A COMPUTER MODEL OF THE IMPULSE NOISE PRODUCED BY OPERATION OF BREAKERS AND SWITCHES IN POWER ELECTRIC SYSTEM

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ABSTRACT

This paper presents a computer model for simulating the impulse noise produced by the operation of circuit breakers and isolator switches in HV electric power systems. The simulator utilizes a recorded sample of the impulse noise as a kernel sequence. The kernel sequence is measured and recorded at the point of connection of the telecommunication equipment to the coaxial cable. The simulator produces the sequence composed of the low-level background noise, and of the train of short-time high-level noise impulses of random amplitudes, which are evenly distributed in time. At the output, the simulator is supplied with the bandpass digital filter with variable bandwidth and variable central frequency. The purpose of the filter is to simulate the impulse noise over the bandwidth of the desired telecommunication channel.

1. INTRODUCTION

Digital communications over high voltage (HV) power lines provide a cost effective solution for power utility systems. Communications on power lines can be classified in two main categories:

- High voltage power-line communications;
- Low and medium voltage power-line communications.

In this paper, we are focused on the high voltage power-line communications (power-line carrier link).

Digital power line carrier (dPLC) equipment is introduced to replace the existing analog power line carrier (aPLC) equipment in order to answer the demand of new communication services requiring higher data rates [1]–[6]. With the applications of optical cables in modern power utility networks, the dPLC are mainly foreseen to provide communications with remote stations, and for the rural areas and areas with mountainous land forms where the construction of optical cables could be costly. Furthermore, the power line carrier links provide an economic solution in the countries with the long distances where the power lines present the only available infrastructure.

The HV power line as a communication channel has specific constrains. Besides the amplitude and phase distortion, the noise is the crucial factor influencing high rate data transmission over power lines [1]–[11]. The existence of high voltage inevitably produces the noise in power-line communication channels. The noise characteristics can be divided in two main categories [8]–[12]:

1. Noise in normal (stationary) operation of the power line, such as corona noise, noise due to interference with other PLC communication systems, and other.
2. Noise at transient and emergency operation. This category comprises noise due to power-line faults, circuit breakers and isolator operation, and lightning discharges. This category is characterised as the impulsive noise.

In this paper, we are focused on the second category, i.e. to the impulsive noise produced by the operation of circuit breakers and isolator switches. The impulsive noise forms a train of short-time high-level noise impulses of random durations and random amplitudes which are evenly distributed in time [1]–[4], [9], [10]. In practice, the duration of an impulse noise train ranges from several milliseconds to even 10 seconds. The presence of the impulsive noise may produce severe damages in dPLC links such as loss of the synchronisation and errors in the transmitted data packets. Therefore, the impulsive noise influences the available time of dPLC link. The goal of this paper is to present an appropriate computer model of the impulsive noise suitable for examination of the noise properties in the frequency range standardized for the dPLC links.

It is to be pointed out that the measurements of the high frequency characteristics on the power line are limited with permission of the power utilities and availability of the coupling equipment. Therefore, the computer simulations of the power line high frequency characteristics are indispensable for the dPLC design. The computer simulation models of the transmission characteristics and that of corona noise have been described in [11], [13]. For modelling the impulsive noise, hidden Markov processes can be generally used, see e.g. [9], [14].

In this paper, we propose an efficient computer model for the impulse noise simulator based on digital signal processing techniques and on the authentic digital record of an impulse noise signal recorded during the transient and emergency operations on the HV power line. The purpose of the model described in the following sections of this paper is to

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provide a realistic simulation of the impulsive noise that can appear in the communication channel realized over a HV power-line.

2. COMPUTER MODEL OF THE IMPULSIVE NOISE

In this section, we describe a new computer model for simulation of the impulse noise produced by the operation of circuit breakers and isolator switches on the HV power line.

The basic idea is to utilize a kernel sequence consisting of the noise voltage data measured and recorded in the telecommunication room of the hydroelectric power plant at the point of connection of the telecommunication equipment to the coaxial cable. Due to the measuring equipment, the recorded noise sequence is usually of a short duration (several milliseconds). Utilizing the authentic record of the noise sequence of a short duration, we construct the computer model that simulates the noise sequence of an arbitrary duration.

The structure of the model is based on the following properties of the impulsive noise:

- Usually, the impulse noise appears as a train of short-time high-level impulses of random durations.
- The impulses in the train are evenly distributed in time.
- The spectrum of the impulse noise covers the frequency range which is standardized for dPLC communications (24kHz – 1MHz) [5].
- The effects of high level impulsive noise to communication channel highly exceed the effects of other noise sources to such a degree that during the presence of the impulse noise the effects of other impairments, such as corona, may be considered as a background noise.

The simulation model, which is the subject of this paper, is based on the multirate and digital signal processing techniques [15], [16]. For the sampling frequency, we chose f_s = 2 MHz to provide signal processing in the range of communication signal (24kHz – 1MHz), and to enable sufficiently accurate implementation of the variable bandpass digital filters of relatively narrow bandwidths of 4, 8, 16, 32, 64 kHz.

The structure of the simulator is demonstrated in Figures 1 and 2. The block diagram of Figure 1 describes the resampling process performed on the kernel sequence. The term kernel sequence denotes the sequence containing the recorded measured data of the impulsive noise. The sampling frequency of the original kernel sequence usually exceeds the desired sampling frequency of the simulator. For example, the sampling frequency of the original data is 10 MHz whereas the simulator operates at the sampling frequency of 2 MHz. Therefore, the down-sampling-by-M is performed in the first stage and the down-sampled sequence $\{x[nT]\}$ is obtained. The down-sampling with the time offset, p is an integer in the range [1, M-1], is applied in order to capture the sample with the highest amplitude. In the second stage of Figure 1, we apply the fractional interpolation to the sequence $\{x[nT]\}$ in order to modify the length of the sequence by a random factor $R[k]$, k = 1, 2, …, N. Here, the interpolation factor $R[k]$ is a real number from the range [0.5, 1.5]. The linear fractional interpolation is used for computing the new sample values of the resampled sequence denoted as $\{x_k[nT]\}$. In this way, for each new k (k = 1, 2, …, N), the down-sampled kernel sequence $\{x[nT]\}$ is compressed or extended depending on the value of the random factor $R[k]$. If the length of the down-sampled kernel sequence $\{x[nT]\}$ is L, the length of the resulting sequence $\{x_k[nT]\}$ amounts $\lfloor LR[k] \rfloor$. Notice, that the fractional interpolation is used to change the sequence length, not the sampling frequency.

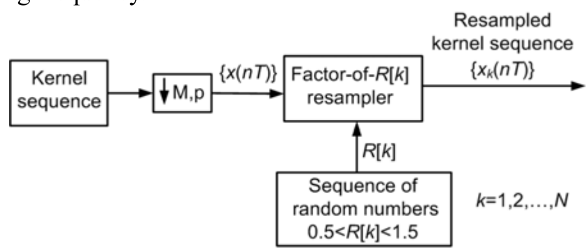

Figure 1 – Generation of the resampled kernel sequence.

The block for generation of the resampled kernel sequence, Figure 1, is introduced into the structure of the impulse noise simulator of Figure 2, which is composed of two main branches:

- Branch 1 for generating the impulses of random amplitudes and of random durations.
- Branch 2 for inserting the time slots of random durations between the impulses generated in branch 1.

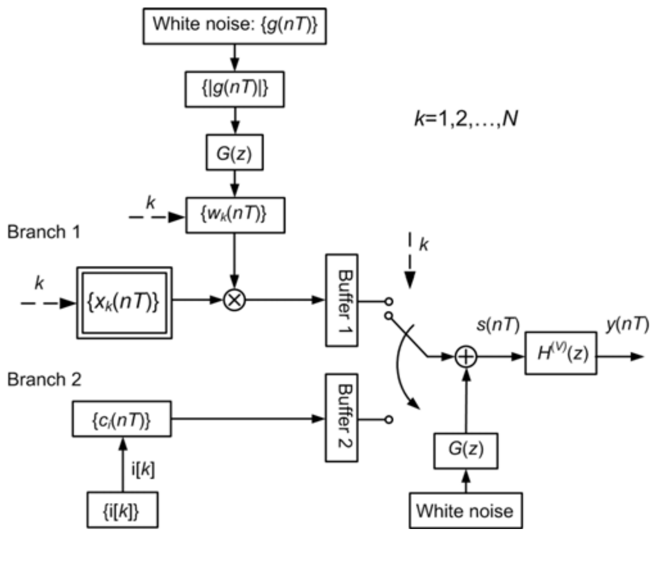

Figure 2 – Block diagram of the impulse noise simulator.

The principal block in branch 1 is the block which generates the new resampled kernel sequence $\{x_k[nT]\}$ of the length $\lfloor LR(k) \rfloor$ for each new value of k. This block, denoted as $\{x_k[nT]\}$, represents the structure of Figure 1. The cascade of the white noise generator, filter $G(z)$, and the sliding window $\{w_k[nT]\}$, produce the noise sequence which is used to modify the amplitudes of the sequence $\{x_k[nT]\}$:

- The white noise generator produces a very long white noise sequence $\{g(nT)\}$.

- In the next stage, the absolute values $\{|g(nT)|\}$ are computed.
- The noise shaping filter $G(z)$ is used to attenuate higher frequencies in the white noise spectrum.
- With each new k, the sliding window $\{w_k[nT]\}$ extracts the new portion of the length $\lfloor LR[k] \rfloor$ from the very long noise sequence $\{|g(nT)|\}$.

Finally, the amplitudes of $\{x_k[nT]\}$ are modified by multiplication with the windowed noise sequence of the length $\lfloor LR[k] \rfloor$. The result is stored in Buffer 1.

The noise shaping filter $G(z)$ is a very simple 2nd order recursive filter whose magnitude response decreases with frequency.

Branch 2 forms the time slots of random durations. The sequence $\{c_i[nT]\}$ is a zero valued sequence of the length $i[k]$, where $i[k]$ is an integer from the set of random integers $\{i[k]\}$. Buffer 2 contains the zero valued sequence $\{c_i[nT]\}$ whose length is randomly changed with each new k.

At the output, for each new k, the commutator picks up the content of Buffer 1, and then the content of Buffer 2. In this way, the impulse train with random amplitudes and random distribution in time is obtained. Finally, the filtered white noise that simulates the background noise of the system is added, and the desired impulsive noise sequence $\{s(nT)\}$ is generated.

The bandpass filter $H^{(V)}(z)$ with variable central frequency and variable bandwidth is used to select the frequency band of the desired communication channel for further processing. The output sequence $\{y(nT)\}$ simulates the impulsive noise over the telecommunication channel.

3. VARIABLE BANDPASS DIGITAL FILTER

The digital filter indicated in Figure 2 as $H^{(V)}(z)$ is a bandpass filter whose purpose is to select from the impulse noise spectrum the bandwidth which corresponds to the bandwidth of desired communication channel. We use a bandpass digital filer with adjustable bandwidth and adjustable central frequency.

The filter structure is based on the prototype half-band lowpass filter of the finite impulse response (FIR) and on the all-pass filter sections [17]. We start from the minimum-phase prototype FIR filter transfer function $H_{FIR}(z)$

$$H_{FIR}(z) = \sum_{k=0}^{N-1} a_k z^{-k} \tag{1}$$

and introduce the lowpass-to-bandpass frequency transformation. Following the procedure as given in [17], we obtain the transfer function of the overall bandpass filter $H^{(V)}(z)$ in the form

$$H^{(V)}(z) = \sum_{k=0}^{N-1} a_k \left(\frac{\alpha_1 - g(1+\alpha_1)z^{-1} + z^{-2}}{1 - g(1+\alpha_1)z^{-1} + \alpha_1 z^{-2}} \right)^k . \tag{2}$$

Parameters α_1 and g are directly related with the 3-dB passband width Δf, lower passband edge frequency f_l, and the sampling frequency f_s:

$$\alpha_1 = \frac{1 - \tan(\pi \Delta f / f_s)}{1 + \tan(\pi \Delta f / f_s)}, \quad g = \frac{\cos(2\pi f_l + \pi \Delta f / f_s)}{\cos(\pi \Delta f / f_s)} \tag{3}$$

The stopband/passband ripples of the resulting bandpass filter (2) are those of the prototype FIR filter (1), whereas the bandwidth, and the central frequency are the adjustable characteristics, see equations (3). Figures 3 and 4 display the variable attenuation characteristics of the filter developed from the 15th order half-band FIR prototype of the minimum phase. Figure 3 illustrates the changes of the bandwidth, and Figure 4 illustrates the changes of the central frequency.

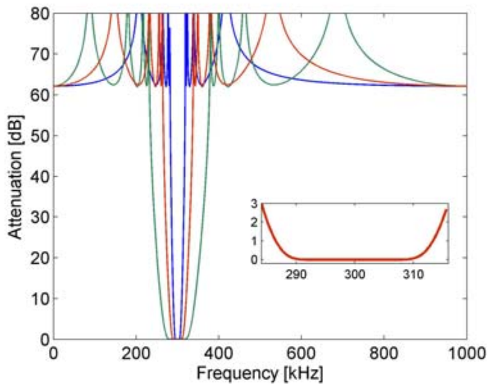

Figure 3 – Variable bandpass filter: $f_c = 300$ kHz, $\Delta f = 16$, 32, and 64 kHz.

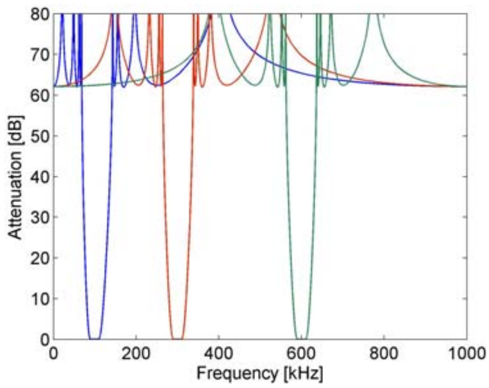

Figure 4 – Variable bandpass filter: $\Delta f = 32$ kHz, $f_c = 100$, 300, and 600 kHz.

4. ILLUSTRATIVE EXAMPLE

In this section, we present the simulation of the impulse noise by means of example. For the kernel sequence of Figure 1, we utilize an authentic noise signal measured and recorded in the telecommunication room of the hydroelectric power plant "Perucica" (Montenegro) at the connection of the coaxial cable (impedance 75 Ohm) to PLC equipment [18]. Data have been recorded with the sampling frequency of 10 MHz, and the duration of the kernel sequence is 1.6 ms, see Figure 5.

The simulation results based on the kernel sequence from Figure 5 are displayed in Figures 6, 7, and 8. Figure 6 illustrates one realization of the generated noise signal denoted by $s(nT)$ in Figure 2. Figure 7 displays the zoom extracted from Figure 6. Evidently, the signal $\{s(nT)\}$ is a train of compressed and extended sequences of Figure 5 with randomly modified amplitudes and random distribution in time. The total duration of $\{s(nT)\}$ is nearly 3 seconds.

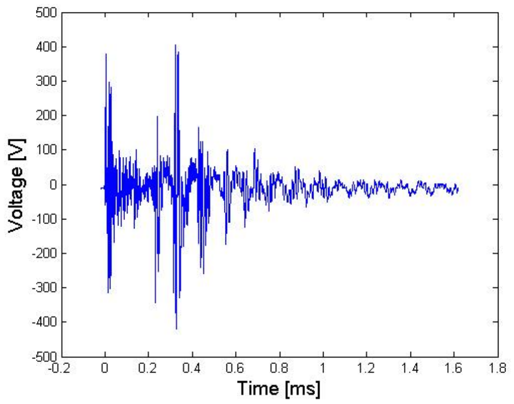

Figure 5 – Kernel sequence

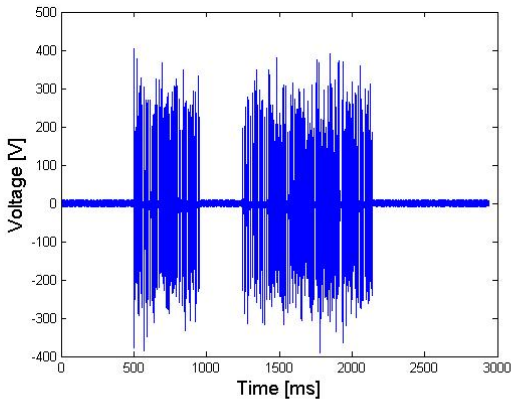

Figure 6 – Impulse noise $\{s(nT)\}$ produced by simulator.

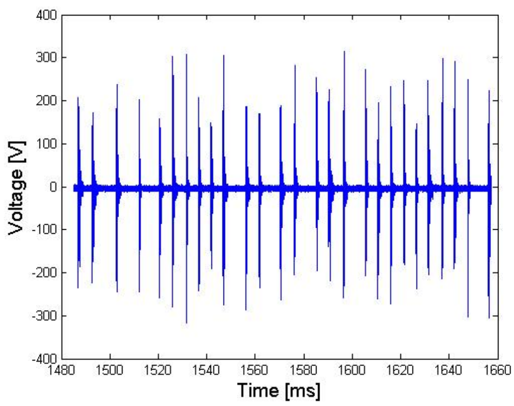

Figure 7 – Segment of the impulse noise $\{s(nT)\}$.

It is to be pointed out that in each realization, the simulator generates a new impulsive noise sequence $\{s(nT)\}$, and therefore, eliminates unwanted repetitions of the experimental results.

In order to examine the effects of noise $\{s(nT)\}$ to various communication channels, the variable bandpass filter $H^{(V)}(z)$ described in Section 3 is applied. Figure 8 presents an example of the short-time Fourier (STFT) analysis performed on the 40 ms long segment of the filtered signal, which contains 80000 samples of $\{y(nT)\}$. The STFT computations are based on the 256 samples long Hamming window with the overlap of 128 samples. The variable band pass filter parameters are the following: central frequency f_c = 300 kHz, the bandwidth Δf = 32 kHz.

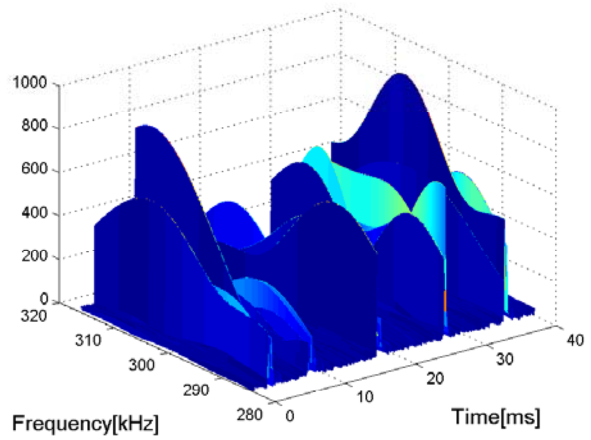

Figure 8 – Spectrum of the impulse noise recorded at the BP filter output (segment of $\{y(nT)\}$) for f_c = 300 kHz, Δf = 32 kHz

5. SPECTRUM ESTIMATION

In this section, we show the results of the estimation of the spectrum of the original kernel sequence and of the sequence generated by the simulator in the range of frequencies standardized for dPLC (24 kHz – 1 MHz). The purpose of the analysis is to compare the estimated spectrum with the average impulse-type noise levels, measures at the coaxial cable in a bandwidth of 4 kHz, which are obtained by measurements and published in the CIGRÉ document [1]. The noise level in [1] is presented as a voltage level measured at the impedance of 150 Ohm and expressed in dBu ($20\log_{10}$(Voltage[V]/0.775).

The spectral analysis of the wideband noise signal is performed by using the Welch's averaged periodogram method of spectrum estimation [19]. The Kaiser window is used in order to provide a good separation between the channels. We compute:

1. The average power spectrum of the original kernel sequence with the resolution of 4kHz and the sampling frequency of 10 MHz.
2. The average power spectrum of the generated impulse noise train without time slots between the impulses (obtained when excluding branch 2 in the structure of Figure 2). The sampling frequency is 2 MHz and the resolution is 4 kHz.

For the resolution of 4 kHz and the sampling frequency of 2 MHz, the Welch's averaged periodogram method returns 251 values of the power spectrum in the frequency range [0, 1MHz]. For each value, we compute the equivalent voltage and the corresponding voltage level in dBu. Since the kernel sequence is measured at 75 Ohm impedance, and the values in [1] are given for 150 Ohm, we increase the computed voltage levels by 6dB. The results are displayed in Figure 9. The red line represents the averaged equivalent voltage levels of the kernel sequence within 4 kHz bandwidths. The blue line shows the averaged equivalent noise levels within 4 kHz for the noise train generated by simulator (without time slots). Notice that the smooth blue line represents the average spectrum of the impulse train composed of 200 impulse sequences generated in the Branch 1 of Figure 2.

Figure 9 demonstrates the following properties of the proposed simulator: (1) the spectrum of the simulated signal (blue line) approximates the spectrum of the kernel sequence (red line) in the frequency band [0, 1MHz]; (2) the noise level decreases when frequency increases.

Reference [1] gives the average noise levels that can be expected at the connection of the PLC equipment to the coaxial cable: for isolator switch (busbar on or off) +25 dBu, and for circuit breaker (line on or off) +20 dBu. From the plots of Figure 9, we observe that in the case of the illustrative example considered in this paper, the noise levels given in [1] are achieved in the lower frequency band.

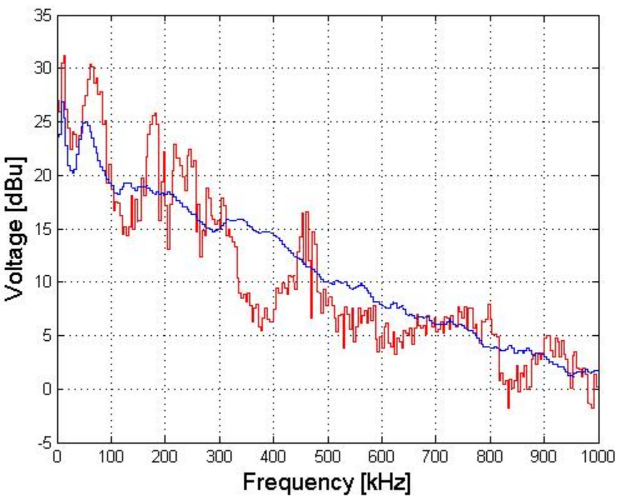

Figure 9 – Spectral characteristics of the kernel sequence (red curve), and of the simulated sequence (blue curve).

It is to be pointed out that the level of the information signal, at the points where the impulsive noise is measured, usually ranges between –10 dBu and –30 dBu. Obviously, the presence of the high-level impulsive noise (although of the short duration) can destroy the transmission process.

6. CONCLUSION

The presented model, realized as the simulation software, is needed for verifying the performances of communication systems applied in a high-voltage network. It may also be used to optimize the algorithms and methods for suppressing the effects of the impulsive noise which is present in a high-voltage channel.

The reliability of a communication network is of vital importance for power utility systems, so this computer model, as a real one, may be used to assess by simulation, the reliability of the applied communication methods of signal processing.

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