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SOFTWARE BASED EXPERIMENTAL SYSTEM FOR ELECTRICAL POWER QUALITY MEASUREMENT USING THE WIRELESS SENSOR NETWORK MODULES

UDC (621.317.337:621.317):004.42LabVIEW

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Abstract. *Experimental system for measurement of standard electrical power quality (PQ) parameters, based on wireless sensor network (WSN), is presented in this paper. System includes generator of reference voltage waveforms, software application for measurement of standard PQ parameters and two microcontroller based wireless sensor modules for transmitting and receiving of measurement results. Reference voltage signals are provided using signal generator with possibility for simulation of typical network disturbances, presented in some previously published papers. This PQ signal generator is functionally supported by the virtual instrumentation software and data acquisition card. Measurements of basic quality parameters for reference test signals are performed using the LabVIEW software application. Time interval for each measurement cycle is 1 s. For communication is used wireless sensor network based on communication standard IEEE 802.15.4 (Zigbee). Hardware configuration includes two wireless sensor modules SPaRCMosquito v.2, based on the microcontroller with Cortex M3 architecture. Transfer of measurement results, between computer and wireless sensor modules on transmitter and receiver points, are provided using standard USB interface.*

Key words: *experimental system, electrical power quality measurement, wireless sensor network, virtual instrumentation software*

1. INTRODUCTION

Increased concern for problems of PQ assurance, indicated in recent years, primarily is caused by limitations of natural resources necessary for electrical power production,

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followed by widespread using of alternative energy sources. Powerful electronic devices can directly cause PQ degradation, which affects the production process costs and reduces reliability of customer electrical devices and equipment. For the purpose of customer protection, PQ level is determined according to the relevant international standards and regulations. This optimal level is determined by acceptable interval values of standard quality parameters and typical network disturbances. Relevant data, necessary for quality assessment, can be provided by measurement and analysis of standard quality parameters and network disturbances at some specific locations in power distribution network [1,2].

Various instruments and equipment for measurement and software based processing of PQ parameters are available at the market. Such instruments are developed for continuous monitoring of power supply quality in single or three-phase power distribution networks. Instruments for PQ measurement can be used as single devices at specific points in power distribution network. Alternatively, a number of individual instruments can be combined into complex distributed measurement system, for permanent monitoring and analysis of the power distribution network quality. Permanent PQ monitoring, with recording of detected network disturbances and software processing of measurement data, is a basic preventive activity. Advances in wireless communications and electronics enable development of wireless sensor networks (WSN), as low cost, low power and multifunctional sensors. WSN sensor nodes are small, suitable to sense the various data, process this data and communicate with each other or with central base station. Basic advantages of WSN sensors are: self organizing capabilities, short range broadcast applications, changing of network topology in order to avoid fading and potential failures, including significant savings in energy consumption, power transmission, memory and data analysis [3].

Progress in research and development of WSN sensor networks provides for many useful applications. WSN can be implemented in monitoring of different physical quantities, from temperature, humidity, light, pressure, object motion, soil composition, noise, object detection and tracking, objects weight, size, etc. Therefore, WSN networks can be used in various military applications, environmental monitoring, home intelligence, prevention of disasters, surveillance, medical care purposes and other applications [3,4]. In this paper are presented some possibilities of using WSN networks for measurement and monitoring of PQ parameters and network disturbances. For this purpose an experimental data acquisition system for measurement of standard quality parameters and testing of WSN based network communication for transferring of measurement results is developed and presented.

2. Hardware Configuration of Experimental Measurement System

Hardware configuration of an experimental system, realized for measurement of standard PQ parameters and testing of WSN based communication for transferring of measurement results, is presented in Fig. 1. LabVIEW software supported generator of reference PQ waveforms is used for generation of standard voltage waveforms. This specific generator is presented and described in the previously published paper [5]. It can generate long time and short time voltage signals, including special functions for simulation and generation of network disturbances typical for real-time power distribution systems. Experimental procedure includes PC computer with control application in LabVIEW environment and multi-channel data acquisition card PCIe NI 6343, supported with standard connection block SCB-68A [6]. Reference voltage waveforms from signal generator need to be sent to the A/D input channels of data acquisition card using SCB-68A connector block (communication line 1). LabVIEW application software implemented on the PC platform performs data acquisition, measurements, data recordings and graphical presentations of measurement results. Measurement data include basic parameters of test voltage signals: RMS voltage values, frequency and levels of individual high-order signal harmonics.

Fig. 1 Hardware configuration of experimental system for power quality measurement based on WSN network communication

WSN network communication for transferring of measurement results includes two microcontroller based WSN modules (transmitter and receiver of measurement results), with Cortex M3 architecture, called SPaRCMosquito v.2. Communication and transferring of measurement data between application software for PQ measurement and microcontroller based WSN module on transmitter side of experimental system is provided using standard USB interface (communication line 2). Cortex architecture of WSN modules is based on the ARM processor. USB virtual COM port is provided between LabVIEW software application and ARM microcontroller. On WSN base module is integrated radio module with MRF24J40 radio chip, which supports data communication standard IEEE 802.15.4 (Zigbee standard). It supports free RF-band of 2.4 MHz, with compact microstrip printed circuit antenna (communication line 3). On receiver side of experimental system VISA drivers in LabVIEW software are used to provide USB communication and transferring of measurement data from receiver WSN module to laptop computer for further analysis.

3. Software Support of Experimental Measurement System

Computer-based generator of standard voltage waveforms used as source of reference test signals is based on LabVIEW software platform. A primary function is generation of reference voltage waveforms, including special functions for simulation of standard PQ network disturbances [5]. The main requirement was to provide the combining a number of disturbances in one complex sequence, but also to include certain level of noise, small voltage and frequency variations. Some basic functions provided using this software supported generator, are: definition of nominal amplitude and frequency values, definition of signal sample rate and duration of final test sequence, generation of noise with Gaussian distributed amplitude, variations of nominal signal frequency value, slow variations of signal amplitude value, definition of signal DC offset, generation of voltage swell and voltage sag, and possibilities for generation of high-order signal harmonics.

LabVIEW control panel of signal generator, for graphical presentation of undisturbed voltage signal and signal with certain level of high-order harmonics, is shown in Fig. 2.

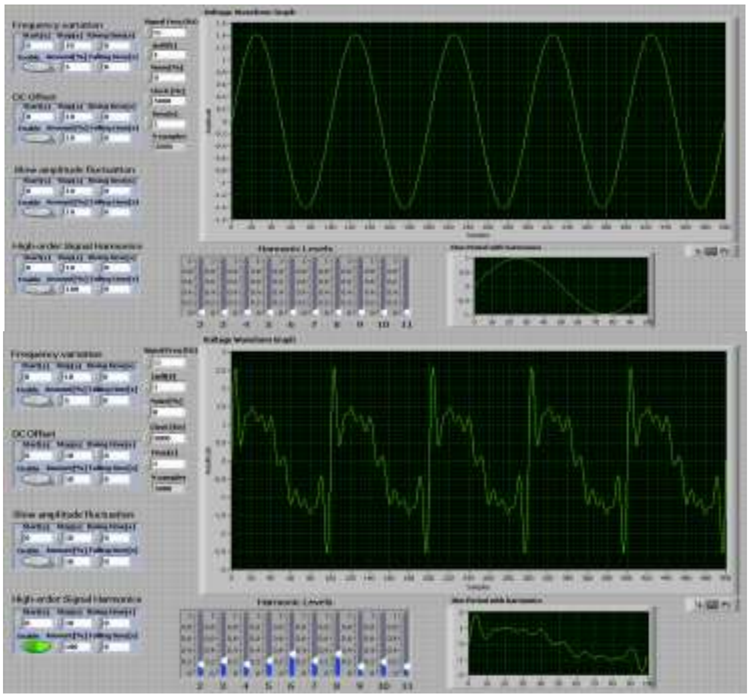

Fig. 2 Control panel of LabVIEW signal generator (undisturbed voltage signal and signal with high-order harmonics)

Each category of signal disturbances, for example voltage swell, sag and high-order harmonics, can be defined and generated by separate functional segments. Disturbances can be combined and unified in the form of a final complex sequence, according to the demands of European PQ standard EN 50160 [7]. Separated segment of control functions on this front panel is used for selection and variation of amplitude levels related to individual high-order harmonics. Content of specific high-order harmonics can be precisely defined by number of control knobs for regulation of harmonic amplitude levels. In order to be more realistic in generation of signal waveforms, for individual network disturbances are enabled separate definitions of nominal frequency variations, signal DC offset, amplitude fluctuations, start and stop times, rising and falling times of specific signal disturbances.

Front panel of virtual instrument in LabVIEW software environment, for presentation and measurement of basic quality parameters related to voltage test signal with certain level of harmonics, is presented in Fig. 3. Shown control software is implemented on transmitter side of experimental measurement system. This software application enables simultaneous presentation of voltage signal, tables with obtained measurement results and write box with chronologically measured values of signal quality parameters: RMS voltage values, frequency values, THD

(Total Harmonic Distortion) factor and values of individual high-order harmonic components. Measurements of basic signal parameters are performed in measurement cycles. Interval for each measurement cycle is set to 1 s.

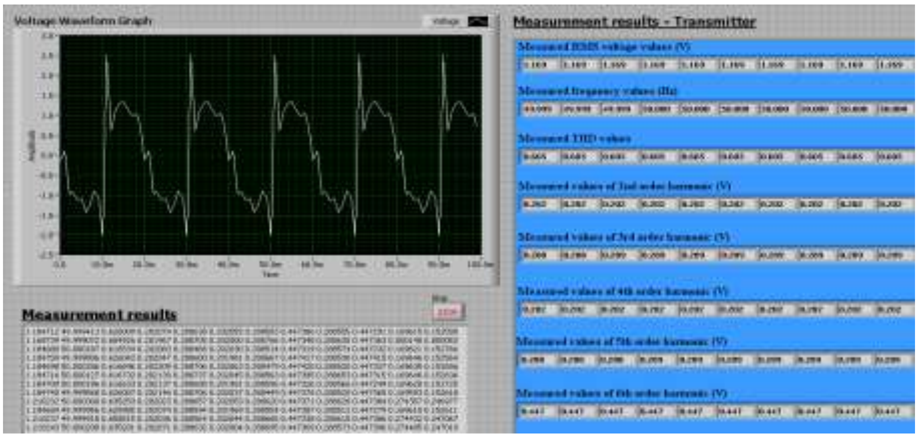

Fig. 3 Software application for signal acquisition, measurement of quality parameters and presentation of measurement results – transmitter point

Software application implemented on receiver system side, developed for presentation of received voltage waveform and received measurement results, is presented in Fig. 4.

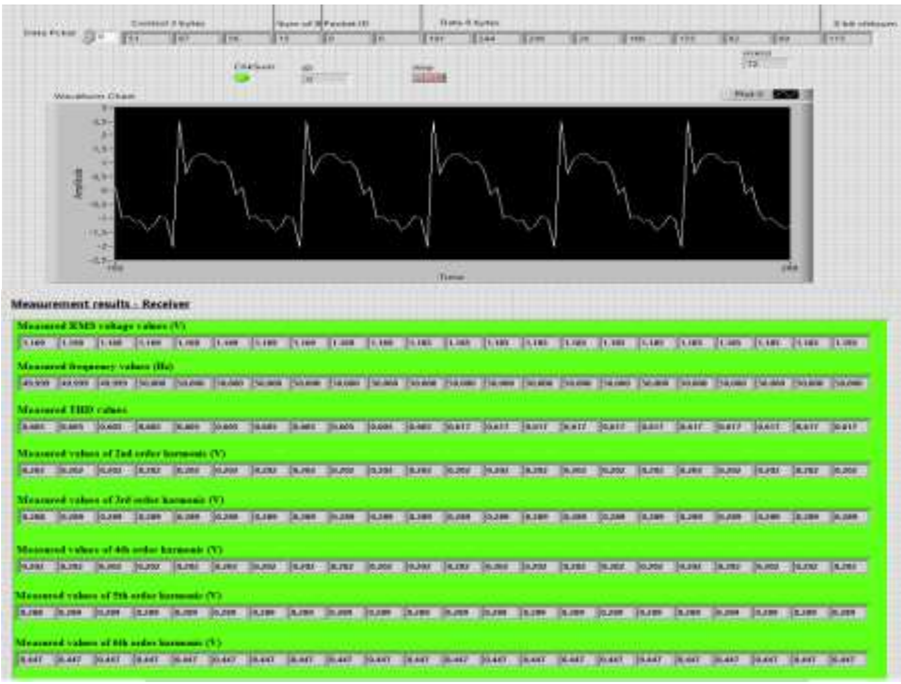

Fig. 4 LabVIEW software application for presentation of voltage signal and received measurement results – receiver point

For transferring of obtained measurement results to the receiver point of the presented experimental system the WSN network communication is applied. A detailed analysis of WSN network communication for transferring of PQ measurement results and evaluation of experimental system performances are given in the following segment of this paper.

4. Design of WSN Communication and Evaluation of System Performances

Hardware segment of network communication for transferring of measurement data consists of two WSN modules, transmitter and receiver, called the SPaRCMosquito v.2, based on microcontroller with Cortex M3 architecture [8]. Functional block diagram and photo of SPaRCMosquito v.2 - WSN Base Module are presented in Fig. 5. On this WSN Base Module is integrated radio module with the radio chip MRF24J40, which supports communication standard IEEE 802.15.4, also known as Zigbee communication standard.

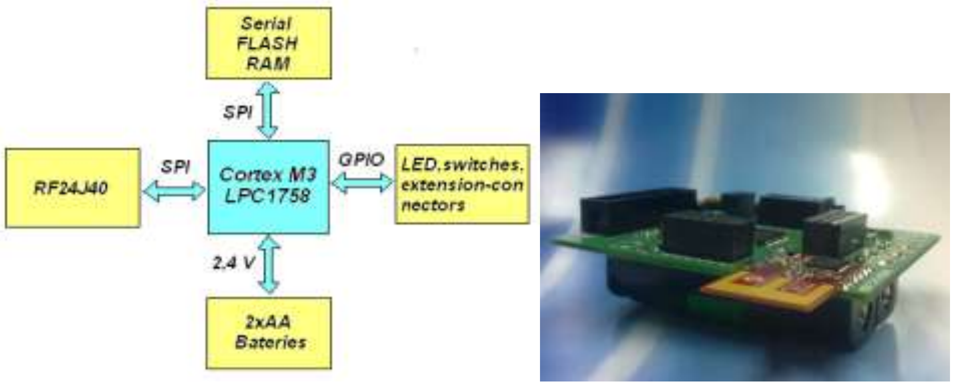

Fig. 5 Block configuration and photo of SPaRCMosquito v.2 - WSN Base Module

WSN Base Module can be extended with the daughter module. It consists of several communication interfaces, which enable communication over different kinds of network, using various communication protocols as: TCP/IP, CAN and USB protocols. Flash RAM on WSN Base Module can be programmed using the USB communication. Cortex M3 processor is enough powerful to emulate web server. Therefore, extended module can be connected over IP network, if it has free IP address. Extended module can be arranged according to specific application purposes, base station or sensor node requirements.

Today, there is an enormous effort to introduce the concept of smart grids in production, distribution and consumption of electrical power, in order to improve energy efficiency level, reliability and stability of power distribution networks [9,10]. Power quality is very important issue in modern electrical power networks and smart grids, especially at the end consumers in the low voltage distribution networks. Smart Grid (SG) network architecture for communication is proposed in the hierarchic way: SG - Wide Area Network (WAN) covers distances up to 100 km, SG - Neighborhood Area Network (NAN) covers distances up to 10 km and SG - Home Area Network (HAN) covers distances up to 100 m. Functions in smart grids are: Advanced Monitoring and Control (AMC), Demand Side Management (DSM), Generation and Storage Management (GSM) and System Protection (SP). Wireless communication and Power Line Communication (PLC) are appropriate communication technologies for low level HANs. PLC communication uses power lines for data transferring (standards: IEEE 1901, ITU-T and G9960/61). Frequencies are 3-500 kHz for Narrowband PLCs and 1-30 MHz for Broadband PLCs. Narrowband PLCs cover transmission distance of 100 km, but only to 100 bps. Broadband PLCs cover transmission distance of 100 m, reaching to 1 Mbps.

WiFi and Zigbee standards are two solutions for wireless network communications. Primary advantage of Zigbee communication standard in relation to WiFi data transfer is significantly lower power consumption, which can be very useful in distribution networks, for transmitting measured values of PQ parameters from remote measurement stations to main base station. A diagram of communication principle (application software and WSN modules on transmitter and receiver points) is presented in Fig. 6. Virtual USB port is established between LabVIEW software and ARM microcontroller. WSN node includes FTDI chip, which creates virtual port. LabVIEW VISA drivers are used for establishing communication between the computer and WSN nodes. Virtual USB port communicates using data frames of 10 bits. One start bit, one stop bit and data field of 8 bits. Due to this limitation in data transfer, floating point numbers are converted to the single byte arrays.

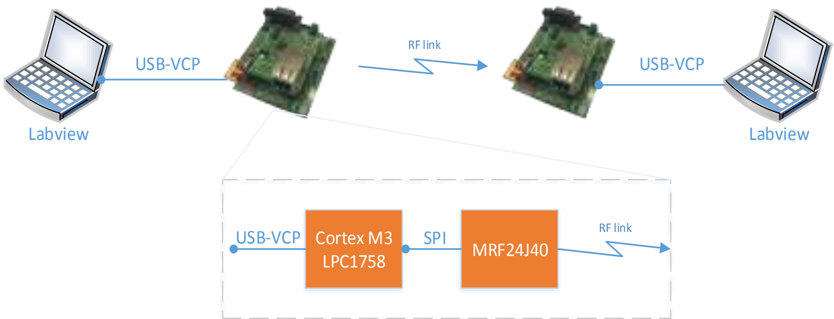

Fig. 6 Block diagram of WSN network communication
(LabVIEW software and WSN modules – transmitter and receiver)

Block diagram (executive software code) of LabVIEW application segment, which provides USB communication between computer and WSN modules, is shown in Fig. 7. Standard quality parameters can be obtained by sampling the three phase voltages and currents, in this specific case using 16-bit A/D converters, with the sampling rate of 1 kHz (maximum rate of 100 kHz). In each inner program loop with duration of one second, 5 periods of 50 Hz sinusoidal waveform are captured. Therefore, we obtained 20 samples per period or 100 samples per one second for each measured value of signal parameters. In ideal case, according to Shannon’s sampling theorem, with sampling rate of 1 kHz for fundamental signal frequency of 50 Hz we can calculate up to 10 higher signal harmonics. But in real case, measured signals are not band-limited and are not infinite in time, so the sampling theorem can only be used to give limits. This important limitation causes certain errors regarding to measured values of 10^{th} high-order signal harmonic component.

Using 100 samples of signal per second, following PQ parameters are calculated: Root Mean Square (RMS), Total Harmonic Distortion (THD), signal frequency value and values of higher harmonic components, from 2^{nd} to 10^{th} high-order harmonics. Therefore, we obtained 12 parameters per measured voltage and current reference waveforms.

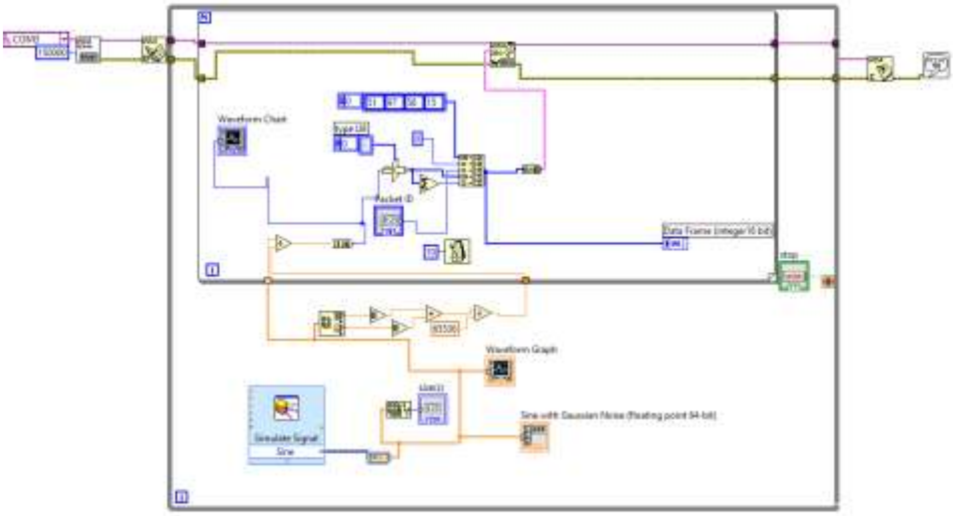

Fig. 7 Software code of LabVIEW application segment for
USB communication between computer and WSN modules

Using the WSN nodes, for USB serial communication we constructed data packets (frames) with additional fields for secure communication (3 bytes for synchronization header, 1 byte for number of bytes information, 2 bytes for frame identification, 2 bytes of payload and 1 byte for error coding - checksum). Therefore, we needed frame size of 9 bytes for each measured signal parameter, for transmitting the 16-bit integer parameter values, as is shown in Fig. 8, where corresponding data frame format is presented.

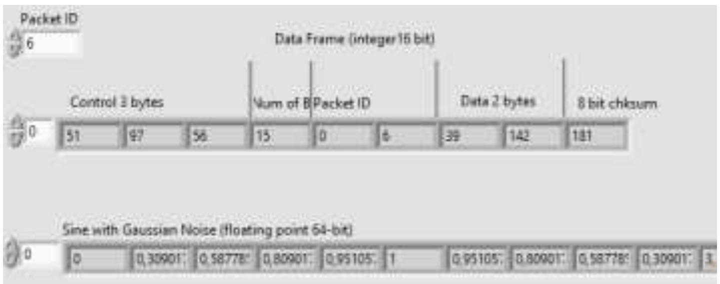

Fig. 8 Front panel in LabVIEW environment – USB communication
with corresponding data frame format

There are two possible solutions for WSN transmission. In the first case are transmitted only measured values of signal parameters, while the second possible solution is that only signal samples are transmitted. In the first case the measured values of 12 parameters for each acquired signal are transmitted from PC measurement station, supported by LabVIEW software. Considering that quality parameters are measured using 16-bit A/D conversion, it was reasonable to transmit parameters in the 16-bit integer format (two bytes). However, in order to avoid additional numerical calculation errors, signal parameters are calculated using floating point arithmetic. ZigBee communication demands Zigbee frame format for data transmission according to the standard IEEE 802.15.4. Total number of measured quality parameters, for three phase voltage and current waveforms, in this case is:

$$number\_of\_parameters = 12 \cdot 6 = 72 \tag{1}$$

Therefore, for transmission of measured signal quality parameters in floating point data format the required transmission data rate is:

$$R = Frame\_size \cdot Frame\_rate = (15 \text{ bytes}) \cdot (72/\text{s}) = 1080 \text{ bytes/s} = 1{,}08 \text{ kbytes/s} \tag{2}$$

For transmission of measured quality parameters in integer data format the required transmission data rate is:

$$R = Frame\_size \cdot Frame\_rate = (9 \text{ bytes}) \cdot (72/\text{s}) = 648 \text{ bytes/s} = 0{,}648 \text{ kbytes/s} \tag{3}$$

Theoretical data transmission rate using the Zigbee communication standard is limited to 250 kbits/s = 31,25 kbytes/s. In this application are provided maximum transmission rate (channel capacity *C*) of 150 kbits/s = 150/8 kbytes/s = 18,75 kbytes/s, in laboratory environment with obstacles and short ranges of few meters. Generally, channel capacity depends on the environment, signal to noise ratio (SNR) and distance. Therefore, for selected sample frequency value of 1 kHz, there is quite a large reserve in data rate for two possible scenarios, sending floating point parameters and integer format parameters.

By increasing sampling frequency value to 3 kHz, we can measure a total number of 30 higher signal harmonics. In this case, the number of signal parameters per second is increased to 3+29 = 32. For three phase voltages and three phase currents, the total number of signal quality parameters for transferring obtained in this case will be:

$$number\_of\_parameters = 32 \cdot 6 = 192 \tag{4}$$

Corresponding data rate required for transmission of measured signal parameters in integer data frame format for this case is:

$$R = Frame\_size \cdot Frame\_rate = (9 \text{ bytes}) \cdot (192/\text{s}) = 1728 \text{ bytes/s} = 1{,}728 \text{ kbytes/s} \tag{5}$$

This data rate required for transmission of signal quality parameters is also very low compared to previously calculated maximum channel capacity *C* of 18,75 kbytes/s.

In the second scenario, instead of the measured signal quality parameters, values of signal samples are transferred as useful data. In the case with sampling frequency of 1 kHz we have 20 signal samples per one period. By capturing 5 periods in each one second loop, we obtained 100 integer 16-bit data values (2 bytes) for each signal. For three phase voltages and currents, we must transmit the following total number of parameters per second:

$$number\_of\_parameters = 100 \cdot \cdot 6 = 600 \tag{6}$$

Frame size is 2 bytes for data field and 7 bytes for overhead, so total frame size is 9 bytes. Consequently, the required data rate for samples transmission in this case is:

$$R = Frame\_size \cdot Frame\_rate = (9 \text{ bytes}) \cdot (600/\text{s}) = 5400 \text{ bytes/s} = 5{,}4 \text{ kbytes/s} \tag{7}$$

The required data transmission rate in this case is also very far from the previously calculated maximum channel capacity value of 18,75 kbytes/s. For increasing sampling frequency value to 3 kHz (enabling calculation up to 30 high-order signal harmonics), the required transmission data rate will be $3 \cdot 5{,}4$ kbytes/s = 16,2 kbytes/s, which is very close to the channel capacity limit. In this case, the implementation of some lossless compression techniques is required. Simple lossless compression technique for PQ parameters data is making difference of two successive parameters. In this way, RF power consumption is achieved. If difference exceeds some threshold value (for example one percentage), new parameter is not sent. In this way, significant reduction of power consumption for RF transmission can be achieved. More sophisticated lossless compression techniques also can be applied, for example differential predictive coding modulation (DPCM), followed by the lossless entropy coding (Huffman coding, Lempel-Ziv coding or other methods).

The further research will be focused on possibilities to implement the presented solution in wider multi-point distributed system for PQ measurement and monitoring, including a number of remote measurement stations in specific network locations and central base station. Remote measurement stations, equipped with sensor nodes for wireless data transmission, need to provide recordings of voltage and current signals, measurement and processing of basic PQ parameters, defined according to the relevant international quality standards.

5. Conclusion

Possibilities of using wireless sensor networks (WSN) in measurement and monitoring of electrical power quality (PQ) parameters and network disturbances are presented in this paper. For this purpose is developed an experimental system for measurement of standard quality parameters and testing of WSN communication for transferring of measurement results. The procedure includes software supported generator of reference signals, LabVIEW software application for measurement of standard PQ parameters and two WSN modules for transmitting and receiving of measurement results. Sensor WSN modules are based on microcontroller with Cortex M3 architecture. For transferring of PQ measurement results from transmitter to receiver WSN module is used communication standard IEEE 802.15.4 (Zigbee standard). In this paper are analyzed two possible cases for data transferring. In the first scenario are transmitted only measured signal parameters, while in the second case are transmitted signal samples. In both scenarios the required system performances for the signal sampling frequency values of 1 kHz and 3 kHz are evaluated. The experimental results and analysis show that in both possible cases the required channel capacity for measurement data transmission is significantly lower compared to the maximum channel capacity value.

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