

Teleprotection Terminal Interface for Analogue Communications over High Voltage Power Lines Implemented on FPGA

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Abstract — The purpose of a telecommunication system in conjunction with protection systems is to transfer a protection signal in due time from the protection equipment to a similar equipment at the remote station. This paper describes an implementation of the interface in the teleprotection terminal dedicated to operate over Power Line Carrier (PLC) links. Properties of the teleprotection terminal are briefly described, and in the sequel, the implementation of the line unit using FPGA technology is described in detail. The presented simulation model can be used to optimize the interface for suppressing noise effects that may appear in a communication channel realized over high voltage power line and PLC equipment.

Keywords — FPGA, teleprotection, Power Line Carrier, Electric Power System.

I. INTRODUCTION

TELEPROTECTION equipment provides electric power utilities (EPU) with secure and reliable signaling between power substations for remote operation of power system circuit breakers. Early fault detection has become of primary interest in modern electric power transmission systems [1]-[7] and has a decisive role in ensuring uninterrupted power supply and avoiding power blackouts. Presently, various solutions of teleprotection terminals are available on the market [3], [4].

Teleprotection equipment transforms the information given by the protection equipment into a form suitable for transmission, and is connected to a telecommunication link between both ends of the protected line [6]. A block diagram of the system is sketched in Fig. 1. For the signal transmission, various transmission media can be used: power-line carrier (PLC) link, fiber optic links, copper wires/pilot cables, microwave-radio links.

Common requirements for teleprotection systems are high dependability, security and short transmission time of teleprotection signals. Dependability is defined as the probability of the successful teleprotection command

transmission, and security is defined as the security against a false command.

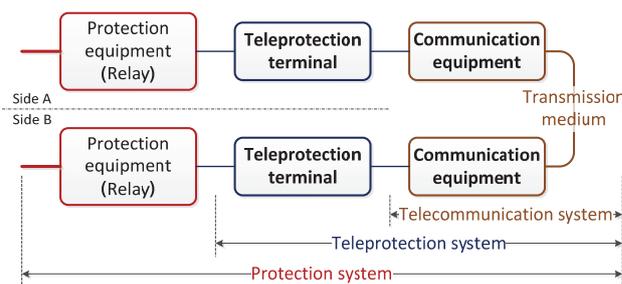


Fig. 1 Typical teleprotection system.

Any communication channel suffers from various types of interferences and impairment that may create false signals, or produce a long delay of the transmitted teleprotection command. When the communication channel is realized over high voltage power line (PLC) links, particularly severe conditions should be faced due to corona noise, variation of attenuation, and impulsive noise [8]. Therefore, the PLC interface design for a teleprotection terminal must provide immunity from unwanted frequencies and, at the same time, must enable transmission of teleprotection commands with high dependability and for the shortest possible time.

The Mihajlo Pupin Institute produced several generations of teleprotection equipment. New generation TZ-600 is designed to support a variety of communication channels in EPU [9]. This paper is focused on the design, implementation and simulation of the PLC interface of TZ-600 terminal.

The purpose of this paper is twofold: (1) to describe a new solution of TZ-600 teleprotection terminal line interface for PLC equipment implemented using FPGA technology, (2) to present the Matlab-Simulink line interface simulation model. The test results obtained with simulation of the channel corrupted with white noise are shown.

This paper is organized as follows. The second section describes the modes for transmission of the teleprotection signals, and the multiplexer equipment specifically designed for their transmission in the electric power system (EPS). The third section presents realization of the TZ-600 line PLC interface based on the FPGA integrated circuit. The fourth section describes the line interface simulation model developed in the Matlab-Simulink environment together with several simulation results. The fifth section is a conclusion.

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II. BASIC PRINCIPLES OF INTERFACE REALIZATION

Generally, the concept of teleprotection equipment can be based on state comparisons schemes (distance protection) or analogue comparisons schemes (differential protection) [2]. The TZ-600 is designed as a distance teleprotection terminal.

A. Transmission of the Teleprotection Commands

Distance protection is based on tracking the transmission line impedance, specifically the impedance between phase transmission lines or the impedance between the phase and ground wire on the local end of the power line segment. Distance protection schemes use signaling to convey a command between local and remote relaying points. Reception of the information is used to aid or speed up clearance of faults within a protected zone or to prevent tripping from faults outside a protected zone. There are several schemes of distance protection: intertripping, permissive tripping and blocking [1]-[3].

Analogue PLC channels are used in teleprotection systems, mostly as a backup path. The PLC equipment is designed for transmission of speech, data and protection signals in the bandwidth of mostly 4 kHz which is transposed by modulation in the projected bandwidth for transmission (frequency range from 40 kHz to 1 MHz). Teleprotection signals are four-wire connected to the audio frequency (AF) part of the PLC equipment, thereby eliminating the transmission of all other signals. During the transmission of protection commands the speech and data signals may be switched off such that the maximum transmit power is available to the protection signal. The PLC equipment must be resistant to interference produced by power system.

When using the analogue transmission channel (as PLC), allowed transmission time (delay) depends on the protection scheme (see Table 1). Data in Table 1 are valid for the signal to noise ratio (SNR) greater than 6 dB, where P_{uc} is the probability for unwanted commands and P_{mc} is the probability for missing commands. Values are corrected for the worse SNR [6].

For the transmission over analogue channels, TZ-600 equipment enables usage of all three kinds of teleprotection (state comparisons) schemes from Table 1.

TABLE 1: REQUIREMENTS FOR TELEPROTECTION SERVICE ON ANALOG CHANNEL [6].

	Protection scheme		
	intertripping	permissive	blocking
Transmission time (ms)	< 40	< 20	< 15
P_{uc}	< 10^{-6}	< 10^{-4}	< 10^{-3}
P_{mc}	< 10^{-4}	< 10^{-3}	< 10^{-3}

B. Equipment for Teleprotection Commands Transmission

TZ-600 has modular design [3], [9], [10]. There are two types of interface modules to enable interface to the protection relay and to the transmission medium (Fig. 2). Power units generate operating voltages from DC or AC power source. A central unit enables monitoring of the terminal over network or locally while a telediagnostic unit enables local LED monitoring and basic tests of the teleprotection command signal status. A line interface unit

(LNU) enables multiplex function and processing of the signal.

When the PLC channel is used, the teleprotection commands are transmitted using one of two possible modulation types: F6 or coded modulation. The coded modulation is used for the teleprotection scheme of the highest priority – intertripping. Frequency bandwidth of the AF (speech) channel from 300 Hz to 3800 Hz is divided into 28 x 125 Hz wide subchannels.

Fig. 2 shows the way of integration of the PLC equipment interface in the TZ-600 terminal, and signal path of the teleprotection commands. Just before sending teleprotection commands, TZ-600 terminal generates a *boost-out* signal towards the PLC equipment, to warn it to switch-off all signals except signals for transmitting teleprotection commands.

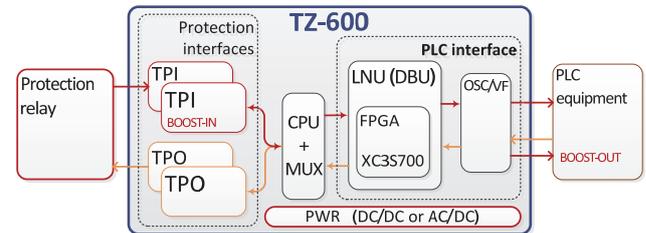


Fig. 2. Block diagram of the TZ-600 terminal with interface to the PLC equipment.

When using F6 modulation type for command transmission, only one signal is transmitted at a time, which does not mean that only one command is transmitted. Signals differ in frequency, and depending on the transmission scheme, 4 independent commands can be transmitted or 8 commands in priority. Table 2 [10] shows all possible schemes for command transmission, the number of the commands that corresponds to each scheme, as well as the number of signals for the realization of the teleprotection scheme.

TABLE 2: NUMBER OF COMMANDS AND SIGNALS FOR VARIOUS TRANSMISSION SCHEMES.

Transmission scheme	Number of commands	Number of signals required + test
4I	4 independent	15 + 1
4P2I	8 in 4 groups with 2 independent	12 + 1
2P2I	4 in 2 groups with 2 independent	6 + 1
6P	6 per priority	6 + 1
3I	3 independent	7 + 1

The most complicated transmission scheme for the teleprotection command signals occurs when 4 simultaneous (independent) commands (4I) are transmitted (where 15 various subchannels are needed). Additionally two subchannels are needed for the *test* and *guard* signal.

Although the presented F6 modulation is ideal for an adequate PLC transmission range, this system is not absolutely immune against the presence of unwanted discrete frequencies. For that reason, F6 modulation is used for applications with lower priority (permissive or blocking tripping). Coded modulation uses two frequencies for the transmission of the protection

command. The receiver must receive each frequency for a specified time period before declaring a valid trip reception. This extends the transmission time, but increases dependability and security. It is also possible to use two frequencies at the same time for the transmission of a protection command, when transmission time remains the same as for non-coded signals, but this modulation has a shorter transmission range [11].

In the receiving path of the equipment the teleprotection command signal comes from the AF channel of the PLC equipment to the PLC interface module of the TZ-600 terminal. This module serves for basic signal processing, such as filtering, sampling and A/D conversion. After that, signal is passed to the receiving block of the LNU module (described in detail in the third section). The function of the module is command detection and checking, as well as generation of the signal for command blocking, if prescribed conditions are satisfied. From the LNU module, detected signal is transferred to the CPU/MUX module, where additional processing is done such as changing signal duration and combining, and further to the TPO (teleprotection command output) module, which serves for signal adapting to the protection relay.

Besides the teleprotection commands, a so called *guard* signal, which is sent when there are no commands, is generated according to the transmission channel. When connection is realized over the PLC equipment, *guard* signal is generated in the equipment, and TZ-600 terminal serves only for detecting the presence of the *guard* signal in the analogue channel. However, when connection is realized over the direct wire link (e.g. leased line), generation and the detection of the *guard* signal is done in the TZ-600 terminal.

III. REALIZATION OF THE LINE PLC INTERFACE

Since LNU module of TZ-600 terminal must support several line interfaces (digital and analogue) with a possibility of their parallel work, the question of optimal hardware solution is very important. Major drawbacks in using FPGA technology are costs and need to integrate peripherals like A/D and D/A converters. However, FPGAs are bringing many benefits in terms of safety, rapidity, and power consumption [12]. Using FPGA technology in realization of these various telecommunication interfaces on a single universal communication module is imposed as a good solution, especially due to the possibility of adding new interfaces and capabilities to the existing. Accordingly, line interface for PLC equipment is mostly realized in FPGA technology and this solution will be briefly described in this section.

After processing (filtering and sampling) in the line receiving part of the TZ-600 equipment (Fig. 2 OSC/VF block), the received signal is processed in the FPGA integrated circuit of the line unit. Fig. 3 shows the block diagram of the PLC line interface realized in the FPGA component of the line module. The main parts of the interface are: a block for generation of transmission signal (Tx), a receiving block (Rx), an alarm block and a control & test block. Control & test block contains a block for

generation and detection of the *test* signal. Tx block contains a block for coding, while Rx block contains a block for decoding of the command signals (in accordance with the transmission scheme in Control & test block, shown in Table 2). The transmission scheme determines how many different commands and different frequencies are transmitted taking into account that the maximum number of different commands is 15. This is illustrated in tables 3 – 5 in [9].

Control and test block serves for interface configuration and testing. Sending of the *test* command is initiated manually. This command has a higher priority than *guard*, and a lower priority than the sending teleprotection command. *Test* command can be detected in the receiving block of the LNU. Test block checks the propagation time of the command, and generates an error signal in the case of a greater delay than prescribed. Most of the parameters (such as transmission and frequency scheme, required minimum duration and level of the command signals, the noise level in the range and out of range, etc.) are set programmatically. A frequency scheme assigns spectral components to the commands of the transmission scheme.

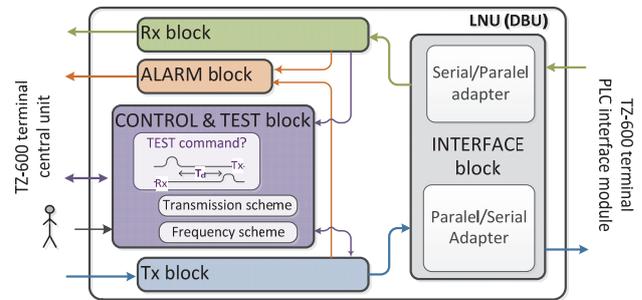


Fig. 3. Block diagram of the line PLC interface.

Alarm block serves for detecting errors in the received signal, such as during generation of the *test* command, high noise signal level or high level of *boost-in* signal.

In this paper two most important blocks are described in detail: block for generation of the transmission signal, and block for detection of the received commands.

A. Transmission Tx Block

Signals of the teleprotection commands coming from the distance relay are converted into a suitable form for digital processing (Fig. 2 TPI block), and forwarded to the transmission block of the line PLC interface (Fig. 4 – Tx register).

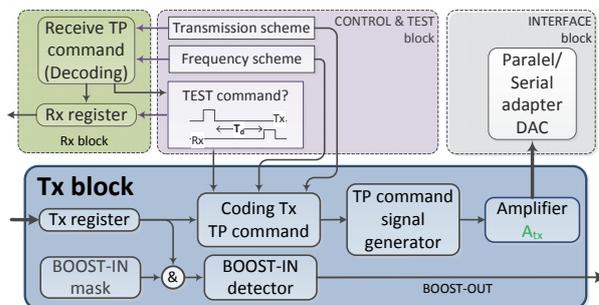


Fig. 4. Block diagram of the Tx block.

This block consists of: a block for coding of transmitted teleprotection command, boost-in detector logic, a signal generator which generates corresponding encoded

command values, and a signal amplifier at the exit of the transmitter. Fig. 4 shows the transmission block in blue mark part.

Signal generation of the teleprotection commands depends on the transmission scheme and modulation type. It is done after the command coding with CORDIC (Coordinate Rotation Digital Computer) algorithm. This is a block from the MATLAB-Simulink program, which generates a sinusoidal signal on the output using the phase translation on its input. The generated command signal in digital form is adjusted with the programmable amplifier, and after that transmitted to the D/A conversion block, and further towards PLC equipment.

B. Receiving Rx Block

In the receiver after the amplification, signal is separated in two paths, one of which leads to the block for detection of the received command, and the other to the block for possible blockade of the received command. Besides the blocks shown in Fig. 5, the receiver contains a block for signal measurement and automatic gain control as well. Realization of the received frequencies extraction in the block for command detection is done with the block from MATLAB-Simulink package for calculating DFT. When DFT is calculated, amplitudes are formed from real and imaginary parts of received signal's spectral components. Next operation is search for a maximum spectral component. Moreover, all components except for a maximum component are summed and averaged, to get the level of inactive components. Depending on the frequency scheme, average noise is also calculated from the part of the spectrum that doesn't contain commands. Levels of noise and inactive components are used for blocking decision.

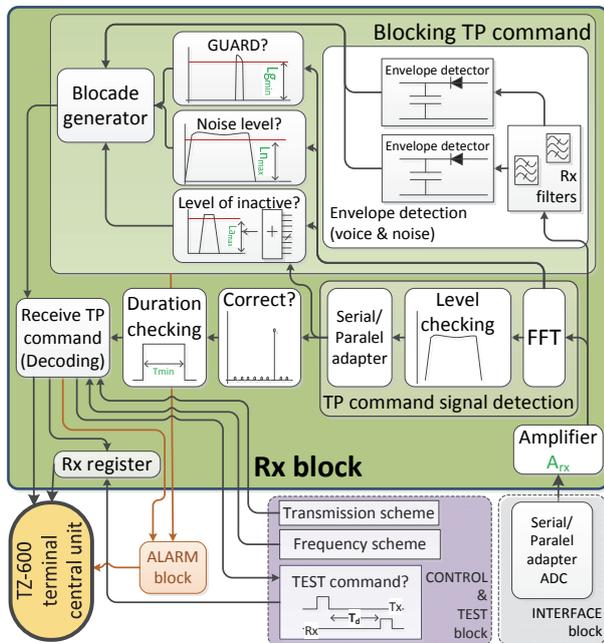


Fig. 5. Block diagram of the Rx block.

Detection of teleprotection command signal received by the receiver requires that:

- *Guard* signal is not detected in the receiver.
- Only one command signal is detected in the useful frequency range, with satisfactory level and duration.

Additional requirements which must be met (otherwise the command is blocked) are:

- Missing of the *guard* signal is detected before expiration of the maximum allowable time interval (depends on the teleprotection scheme of the channel).
- The level of the noise measured outside the range of the command signals and the *guard* signal is not over the maximal allowable value.
- No speech signal is detected in the useful frequency range (speech signals have a slow varying envelope).
- The levels of the signals, excluding the detected command signal, in the frequency range of the command signals are less than a maximum level.
- The second and third criteria are tested using the envelope detectors shown in Fig. 5.

Detected command in the receiver's line interface is forwarded to the user interface (TPO block in Fig. 2), where it is forwarded towards the distant relay after the signal conversion.

C. FPGA Resource Estimation

As far as the resources for the implementation are concerned, most resources are taken by the *Simulink* component for the FFT calculation. When adjusting components, for the optimization, it is possible to define various parameters that choose the implementation algorithm, making it possible to save resources sacrificing speed and vice versa. In this simulation the system clock of 98.304 MHz is used, and the data flow of 4 MSPS.

An estimate of the availability of resources for the different implementations (number of FFT points) is given in Table 3.

TABLE 3: RESOURCE ANALYSIS (XC3S700AN).

	available	Implementation (number of points)		
		64	128	256
<i>slice</i>	5888	48%	47%	48%
<i>flip-flop</i>	11776	22%	23%	23%
<i>4-input LUT</i>	11776	27%	28%	28%
<i>multiplier</i>	20	30%	30%	30%

IV. SIMULATION OF THE LINE INTERFACE

It should be noted that measurements of HF characteristics of the power line are limited with the permission of the power utilities, and availability of coupling equipment. Moreover, due to the nature and importance of the teleprotection system, all communications aspects must be taken into account. Therefore, the computer simulations of the power line HF characteristics are indispensable for investigations and design of teleprotection systems [13]. In this section the results of testing the implemented model using simulation of the channel corrupted with white noise are presented. For more complete testing, the presence of the impulsive noise must be considered [14]-[17].

A. Simulation in the Matlab-Simulink Environment

The FPGA design of the system can be done in the *Xilinx* addition for the *Simulink – System Generator*. This program enables using of predefined elements (primitives) of the elementary logical and arithmetical circuits [13].

Design is formed as a block diagram with interconnections, as it is usually done in the *Simulink*. Signals are separated from basic *Simulink*'s environment, with special elements (input and output ports), so that the design for FPGA is a separate entity.

The highest frequency in the system is 4 kHz, so the sampling frequency should not be less than 8 kHz. According to this, behavior of the system is tested using the 3 sampling frequencies: 8 kHz, 16 kHz and 32 kHz. In order to make the resolution of spectral components the same for all three values of the sampling frequency, the length of FFT calculation is defined to be: 64, 128 and 256, respectively. For all three cases, the distance between adjacent points in the spectrum is 125 Hz. The simulation scheme which was tested in this environment is shown in Fig. 6.

Block "TZ-600" (Fig. 6, blue block) simulates the receiving and transmitting part of the equipment, more precisely, a model designed to operate with the PLC device. The outputs from the transmitting part are signals Tx DAC and BOOST, and the output from the receiving part is the signal of the decoded received command Rx CMD.

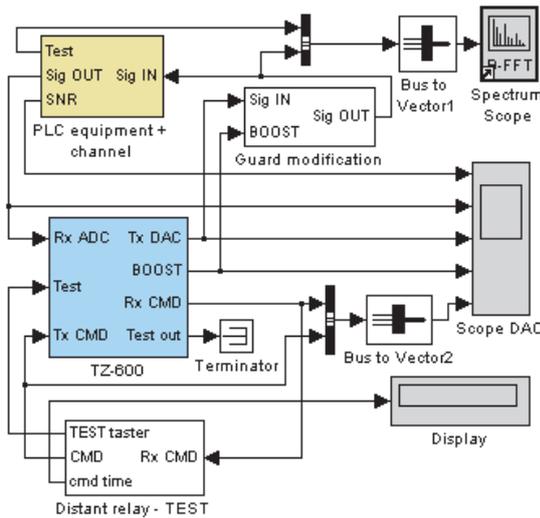


Fig. 6. Simulation of the TZ-600 terminal working with PLC link.

Spectrum Scope and *Scope DAC* tools of the *Simulink* program, enable tracing of the signal spectrum, and signal in the time domain. Block "Distant relay – Test", enables generation of the TP commands, as well as *test* signal. Signal of the generated command is led to the block "TZ-600". To this block also arrives the received signal from the block which simulates PLC equipment and a line channel for transmission of the TP command. Simulation is done without or with a noise signal, or some other disturbing signal (such as speech signal, DTMF etc.), or their combinations.

B. Simulation Results

In the process of simulation, the generation of the whole range of commands was tested for both types of modulations: F6 and coded. Also the level of the generated white noise was changed in the block PLC equipment + channel. Some simulation results are shown in Fig. 7 and 8, and are in accordance with the requirements given in

(Table 1). Fig. 7 shows the simulation of sending command number 13. The first graph shows the output signal, that is sending *guard* signal (frequency 2500 Hz) in the most of the time period, interrupted with sending a command signal, which according to the frequency scheme corresponds to the frequency of 2125 Hz. Signal is superimposed with the white noise to obtain a signal which is close to real conditions (the second graph). Third graph displays the received (blue line) and transmitted command (red line). SNR was 6dB in this simulation.

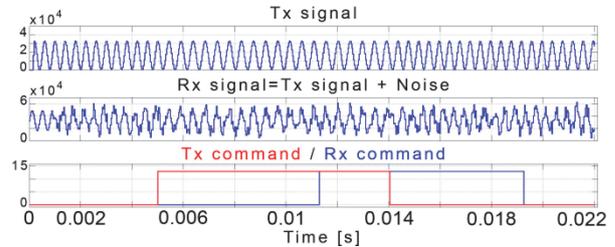


Fig. 7. Command number 13 (2125 Hz) decoded with FFT in 64 points (SNR is 6 dB).

Fig. 8 shows the simulation results for sending and receiving the command number 8, decoded with the 64 point FFT, and in the presence of the noise with a higher level than in the simulation shown in Fig. 7. (SNR was 2 dB). The first graph shows the output signal. The second graph shows a received signal (with white noise), and the third graph shows transmitted and received commands colored with red and blue, respectively. This graph shows that the received commands are much narrower than transmitted, and in some places not continuous.

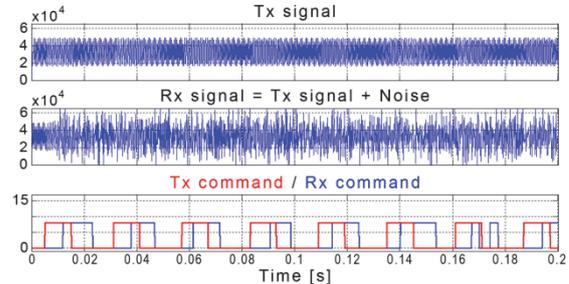


Fig. 8. Command number 8 (1500 Hz) decoded with 64 points FFT and signal to noise ratio 2 dB.

A better insight into signal and noise power can be seen in Fig. 9 showing the spectral components of the transmitted command signal, and the spectrum of the added white noise.

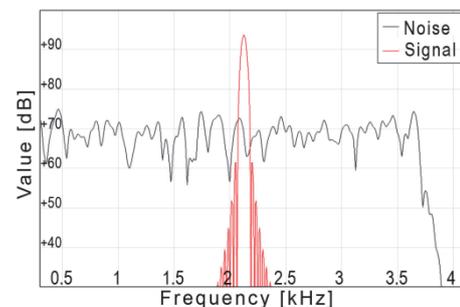


Fig. 9. Example of the command signal spectrum with added noise.

System response is tested for different commands and sampling frequency. In the case of the FFT with 64 points,

the response is slower than with 128 points, and both are slower than the case with 256 points. This affects the minimal duration of the command which can be successfully decoded. Low frequency commands must be of greater duration (Table 4).

TABLE 4: MINIMAL COMMAND DURATION AS A FUNCTION OF FFT IMPLEMENTATION.

Command	Number of FFT points		
	64	128	256
1 (625 Hz)	10 ms	8.5 ms	8 ms
7 (1375 Hz)	9 ms	8 ms	7.5 ms
14 (2250 Hz)	8.5 ms	8 ms	7.5 ms

The delay of the received command is almost the same for various commands (the highest is for the lowest frequency command 625 Hz - ~6 ms). If the required time for A/D and D/A conversion and additional hardware processing on the transmission and reception is 4 ms, total nominal transmission time is less than the requested 15 ms.

Fig. 10 shows distribution of the time delay of TP commands, due to the signal processing in the "TZ-600" transmitting and receiving block (shown in Fig. 6).

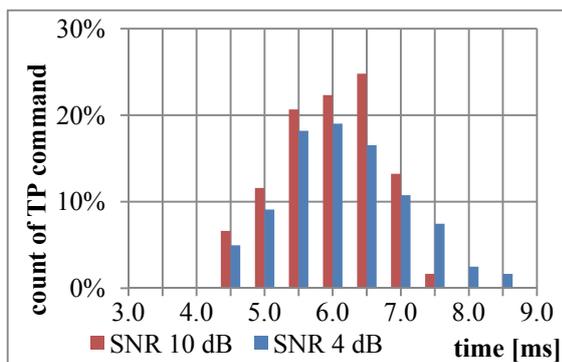


Fig. 10. Time delay distribution of command signal.

Insertion delay due to signal propagation through the test blocks which simulates the channel is negligible. Decoding has been done with the 64 point FFT, and the number of processed commands was of the order of 100. The results were shown for SNR of 10 dB at which there were no errors in the transmission of commands, and for SNR of 4 dB at which errors were detected. During the command transfer through the channel with a worse SNR, there was a slight delay in transmission of commands.

TABLE 5: MEASUREMENT OF MISSING, UNWANTED AND AVERAGE DELAY OF THE TP COMMANDS IN FUNCTION OF SNR.

additional processing	SNR [dB]	Commands				
		Tx	Rx missing	Rx unwanted	delay [ms]	
No	0	12	107	0	0	5,7
	6	6	102	0	2	5,9
	3	3	107	0	4	6,1
yes	2	6	102	0	0	7,9
	4	3	107	0	0	10,5

Under lower levels of the SNR, it is possible to apply additional processing at the signal reception, which would increase signal delay from end to end, but will increase the

dependability and security of the TP command transmission. For example, Table 5 shows simulation results of a simple additional processing like filtering the signal by duration (threshold is proportional to the SNR).

V. CONCLUSION

The described teleprotection PLC line interface significantly complements the performance of TZ-600 equipment used for teleprotection in modern EPU. Integrated solution of the line interface provides merging of the existing and new capabilities for connecting TZ-600 to the digital and analogue telecommunication channels. Realization using FPGA has required some specific features in the design, such as the use of FFT instead of digital filters, and also in the realization of some other interface components.

The applied simulation model confirmed the assumed good projected characteristics of the line interface, and avoids complicated and expensive testing in real environment. While developing the simulation model, it was tended towards a more realistic representation of the equipment and its environment, so in future investigations, simulations of the HF channel will include the impulse noise as well.

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