Real-Time Virtual Instrument for Polyphase Nonlinear Loads Analysis

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Abstract— **In this paper we will present a new approach to power factor and distortion analysis in polyphase systems. The solution is based on Xilinx Virtex II field programming gate array (FPGA), National Instruments NI9225 and NI9227 acquisition modules and PXI controller running real-time operating system (RTOS). It brings all advantages of virtual instrumentation, preserving reliability and real-time capabilities of traditional, standalone instrument. Virtual instrument is implemented using LabVIEW software platform. It is capable for measuring and calculating various electrical, power, and power quality parameters. The application is highly flexible; it can be also implemented using industrial PC or programmable automation controller (PAC).**

Keywords-power factor, real-time, total harmonic distortion, virtual instrument

I. INTRODUCTION

Power quality analysis of electrical loads is related to measurement of power factor and total harmonic distortion. In linear circuits, consisting of linear loads, the currents and voltages are sinusoidal and the power factor effect arises only from the difference in phase between the current and voltage. In single phase system it is referred to as the displacement power factor or $\cos(\varphi)$ [1]. The power concepts developed for single-phase circuits with sinusoidal voltages and currents can be extended to polyphase circuits. Such circuits can be considered to be divided into a group of two-wire sets, with the neutral conductor (or a resistively derived neutral for the case of a delta-connected, three wire circuit) paired with each other conductor [2].

When nonlinear loads are present one should introduce new quantities in the calculations emanated by the harmonics and related power components [3]. Now the power factor can be generalized to a total or true power factor where the apparent power, involved in its calculations, includes all harmonic components. This is of importance in characterization and design of practical power systems which contain non-linear loads such as switched-mode power supplies [4].

Electronic loads are strongly related to the power quality thanks to the implementation of switched-mode power supplies that in general draw current from the grid in bursts. In that way, while keeping the voltage waveform almost unattached, they impregnate pulses into the current so chopping it into seemingly arbitrary waveform and, consequently, producing harmonic distortions [5]. The current-voltage relationship of these loads, looking from the grid side, is nonlinear, hence nonlinear loads. The existence of harmonics gives rise to interference with other devices being powered from the same source and, having in mind the enormous rise of the number of such loads, the problem becomes serious with serious, sometimes damaging, consequences and has to be dealt with properly.

Power factor and distortion measuring usually requires dedicated and expensive equipment. As an alternative to traditional instruments, a PC-based virtual instrument for one phase power factor and distortion analysis with National Instruments data acquisition module was developed [6]. Based on that experience, in this paper we will present a new approach to power factor and distortion analysis in polyphase systems. The solution is based on Xilinx Virtex II field programming gate array (FPGA), National Instruments NI9225 and NI9227 acquisition modules and PXI controller running real-time operating system (RTOS). It brings all advantages of virtual instrumentation, preserving reliability and real-time capabilities of traditional, standalone instrument. Virtual instrument is implemented using LabVIEW software platform. It is capable for measuring and calculating various electrical, power and power quality parameters in real time. The application is highly flexible; it can be also implemented using industrial PC or programmable automation controller (PAC).

In the next we will first introduce the basic definitions that are expressing how the measured quantities are calculated from the current and voltage waveforms according to IEEE Std 1459-2000 [7] and IEEE Std. 1459-2010 [8] standards. Then, the system architecture will be described. We will introduce implementations of all subsystems and explain their roles in acquisition, data processing, and presentation. Finally, we will highlight some potentials of the given concept.

II. THE DEFINITIONS OF THE FUNDAMENTAL QUANTITIES

A. Sinusoidal Voltage and Current in Single-Phase Circuits

Sinusoidal voltage source

$$v(t) = \sqrt{2}V_{\text{RMS}}\sin(\omega t) \tag{1}$$

supplying a linear load, will produce a sinusoidal current of

$$i(t) = \sqrt{2}I_{\text{RMS}}\sin(\omega t - \varphi) \tag{2}$$

where V_{RMS} is the RMS value of the voltage, I_{RMS} is the rms value of the current, ω is the angular frequency, φ is the phase angle and t is the time. The instantaneous power is

$$p(t) = v(t) \cdot i(t) \qquad (3)$$

and it can be represented as

$$p(t) = 2V_{\text{RMS}} I_{\text{RMS}} \sin \omega t \cdot \sin(\omega t - \varphi) = p_p + p_q. \qquad (4)$$

Using transformations we can write:

$$p_p = V_{\text{RMS}} \cdot I_{\text{RMS}} \cdot \cos \varphi \cdot (1 - \cos(2\omega t)) = P \cdot (1 - \cos(2\omega t)) \qquad (5)$$

and

$$p_q = -V_{\text{RMS}} \cdot I_{\text{RMS}} \cdot \sin \varphi \cdot \sin(2\omega t) = -Q \cdot \sin(2\omega t) \qquad (6)$$

where

$$P = V_{\text{RMS}} \cdot I_{\text{RMS}} \cdot \cos \varphi, \ Q = V_{\text{RMS}} \cdot I_{\text{RMS}} \cdot \sin \varphi \qquad (7)$$

represent real (P) and reactive (Q) power.

It can be easily shown that the real power presents the average of the instantaneous power over a cycle:

$$P = \frac{1}{T} \int_{t_0}^{t_0+T} v(t) \cdot i(t) \cdot dt \qquad (8)$$

where t_0 is arbitrary time (constant) after equilibrium, and T is the period (20ms in European and 1/60s in American system, respectively).

The reactive power Q is the amplitude of the oscillating instantaneous power p_q. The apparent power is the product of the root mean square value of current times the root mean square value of voltage:

$$S = V_{\text{RMS}} I_{\text{RMS}} \qquad (9)$$

or:

$$S = \sqrt{P^2 + Q^2}. \qquad (10)$$

Power factor is simply defined as the ratio of real power to apparent power:

$$PF = P/S. \qquad (11)$$

For pure sinusoidal case, using equations (7), (10) and (11) we can calculate:

$$PF = \cos \varphi. \qquad (12)$$

B. Sinusoidal Voltage and Current in Polyphase Circuits

The power concepts developed for single-phase circuits with sinusoidal voltages and currents can be extended to polyphase circuits. Equations (7) can be rewritten to define power terms equivalent to the single-phase terms. In these equations, n represents a phase number, N is the total number of phases, and φ_n phase difference:

$$P = \sum_{n=1}^{N} I_{n,\text{RMS}} V_{n,\text{RMS}} \cos \varphi_n, \ Q = \sum_{n=1}^{N} I_{n,\text{RMS}} V_{n,\text{RMS}} \sin \varphi_n \qquad (13)$$

The apparent power is defined by equation (10).

Power factor is defined by equation (11). Note that the power factor is not always equal to the cosine of the phase angle. In many three-phase balanced systems, the phase angles of all three phases are equal and the cosine relationship holds. In unbalanced systems, each phase has a different phase angle, the phase voltages and currents are not equal, and the cosine relationship is no longer valid.

C. Nonlinear Loads in Single-Phase Circuits

In the presence of nonlinear loads the system no longer operates in sinusoidal condition and use of fundamental frequency analysis does not apply any more. Traditional power system quantities such as effective value, power (active, reactive, apparent), and power factor need to be numerically calculated from sampled voltage and current sequences by performing DFT or FFT algorithm.

The RMS value of some periodic physical entity X (voltage or current) is calculated according to the well-known formula:

$$X_{\text{RMS}} = \sqrt{\frac{1}{T} \int_{t_0}^{t_0+T} (x(t))^2 \, dt} \qquad (14)$$

where $x(t)$ represents time evolution, T is the period and t_0 is arbitrary time. For any periodic physical entity $x(t)$, we can give Fourier representation:

$$x(t) = a_0 + \sum_{k=1}^{+\infty} (a_k \cdot \cos(k\omega t) + b_k \cdot \sin(k\omega t)) \qquad (15)$$

or

$$x(t) = c_0 + \sum_{k=1}^{+\infty} c_k \cdot \cos(k\omega t + \psi_k) \qquad (16)$$

where $c_0 = a_0$ represents DC component, $c_k = \sqrt{a_k^2 + b_k^2}$ magnitude of kth harmonic, $\psi_k = \arctan \frac{b_k}{a_k}$ phase of kth harmonic and $\omega = \frac{2\pi}{T}$, angular frequency.

Fourier coefficients a_k, b_k are:

$$a_0 = \frac{1}{T} \int_{-T/2}^{+T/2} x(t)dt, \quad a_k = \frac{2}{T} \int_{-T/2}^{+T/2} x(t) \cdot \cos\left(\frac{2k\pi t}{T}\right) dt \qquad (17)$$

and

$$b_k = \frac{2}{T} \int_{-T/2}^{+T/2} x(t) \cdot \sin\left(\frac{2k\pi t}{T}\right) dt. \qquad (18)$$

The RMS value of kth harmonic is

$$X_{k,\text{RMS}} = c_k / \sqrt{2}. \qquad (19)$$

We can calculate total RMS value

$$X_{\text{RMS}} = \sqrt{\sum_{k=1}^{M} X_{k,\text{RMS}}^2} = \sqrt{X_{1,\text{RMS}}^2 + X_{\text{H,RMS}}^2} \qquad (20)$$

where M is highest order harmonic taken into calculation. Index "1" denotes first or fundamental harmonic, and index "H" denotes contributions of higher harmonics.

Equations (14) – (20) need to be rewritten for voltage and current. Practically, we operate with sampled values and integrals (17) and (18) are transformed into finite sums.

For a single-phase system where k is the harmonic number, φ_k phase difference between voltage and current of kth harmonic and M is the highest harmonic, the total active power is given by:

$$P = \sum_{k=1}^{M} I_{k,\text{RMS}} \cdot V_{k,\text{RMS}} \cdot \cos\varphi_k = P_1 + P_{\text{H}}. \tag{21}$$

The first addend in the sum (21), denoted with P_1, is fundamental active power. The rest of the sum, denoted with P_{H}, is harmonic active power.

Total reactive power is given by:

$$Q = \sum_{k=1}^{M} I_{k,\text{RMS}} \cdot V_{k,\text{RMS}} \cdot \sin\varphi_k = Q_1 + Q_H. \tag{22}$$

It should be noted that the actual contribution of harmonic frequencies to active and reactive power is small (usually less than 3% of the total active or reactive power). The major contribution of higher harmonic to the power comes as distortion power D:

$$D^2 = \sum_{\substack{j \neq k \\ j=1, k=1}}^{M} I^2_{j,\text{RMS}} \cdot V^2_{k,\text{RMS}} \tag{23}$$

The apparent power is given by formula (9) and it can be written:

$$S^2 = \underbrace{I^2_{1,\text{RMS}} \cdot V^2_{1,\text{RMS}}}_{S_1^2} + \underbrace{I^2_{1,\text{RMS}} \cdot V^2_{\text{H,RMS}}}_{D_V^2} + \\ + \underbrace{V^2_{1,\text{RMS}} \cdot I^2_{\text{H,RMS}}}_{D_I^2} + \underbrace{V^2_{\text{H,RMS}} \cdot I^2_{\text{H,RMS}}}_{S_{\text{H}}^2} \tag{24}$$

where S_1 represents fundamental apparent power, D_V voltage distortion power, D_I current distortion power and S_{H} harmonic apparent power. S_1 and S_{H} are

$$S_1 = \sqrt{P_1^2 + Q_1^2}, \ S_{\text{H}} = \sqrt{P_{\text{H}}^2 + Q_{\text{H}}^2 + D_{\text{H}}^2} \tag{25}$$

where D_{H} represents harmonic distortion power. The total apparent power is

$$S = \sqrt{P^2 + Q^2 + D^2}. \tag{26}$$

It is obvious that for sinusoidal voltages and currents, (26) reduces to (10).

The total harmonic distortions, THD, are calculated from the following formula:

$$THD_I = \frac{I_{\text{H,RMS}}}{I_{1,\text{RMS}}} = \frac{1}{I_{1,\text{RMS}}} \sqrt{\sum_{j=2}^{M} I^2_{j,\text{RMS}}} = \sqrt{\frac{I^2_{\text{RMS}} - I^2_{1,\text{RMS}}}{I^2_{1,\text{RMS}}}}$$
$$\tag{27}$$

and

$$THD_V = \frac{V_{\text{H,RMS}}}{V_{1,\text{RMS}}} = \frac{1}{V_{1,\text{RMS}}} \sqrt{\sum_{k=2}^{M} V^2_{k,\text{RMS}}} = \sqrt{\frac{V^2_{\text{RMS}} - V^2_{1,\text{RMS}}}{V^2_{1,\text{RMS}}}} \tag{28}$$

where $I_j, V_k \ j, k=1, 2, \ldots, M$ stands for the harmonic of the current or voltage. It can be shown that:

$$D_I = V_{1,\text{RMS}} \cdot I_{\text{H,RMS}} = S_1 \cdot THD_I$$
$$D_V = V_{\text{H,RMS}} \cdot I_{1,\text{RMS}} = S_1 \cdot THD_V \tag{29}$$
$$S_H = S_1 \cdot THD_I \cdot THD_V.$$

Fundamental power factor or displacement power factor is given by the following formula:

$$PF_1 = \frac{P_1}{S_1} = \cos\varphi_1. \tag{30}$$

Total power factor DPF, defined by equation (11), taking into calculation (21) and (24), is

$$TPF = \frac{P}{S} = \frac{P_1 + P_{\text{H}}}{\sqrt{S_1^2 + D_I^2 + D_V^2 + S_{\text{H}}^2}} \tag{31}$$

and substituting (29) and (30):

$$TPF = \frac{\left(1 + \dfrac{P_{\text{H}}}{P_1}\right)\cos\varphi_1}{\sqrt{1 + THD_I^2 + THD_V^2 + \left(THD_I THD_V\right)^2}} \tag{32}$$

In real circuits, $P_{\text{H}} \ll P_1$ and voltage is almost sinusoidal ($THD_V < 5\%$), leading to simpler equation for TPF:

$$TPF = \frac{\cos\varphi_1}{\sqrt{1 + THD_I^2}}. \tag{33}$$

D. Nonlinear Loads in Polyphase Circuits

For polyphase systems, active, reactive and distortion powers are defined for each phase and total powers are sum of all phase powers:

$$P = \sum_{n=1}^{N} \sum_{k=1}^{M} I_{n,k,\text{RMS}} \cdot V_{n,k,\text{RMS}} \cdot \cos\varphi_k$$
$$Q = \sum_{n=1}^{N} \sum_{k=1}^{M} I_{n,k,\text{RMS}} \cdot V_{n,k,\text{RMS}} \cdot \sin\varphi_k \tag{34}$$
$$D^2 = \sum_{n=1}^{N} \sum_{\substack{j \neq k \\ j=1, k=1}}^{M} I^2_{n,j,\text{RMS}} \cdot V^2_{n,k,\text{RMS}}.$$

Voltages $V_{n,k,\text{RMS}}$ are phase-to-neutral voltages. Indexes n and k denotes phase number and harmonic order, respectively. N is number of phases and M is number of harmonics taken into calculation.

The apparent power can be defined as sum of apparent powers per phase – arithmetic apparent power (S_A) or as vector apparent power (S):

$$S_A = \sum_{n=1}^{N} V_{n,\text{RMS}} \cdot I_{n,\text{RMS}}$$
$$S = \sqrt{P^2 + Q^2 + D^2} \tag{35}$$

Note that $V_{n,\text{RMS}}$ and $I_{n,\text{RMS}}$ are total RMS values per phase, and n is a phase index.

S_A uses arithmetic addition of vector magnitudes and is equal to apparent power S only if the polyphase voltages and currents have equal magnitudes and equal phase difference; a situation that often exists in balanced three-phase systems. The

two alternative definitions of apparent power, *S* and S_A, give rise to two possible values for power factor, calculated using equation (11).

III. SYSTEM IMPLEMENTATION

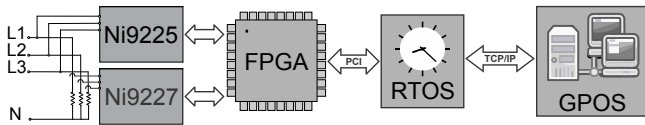The system structure is shown in Fig. 1.

Figure 1. The system structure

The system consists of four components:

- Acquisition subsystem;
- FPGA;
- PC or controller running real-time operating system (RTOS);
- PC running general purpose operating system (GPOS).

A. Acquisition and Conditioning

The acquisition and conditioning of the electrical quantities mentioned in previous section is performed by the acquisition subsystem. It is connected to the power grid from one side, and transfers the power to the load while sampling the values of three voltage and four current signals (Fig. 2). The modules for signal conditioning of the voltage and current waveforms provide attenuation, isolation and anti-aliasing. The sampled values are appropriately conditioned, and then directly delivered to the FPGA.
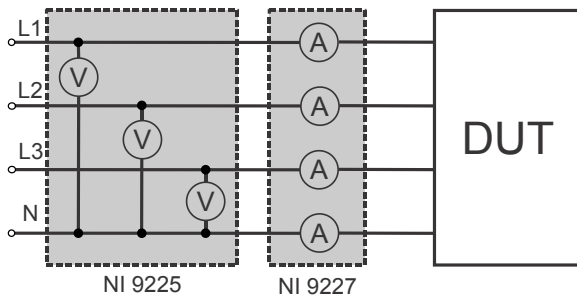

Figure 2. Connection diagram

The acquisition subsystem is based on National Instruments cRIO-9151 expansion chassis, providing hot-plug module connectivity [9]. The chassis is equipped with two data acquisition modules: NI9225 and NI9227.

NI9225 has three channels of simultaneously sampled voltage inputs with 24-bit accuracy, 50 kSa/s per channel sampling rate and 600 VRMS channel-to-earth isolation, suitable for voltage measurements up to 100th harmonic (5 kHz). The 300 VRMS range enables line-to-neutral measurements of 240 V power grids [10].

NI9227 is four channels input module with 24-bit ac-curacy, 50 kSa/s per channel sampling rate, designed to measure 5 ARMS nominal and up to 14 A peak on each channel with 250 VRMS channel-to-channel isolation [11].

B. Data Processing

The FPGA provides timing, triggering control, and channel synchronization maintaining high-speed, hardware reliability, and strict determinism.

In this application, Xilinx Virtex II FPGA is used. The FPGA is placed on National Instruments PXI-7813R card embedded into NI-8014 PXI controller. The interface connecting controller and FPGA is PCI.

The FPGA code is implemented in a LabVIEW development environment. The function of the FPGA circuit is acquisition control.
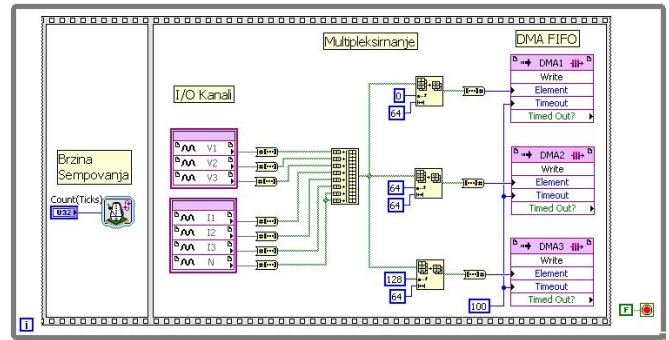

Figure 3. FPGA code implemented in LabVIEW

Calculated data are transferred to the next processing level, the real time subsystem, over tree DMA FIFO channels.

The real time subsystem is PXI controller or PC running PharLap real time operating system and real time multithread application which represents the second data processing stage.
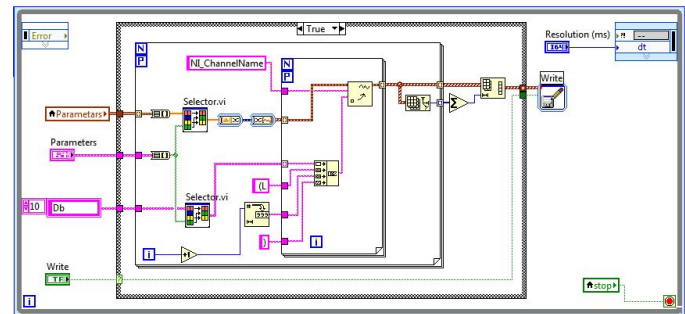

Figure 4. A part of the real-time application

The application implemented using LabVIEW developing package consists of three threads, exploiting contemporary multicore capabilities. First thread receives data from FPGA level. Second thread calculates power quantities: apparent power, active power, reactive power and energy; power quality parameters including total harmonic distortion (THD_I, THD_V), crest factors, total power factor and displacement power factor. Third thread handles TCP/IP communication with user interface.

The application is capable of logging measured values and calculated parameters and events locally on a hard disk drive (Fig. 4). All measured and calculated parameters, transient analysis, as well as triggered events are stored on hard disk or other type of data storage. The data quantity and therefore the

measurement time, depends on the storage capacity. A separate thread is responsible for network communication with the user PC.

C. User Interface

The user interface virtual instrument is implemented in National Instruments LabVIEW developing package, which provides for simple creation of virtual instruments [12], [13]. The virtual instrument is an application running on general purpose operating system (GPOS) such as Microsoft Windows, Linux or MacOS, connected with RTOS over the network. It consists of an interface to real-time application and a graphic user interface. The communication between the user interface and the real-time application is implemented using TCP/IP protocol.
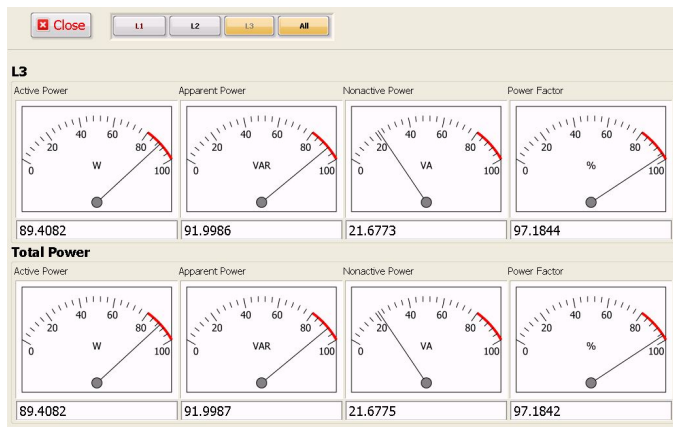

Figure 5. Virtual instrument graphic interface displaying active, apparent and non-active power ($N = \sqrt{S^2 - P^2}$), as well as power factor for L3 phase and all phases

The user interface of the virtual instrument consists of visual indicators. It provides basic functions for measurement. The indicators – gauges and graphs – show measured values. User interface also provides controls for data manipulation and saving the measured values (Fig. 5).

Figure 6. Virtual instrument shows voltage and current spectra for L1 phase

The virtual instrument shows waveforms and spectra of measured voltages and currents (Fig. 6 and 7). Measured electrical quantities such as RMS and DC values, as well as

calculated power quantities are shown in the front panel using virtual gauges and numeric indicators. Power factor and other power quality parameters are shown numerically. The virtual instrument can operate in one phase or three phase mode.
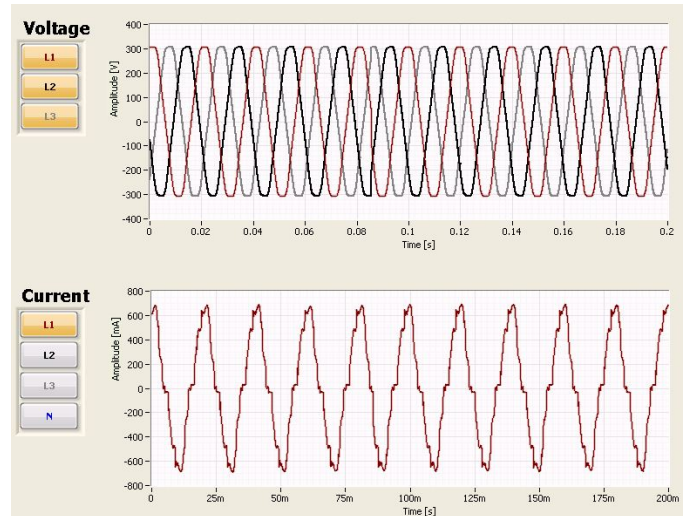

Fig. 7. Voltage waveforms for all phases, current waveform of L1

Harmonic magnitudes are shown in a table and each magnitude can be represented separately.

Industrial PCs and PXI controllers have multicore architectures with sufficient processor power and operating memory capacity to support hardware virtualization. The operating system which hosts the user interface can be executed concurrently with RTOS in a real-time hypervisor [14].

IV. CONCLUSION

A new approach to power factor and distortion analysis in polyphase systems was presented. It aggregates the advantages of virtual instrumentation and the real-time response of classical instruments, capable for real-time sampling and measuring voltage and current of the device under test, providing possibility for transient analysis in time and frequency domain. FPGA and RTOS are taking the main role in data processing of all kind. In this way we introduced a flexible and versatile system with practically unlimited possibilities. The network PC has the control and user interface function.

The system elaborated in this paper is implemented as laboratory instrument using PXI-8105 controller running PharLap OS, equipped with PXI-7813R Virtex-II 3M gate FPGA programmable card and cRIO-9151 expansion chassis. Alternatively, it can be realized using programmable automation controllers (PAC) such National Instruments CompactRIO series. The small-sized CompactRIO system includes acquisition modules, FPGA chassis and a real-time controller running VXWorks RTOS. It is suitable for long time executions and hard-ware-in-the-loop tests.

The presented application is capable for three-phase operation. However, the system is exceedingly scalable – it can

be easily extended by adding additional acquisition modules into the expansion chassis.

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