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CompactRIO Embedded System in Power Quality Analysis

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***Abstract*—Electrical measurement department of VSB-Technical University has been involved for more than 14 years in research and development of Power Quality Analyzer built on Virtual Instrumentation Technology. PC-based power quality analyzer with National Instruments data acquisition board was designed and developed in this time frame. National Instruments LabVIEW is used as the development environment for all parts of power quality analyzer software running under MS Windows OS. Proved PC-based firmware was ported to new hardware platform for virtual instrumentation – National Instruments CompactRIO at the end of 2007. Platform change from PC to CompactRIO is not just code recompilation, but it brings up many needs for specific software redesigns. Paper describes how the monolithic executable for PC-based instruments was divided into three software layers to be ported on CompactRIO platform. The code for different parts of CompactRIO instrument is developed in a unified development environment no matter if the code is intended for FPGA, real-time processor or PC running Windows OS.**

***Keywords*—CompactRIO, FPGA, VxWorks, LabVIEW, Power Quality**

I. Introduction

THE MEMBERS of the Electrical Measurements Department have been involved into the research and development in the area of electrical power quality for more than fourteen years. During this period the PC-based power quality analyzer has been developed.

The basis of the solution is the software application designed and developed in the graphical development environment LabVIEW and running on a PC. The core of the application is the data acquisition process with adaptive sampling frequency. The sampling frequency and the length of the time window are chosen to follow the requirements of elemental standards for power quality area: IEC 61000-4-30 and IEC 61000-4-7. The software provides so called „gap free“ measurement by continuous data acquisition. The algorithm in conjunction with the 16-bit plug-in data acquisition board allows change of the sampling frequency on the fly. This eliminates measurement errors in frequency domain caused by the leakage that normally appears when the frequency of the measured signal is changing during the measurement period.

Under this data acquisition core the software modules provide particular instrument functionality from the user point of view, such as FFT analyzer, power and energy analyzer, voltage quality analyzer etc. The power quality analyzer allows analyzing up to 4 voltages and 4 currents.

The concept of PC-based instrumentation has been used by measurement instrument manufacturers for long time period; it has many advantages, but it is difficult to design such instruments with small size and low power consumption. A new possibility in this area is brought by the CompactRIO hardware platform described in this paper.

The goal of this paper is the description of software and instrument firmware developed by the authors for this particular problem.

II. Virtual instrumentation

The instrumentation has often evolved into computer-based measurement systems. These systems are built with

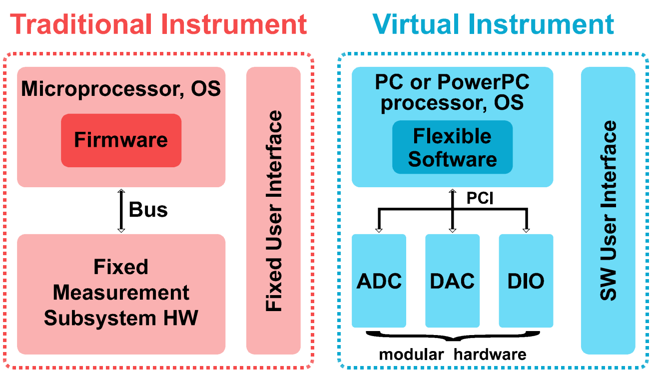


Fig. 1. Traditional instruments (left) and software based virtual instruments (right) share the same architectural components, but radically different philosophies

measurement hardware consisting of a digitizing element whose performance is characterized by its resolution and sample rate. The performance of this hardware, including bandwidth, accuracy and resolution, has increased dramatically in the past 10 years to the extent that the performance of the computer-based digitizers is comparable to traditional instruments. Virtual instruments are defined by the user while traditional instruments have fixed manufacturer-defined functionality, see Fig.1

III. PC based Power Quality Analyzer

The basic components of PC based power quality analyzer are common, no matter whether it is a desktop PC, stationary instrument or hand-held instrument.

The PC is equipped with the plug-in data acquisition board from National Instruments. Currently the M-series PCI and USB boards are supported. M-series boards provide 16 analogue inputs and the aggregated sampling rate is at least 250 kS/s. The data acquisition process of instrument SW uses sampling frequency 9.6 kS/s per channel.

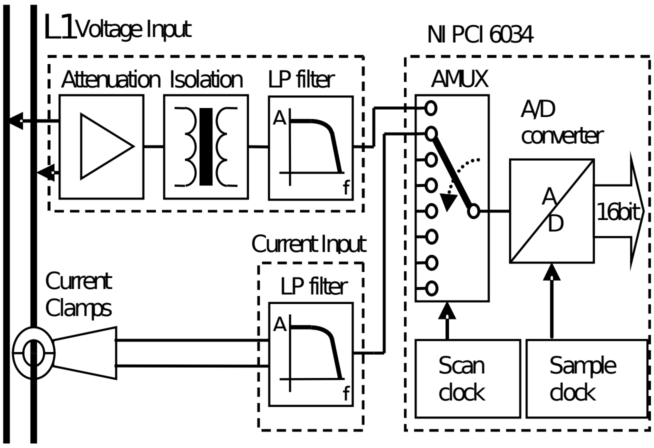


Fig. 2. Power Quality Analyzer input circuit diagram.

Modules for signal conditioning of voltage and current signals provide attenuation / amplification, isolation and anti-aliasing filtering. Modules for signal conditioning are programmable via digital lines or serial interface. This allows inputs range selection and anti-aliasing cut-off frequency set-up. The block diagram of signal conditioning modules connected to analog to digital converter is shown on Fig. 2.

The operating system used for the PC based instrument is Windows XP or Windows XP Embedded. Power quality analyzer firmware fully written in LabVIEW is running in the operating system as EXE application. In case if instrument is equipped with a touch-in display, the user can operate the instrument without keyboard or mouse, because complete firmware is ready to use soft-keyboards.

IV. Signal Sampling According To IEC61000-4-30

According to IEC61000-4-30 the basic measurement time interval for voltage quality parameters (supply voltage, harmonics, interharmonics and unbalance) shall be a 10-cycle time interval for 50 Hz power system or 12-cycle time interval for 60 Hz power system. It is not a fixed interval in time, but measurement interval varies in time as the fundamental frequency of power network changes. The adaptive sampling frequency solves this requirement and avoids not wanted phenomena in frequency domain like leakage and scalloping loss.

The easiest way to achieve adaptive sampling frequency is PLL (Phase Lock Loop). Data acquisition boards are not equipped with PLL hardware and thus software version of

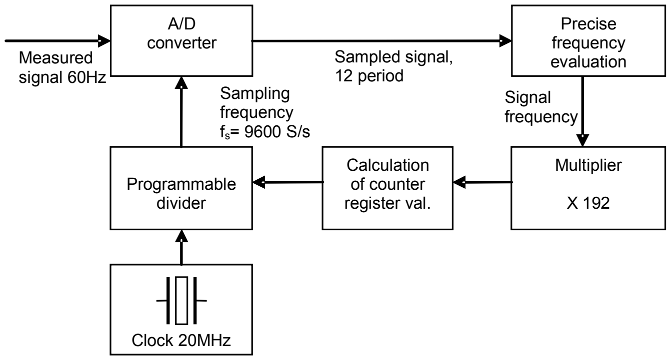


Fig. 3. Software implementation of PLL

PLL principle was developed, see Fig.3. The most important on the “software PLL” is a very precise frequency measurement algorithm from 12 periods of signal.

The method using envelope curve of the spectral lines in frequency domain was used. If rectangular window is used in time domain then the envelope curve in frequency domain is a function *sin(x)/x*. The precise frequency can be calculated from amplitudes of two nearest spectral line from signal frequency, even if the frequency is not integer multiply of the step in frequency domain.

V. Analyzed quantities and Measurement uncertainty achievment

According to IEC61000-4-30 Power Quality Analyzer should analyze and evaluate these quantities: power frequency, magnitude of the supply voltage, flicker, harmonics and interharmonics, supply voltage unbalance, rapid voltage changes and voltage dips, swells and interruptions. It is suggested that currents will be also monitored and analyzed. For any mentioned quantity the measurement uncertainty is specified. The requested uncertainty on voltage and current magnitude should be better than 0.1% for the complete instrument including sensors (e.g. current clamps).

To understand the type and magnitude of errors, FLUKE 6100A Electrical Power Standard programmable calibrator has been used. Numerous errors were discovered: frequency amplitude errors, frequency phase errors, amplitude and phase error (depending on the magnitude of signal within the measurement range). After thorough analysis of the discovered errors a solution was designed to accomplish the error compensation. Some errors can be corrected in time domain; some errors must be corrected in frequency domain. An appropriate structure of calibration tables was designed and implemented as automated calibration software.

VI. CompactRIO Hardware Description

CompactRIO does not replace PC-based instruments for virtual instrumentation, but it is collateral hardware platform with smart structure.

CompactRIO combines an embedded floating point processor (PowerPC) with real-time operating system VxWorks, a high-performance FPGA and hot-swappable I/O modules. Each I/O module is connected directly to the

FPGA, providing low-level customization of timing and I/O signal processing. The FPGA is connected to the embedded real-time processor via a high-speed PCI bus, see Fig.4. This represents architecture with open access to low-level hardware resources. Both PowerPC processor and FPGA are programmed in graphical programming language LabVIEW. LabVIEW contains built-in data transfer mechanisms to pass data from the I/O modules to the FPGA and also from the FPGA to the embedded processor for real-time analysis, postprocessing, data logging, or communication to a networked host computer.

CompactRIO in comparison with PC-based instruments brings compact solution, small size 88 x 180 x 90mm (HxWxD), wide operating temperature -40°C to +70°C and very low power consumption (approximately 8W).

VII. CompactRIO Based Quality Analyzer

After long time development and improvements of PC-based Power Quality Analyzer it was decided to port the proved PC code to CompactRIO. The original code of PC-based instrument was divided into three layers:

- FPGA (data acquisition process, SW PLL)
- real-time processor, (data analysis functions)
- host PC (user interfaces)

All three described parts were implemented in the same development environment: National Instruments LabVIEW. Very powerful part of CompactRIO is FPGA. It can solve functionality between I/O modules without interaction with real-time processor. Fixed point arithmetic library and even FFT routines for FPGA are available in LabVIEW. The code on FPGA is extremely fast in comparison with embedded processor.

It was decided to move adaptive sampling frequency algorithm directly on FPGA. All blocks on Fig.3 are implemented on FPGA. FPGA ensures sampling of 3 voltage signals and 4 current signals. Other parallel task running on FPGA is mechanism of data transfer to real-time processor, digital input acquisition and transfer, GSM modem data transfer. LabVIEW code implementation for FPGA is not fast and easy, because compilation of this part of code takes several tens of minutes. As an optional way of software PLL was developed resampling algorithm. Resampling algorithm was implemented on FPGA and provides signal samples with different sampling frequency than AD converter. This algorithm is still under testing process.

PowerPC processor runs VxWorks operating system and LabVIEW application with several parallel tasks.

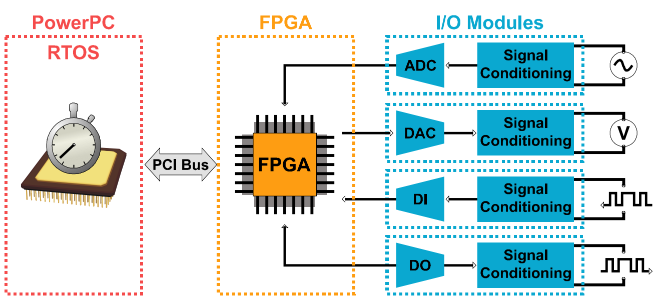


Fig. 4. Compact-RIO internal structure

Application receives data samples from FPGA and calculates from them many parameters including: RMS values, frequency, harmonic spectra, total harmonic distortion, flicker, three-phase system unbalance, active power, reactive power, energies and many other quantities. Calculated quantities are aggregated in time and some data are statistically evaluated before storing. Data are stored periodically with defined time interval and event-based data are stored just in time when event appears. Data are stored to local solid state disc. Real-time processor ensures also TCP communication with host PC. LabVIEW code implementation for PowerPC is fast because LabVIEW provide on the fly compilation of code fragments.

Host PC applications, also developed in LabVIEW, serve as graphical user interface for CompactRIO instrument. CompactRIO and host PC are connected each other by Ethernet and they use TCP protocol to communicate.

VIII. Power Quality Analyzer Software Suite

The project name of complete software suite for power quality analyzer is ENA. Directly on CompactRIO runs ENA-Node firmware. ENA-Node runs on FPGA and on PowerPC embedded in CompactRIO.

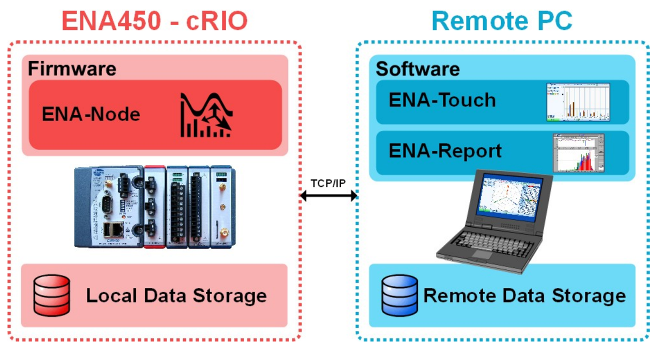


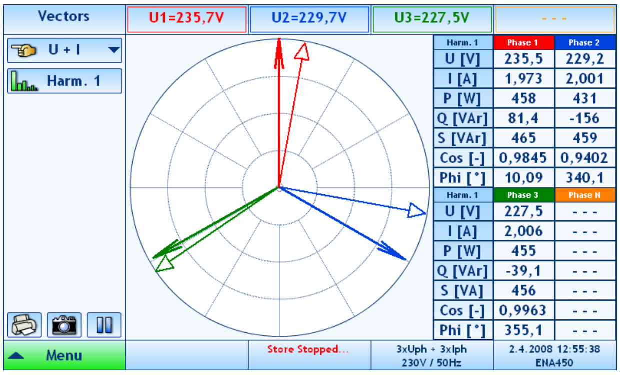
Fig. 5. ENA Power Quality Analyzer Software Suite

The user interface ENA-Touch runs on host PC connected to ENA450 and allows instrument set-up and on-line data visualization, see Fig.5.

The main concern of ENA-Touch development cycle was user friendliness, ease of operation and compliance with international standards. ENA-Touch can control ENA-Node remotely by using TCP protocol over Ethernet. New original approach to instrument set-up and to display measured quantities allows easy and well arranged configuration and measured data presentation. In ENA-Touch exist numerous ways how to present data: tables, time and frequency domain graphs, scope, vectorscope (see Fig.6) and statistical results for power quality.

IX. Conclusion

CompactRIO is a combination of powerful hardware and software running on real-time processor and FPGA in parallel. CompactRIO brings even better flexibility for virtual instrumentation than PC platform. The same graphical development environment LabVIEW used for three levels of hardware FPGA, real-time processor and PC dramatically simplifies the SW maintenance and further



Harm. 1	Phase 1	Phase 2
U [V]	235,5	229,2
I [A]	1,973	2,001
P [W]	458	431
Q [VAr]	81,4	-156
S [VAr]	465	459
Cos [-]	0,9845	0,9402
Phi [°]	10,09	340,1

Harm. 1	Phase 3	Phase N
U [V]	227,5	- - -
I [A]	2,006	- - -
P [W]	455	- - -
Q [VAr]	-39,1	- - -
S [VA]	456	- - -
Cos [-]	0,9963	- - -
Phi [°]	355,1	- - -

Fig. 6. ENA-Touch user interface example - Vectorscope

development. The development process for CompactRIO is not as fast as on PC platform, but there is no need to know VHDL language to program FPGA, no need to be deeply familiar with real-time operating system VxWorks. The main advantage of described CompactRIO-based solution is its flexibility and scalability. Big support of advanced math functions for FPGA becomes available; this will allow moving many calculation routines from real-time processor to FPGA.

Porting of PC-based instrument code to CompactRIO hardware platform was not a trivial task. There are many differences between PC and CompactRIO approaches to the same problem. Even an author with more than 12 years of experience and deep knowledge of LabVIEW needs several months to have fully functional and tested solution ready to be a product. There is a long way from simple CompactRIO demo showed on trade shows to functional and reliable complex instrument. The goal of the team was to test if CompactRIO hardware together with LabVIEW graphical development environment is a usable platform for future implementations of such complex measurement instruments like power quality analyzer is. The project confirms that a suite CompactRIO and LabVIEW is a reliable platform for virtual instrumentation of this sort.

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