/ \left(\sum_{n=1}^{M} c^2(n)\right),$$

(3) $$\sigma_{\mathrm{RMS}} = \sqrt{\left(\sum_{n=1}^{M} (n-\mu)^2 c^2(n)\right) \Big/ \left(\sum_{n=1}^{M} c^2(n)\right)}\ ,$$

where $c(n)$ is the sampled IR, M – number of samples defining IR duration. The values are obtained in number of sampling steps. It can be considered [7] that if no techniques are used to equalize the channel, the maximal rate of data transfer is limited to $\approx \frac{1}{2\sigma_{\mathrm{RMS}}}$. This is a rather rough estimate, since it accounts the energy accepted, but it does not take into account the inter-symbol interference.

The time-varying channels (multi-path channels with fading) may be described with the help of correlation functions and power spectral density functions. Their definitions and mutual relations are shown in [9].

The integration of the IR $c(\tau, t)$ in relation to τ gives the averaged coefficient of transmission, and its Fourier image is the time-variant frequency characteristics (TVFC) of the channel

(4) $$C(f;t) = \int_{-\infty}^{+\infty} c(\tau,t) e^{-j2\pi f\tau} d\tau.$$

The multi-path components, detectable with respect to the frequency shift λ and delay τ are overlapped, which leads to time- and frequency-varying fluctuations (fading). The resolution capacity is determined by the duration of the observed time or frequency interval. The system functions enable the determination of the output signal at known input signal.

When there exist many paths (of the information signals propagation in an EN), the fading statistics may be considered stationary (according to the central limit theorem) for sufficiently long time intervals. This enables their categorizing as a subclass of channels that are stationary in wide sense (WSS).

At known complex envelope, two auto-correlation functions are necessary for the unambiguous determination of the auto-correlation function (ACF) of the initial real process [1]

(5) $$\phi_{\mathrm{c}}(\tau_1, \tau_2; \Delta t) = \frac{1}{2}\mathrm{Re}\left(E\left[c^*(\tau_1, t)c(\tau_2, t+\Delta t)\right]\right) + \frac{1}{2}\mathrm{Re}\left(E\left[c(\tau_1, t)c(\tau_2, t+\Delta t)\right]\right).$$

If $c(\tau, t)$ is stationary in wide sense, the second (complex) term of equality (5) is zero and the auto-correlation function gets the form:

(6) $$\phi_{\mathrm{c}}(\tau_1, \tau_2; \Delta t) = \frac{1}{2}E\left[c^*(\tau_1, t)c(\tau_2, t+\Delta t)\right].$$

The complex coefficients of transmission (for the separate paths) are most often accepted as non-correlated. This is undoubtedly so for the cell networks. For the power line this is not obvious due to the multifold reflections by one and the same user, in spite of the fact, that the separate loads are turned on/off at random moments, in random points. Assuming non-correlativity, the ϕ_{c} of IR becomes:

$$(7) \qquad \frac{1}{2}E\left[c^*(\tau_1,t)c(\tau_2,t+\Delta t)\right]=\phi_c(\tau_1;\Delta t)\delta(\tau_1-\tau_2)$$

At $\Delta t = 0$, the auto correlation function obtained $\phi_c(\tau, 0) \equiv \phi_c(\tau)$ is the averaged power of the channel output, as a function of the time delay τ and $\phi_c(\tau)$ may be regarded as a profile of the multi-path spread (time dispersion). The dispersion of a random stationary function does not depend on time. In its essence $\phi_c(\tau, \Delta t)$ is ACF of the IR for the delay τ. The interval τ, for which $\phi_c(\tau)$ is above the level of permission ϕ_{th}, is accepted as spread of the multi-path propagation T_m. The level of the channel noise may be regarded as a lower limit of $\phi_c(\tau)$.

As a linear transformation of $c(\tau, t)$, TVFC is also a random function of time t. Its variability may be evaluated with the help of the auto correlation function according to the expression:

$$(8) \qquad \phi_c(f_1, f_2;\Delta t)=\frac{1}{2}E\left[C^*(f_1,t)C(f_2,t+\Delta t)\right]$$

It can be shown [2] that

$$(9) \qquad \phi_c(f_1, f_2;\Delta t)=\int_{-\infty}^{+\infty}\phi_c(\tau_1;\Delta t)e^{-j2\pi\Delta f\,\tau_1}d\tau_1=\phi_c(\Delta f;\Delta t), \quad \Delta f = f_2 - f_1 .$$

At $\Delta t = 0$, $\phi_c(\Delta f; 0) = \phi_c(\Delta f)$ and $\phi_c(\tau; 0) = \phi_c(\tau)$:

$$(10) \qquad \phi_c(\Delta f)=\int_{-\infty}^{+\infty}\phi_c(\tau)e^{-j2\pi\Delta f\,\tau}\,d\tau.$$

$\phi_c(\Delta f)$ is ACF in the frequency domain, which enables the determination of the area of channel frequency coherence. Expression (10) gives the spectral density of the power of the multi-path distribution profile and it characterizes the frequency characteristic of the averaged IR. $\phi_c(\Delta f)$ is a value very close to the physical content of $|H(f)|^2$ for the linear time invariant chains (LTIC), where $H(f)$ is the transfer function of LTIC.

$\phi_c(\Delta f)$ and $\phi_c(\tau)$ are connected by a Fourier transform and define the profile of IR power in the frequency and time domain respectively. The intervals $(\Delta f)_c$ and T_m, for which $\phi_c(\Delta f)$ and $\phi_c(\tau)$ reserve considerable constancy and a large value, are considered as frequency coherence and spread from the multi-path propagation of the channel correspondingly and they are approximately reciprocal one to another.

$$(11) \qquad (\Delta f)_c \approx 1/T_m.$$

where $(\Delta f)_c$ is the coherence band. For a Gaussian distribution of $\alpha(t,\tau)$ in (1), the coherence interval is determined by the expression $(\Delta f)_c \approx \dfrac{1}{5\sigma_{RMS}}$ [12].

Let the information signal transmitted is with a symbol rate of $1/T$ (a symbol period T). The influence of the channel on it is a function of its frequency band and time duration. At $T >> T_m$, the channel introduces insignificant inter-symbol interference and if the frequency band of the signal transmitted is $W \approx 1/T$, then:

$W << 1/T_m \approx (\Delta f)_c$, the signals transmitted are included in the frequency-time coherence of the channel and it is defined for these signals as frequency-nonselective.

The time variability of the channel causes phase variability of the IR. Quantitatively, this variability is expressed by the power spectral density of $\phi_c(\Delta f;\, \Delta t)$.

$$S_c(\Delta f;\lambda)=\int_{-\infty}^{+\infty}\phi_c(\Delta f;\Delta t)e^{-j2\pi\lambda\Delta t}d\Delta t. \tag{12}$$

$S_c(\Delta f;\, \lambda)$ is regarded as Doppler's power, function of Doppler's frequency λ. In transmitting a coherent signal through a time variable channel, the received one is already frequency spread. If $S_c(\Delta f;\, \lambda)$ contains $\delta(\lambda - \lambda_i)$ functions, then a frequency (Doppler's) shift appears.

At $\Delta f = 0$ and $S_c(0;\, \lambda) = S_c(\lambda)$, (12) becomes:

$$S_c(\lambda)=\int_{-\infty}^{+\infty}\phi_c(\Delta t)e^{-j2\pi\lambda\Delta t}d\Delta t. \tag{13}$$

In case the channel is time invariant $\phi_c(\Delta t) = 1$ and $S_c(\lambda) = \delta(\lambda)$, i.e. there is no frequency shift or frequency spread.

The interval λ, for which $S_c(\lambda)$ is not negligible, is considered as Doppler's spread B_D of the channel. Since $S_c(\lambda)$ is connected with $\phi_c(\Delta t)$ by Fourier transform, the reciprocal value of B_D is an estimate for channel coherence time.

$$(\Delta t)_c \approx \frac{1}{B_D}. \tag{14}$$

In frequency-nonselective channels $W < (\Delta f)_c$, if the symbol period is $T < (\Delta t)_c$, the attenuation and the phase shift remain unalterable for more than one symbol period and the channel is defined as a channel with slow fading; otherwise ($T \geq (\Delta t)_c$) the channel is with fast fading. When $W \approx 1/T$, the condition that the channel is frequency nonselective and with slow fading is: $T_m B_D < 1$. One parameter which indicates the propagation conditions in the channel, is the surface of the time-frequency coherence $q_c = T_m B_D$. If the signals transmitted through the channel are $WT < q_c$, then the channel is considered not sufficiently compact and reverse, at $WT > q_c$ the channel is super compact.

At time-dispersion channels (fading and frequency selectivity), equalization is necessary to suppress the inter-symbol interference (ISI), and also the inter-channel one in the communication systems with common (multi) access. An approach to avoid the equalization is the selection of a sufficiently large duration of the separate symbol. The prolongation of T has its limit as well. It cannot be greater than the short time stationarity of the channel.

The slow altering channels have a large time of coherence and hence a small spectral spread.

The channel variability and the spectral spread can be connected with the Fourier transform of the autocorrelation function of the IR:

$$S(\tau;\lambda)=\int_{-\infty}^{+\infty}\phi_c(\tau;\Delta t)e^{-j2\pi\lambda\Delta t}d\Delta t. \tag{15}$$

3. Measurement equipment

In order to define the relations and indicators introduced, the measurement equipment shown in Fig. 1 is realized. With the purpose to investigate the cyclic recurrence, the network period (20 ms) is sampled into 24 points with an initial point – the zero descending transition of the power voltage. The co-phasing with the basic harmonic (50 Hz) of the supply voltage is maintained with accuracy better than ±20 μs. The synchronizer *N* (4) generates the j-th window set by the computer (6), which activates the generator of test impulses (1). The test impulses $e(t)$ are almost rectangular with width of 15 ns, voltage – 8 V and repetition frequency (in the window set) of 100 kHz. With the help of the matching device MD (3), the test signal is input to the network (2), it limits simultaneously the lower bound frequency of the test signal up to 300 kHz. The output resistance of the generator, together with MD is low, below 1 Ω. As a rule, the generator is connected in an intermediate point and it divides the network into a left and right part. The low-ohm connection of the generator limits the mutual influence of the line left and right part.

With the help of a high-resistance matching device ($|Z_{ex}|$ > 4 kΩ), the signal received is transmitted in the reception point through a high quality coaxial cable with known parameters and input into a storing digital oscillograph (5) with transmission band of 100 MHz and sampling frequency of 500 MHz. The short time stationarity of the channel is about ten minutes, which enables the averaging of the signal received after multifold accumulation. For the equipment discussed, the DO (5) operates in a mode of synchronous accumulation of 64 signals. The experiments indicate that such accumulation allows a sufficiently high (above 40 dB) signal/noise ratio (SNR). The flow of the two channels of the DO is through a serial port RS232 and the data are stored in a personal computer (6). The measurements of the real network are accomplished into 3 lengths (defined by IR delay, the speed of signal propagation being considered 4.5 ns/m) – 4, 10 and 44 m.

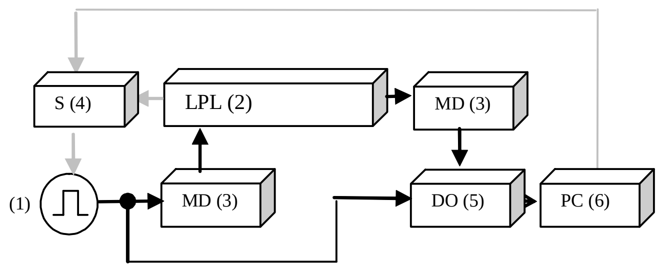

Fig. 1. Measurement equipment: (1) Generator; (2) LPL – lowvoltage power line; (3) MD – matching device; (4) S – synchronizer; (5) DO – digital oscillograph; (6) PC – personal computer.

The time and frequency presentation of the test pulse $e(t)$ transmitted to the network, is indicated in Fig. 2a and 2b. Its duration is 15 ns and the repetition period 10 μs. The sampling frequency for Fig. 2 is 2.5 GHz.

The length of the cable used is 75 m. In order to account the influence of the test cable used, the measured transfer function (TF) of the supply line is divided by the TF of the cable for the efficient frequency range of the test signal from 0 up to 66.7 MHz.

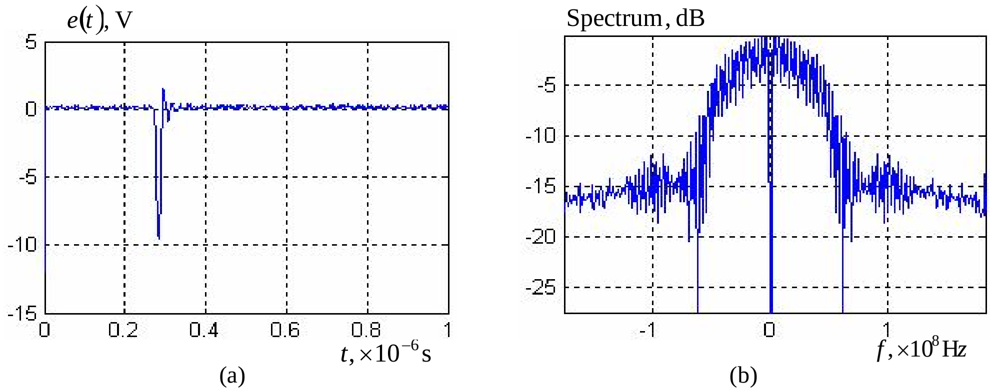

Fig. 2. Time (a) and frequency (b) presentation of test impulse $e(t)$

4. Experimental results

Some measurements are realized to determine the basic parameters which characterize the power network as a time-varying multi-path communication channel with fading. The study is done according to the scheme shown in Fig. 1 on a real network in a development unit, including various electronic devices – personal computers, oscillographs, photo copying machines, signal generators, etc. The test signal is not loaded on a carrier frequency, but it is wide band with duration of 15 ns. The measurements are executed during different days of the week, in different hours. The present exposition refers mainly to the relation of the channel parameters and the power voltage phase (segments). The cycle of the supply voltage (20 ms) is divided into 24 equal in length segments.

Fig. 3 shows a realization of the IR for the 5th and 14th segment, in 20 ms cycle of the power voltage, obtained after 64 times of averaging. The same figures indicate also the durations of the IR, determined by different methods represented by the algorithms:

SEE(L = 600; k = 0.98), GAIC(L = 1500; γ = 1.8); GLRT(L = 1500; K = 10; α = 0.99); mGLRT(L = 2000; K = 4; α = 0.99) [7] .

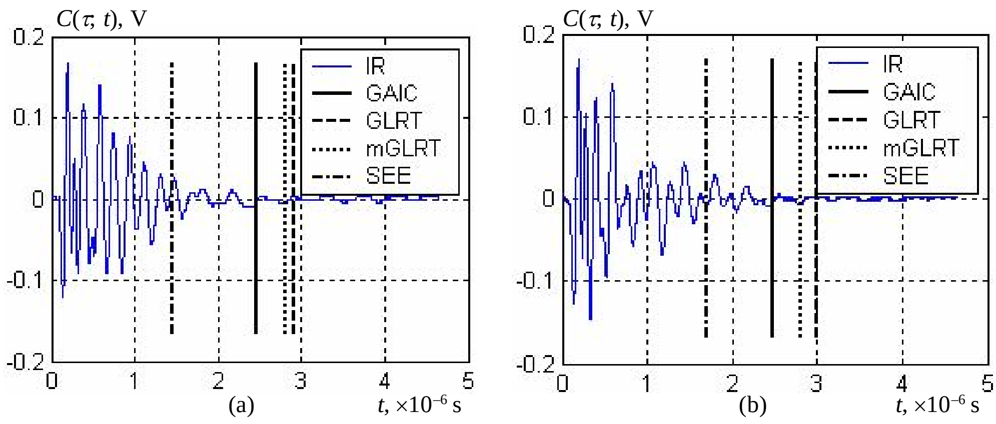

Fig. 3. A realization of the IR for the 5th (a), and 14th (b) segment and its durations determined by algorithms SEE, GAIC, GLRT and mGLRT

The use of a given duration depends on the problem solved. SEE algorithm gives efficient duration that accounts the intervals with great power (the concentrated part of the total energy (for example 80 %)). The estimate obtained is considerably smaller than the real one, in which the IR has still a noticeable value. Very often in the applied measurements 2-3 times increased efficient duration, obtained in this method, is accepted as real duration. The duration in other cases is determined by the interval in which the IR has a value above a threshold level (the channel noise, for example). GLRT and mGLRT algorithms are based on this method, using the χ^2- and F- statistical distributions for this purpose. In some other methods an evaluating function is used, the minimization of which gives the sought limit of the IR, like GAIC algorithm.

The main characteristics of the algorithms above used should be noted: SEE and GAIC algorithms include parameters ($k = 0.98$ and $\gamma = 1.8$) determined subjectively by the user and the estimate obtained is influenced by this choice; SEE algorithm gives a smaller efficient duration of the IR in low noise medium than at increased noise dispersion. The duration according to GLRT algorithm requires a large number of discretes $N \to \infty$ of the IR sample measured and it may be considered that it gives the upper limit of the possible duration. The least influenced by the medium noise and by incorrectly set parameters is the one determined by mGLRT algorithm, which is applied in the present paper.

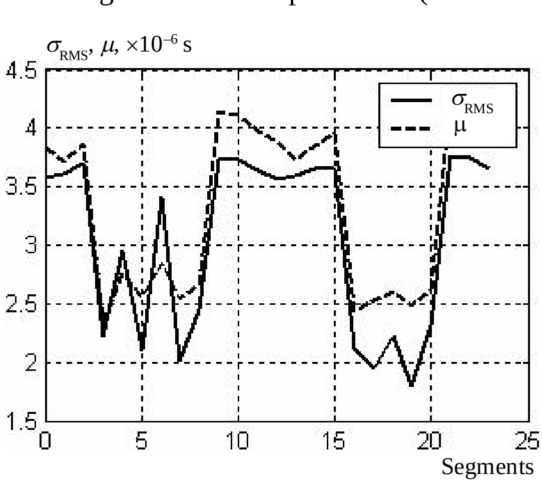

Fig. 4. The centre μ and the efficient duration σ_{RMS} of the IR, dependent on the phase of the basic harmonic of the power voltage

The centre μ and the efficient duration σ_{RMS} of the IR, defined according to (2) and (3) are dependent on the phase of the basic harmonic of the power voltage. Fig. 4 indicates this relation determined in the network studied at distance transmitter/receiver of 10 m.

Fig. 5a shows the auto correlation functions of the impulse response $\phi_c(\tau_{1\div 24})$ as a function of the main harmonic phase, defined according to (7). In Fig 5b the relation is indicated in pseudo-tri-dimensional coordinates, and in Fig. 5b – a projection on the plane (τ, n), where n is the phase of the main harmonic of the power voltage sampled into 24 segments. The figures demonstrate the strong dependence of $\phi_c(\tau)$ on the phase of the power voltage. The IR duration T_m determined as width of $\phi_c(\tau)$, is shown in Fig. 5c), according to mGLRT algorithm (at parameters $L = 2000$; $K = 4$; $\alpha = 0.99$ [7]). The clearly expressed dependence on the phase of the power voltage is observed from min $T_m \approx 1.4$ μs up to max $T_m \approx 2.4$ μs. This alters the coherence band from min $(\Delta f)_c = 417$ kHz up to max $(\Delta f)_c = 714$ kHz defined as $(\Delta f)_c \approx 1/T_m$.

The time-frequency correlation function defined by (9) $\phi_c(\Delta f, \Delta t)$ is shown in Fig. 6a. Fig. 6b shows Doppler power $S_c(\Delta f, \lambda)$ of the channel for a 20 ms period calculated according to (12). Fig. 6c shows $S_c(\lambda)$, $S_c(\Delta f, \lambda)$ at $\Delta f = 0$, and depending on the selection of the threshold level, the spread B_D may be estimated at min $B_D = 200$ Hz and max $B_D = 400$ Hz and the coherence time $(\Delta t)_c \approx 1/B_D$ at $\max(\Delta t)_c = 5$ ms and $\min(\Delta t)_c = 2.5$ ms.

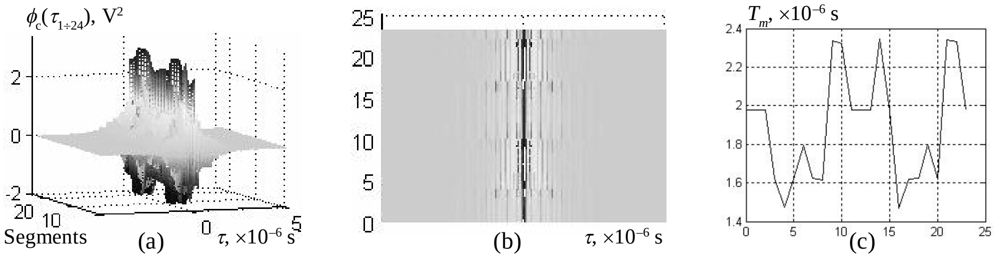

Fig. 5. (a) $\phi_c(\tau_{1\div24})$; (b); (c); – for 24-segments of the 50 Hz, on distance 10m.

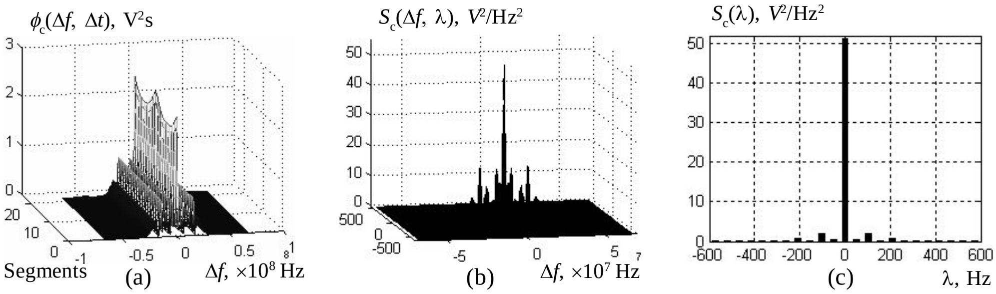

Fig. 6. (a) $\phi_c(\Delta f; \Delta t)$; (b) $S_c(\Delta f, \lambda)$; (c) $S_c(\lambda)$ – for 24-segments of the 50 Hz, on distance 10 m

The experimental results here presented give some idea of the important parameters in the electrical network. They show the strong influence of the network phase on significant parameters of the information channel. The technical and software tools developed enable information acquisition for statistical estimates.

5. Conclusion

An important part in the research realized is the evaluation of the parameters of the 220 V network, considered as a time-varying channel with multi-path propagation and fading, for separate segments of the power voltage cycle. The modularity of the characteristics established enables the achieving of optimal conditions in information signals transmission by synchronization of the communication systems with 50 Hz and division of the medium into time and frequency slots.

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