Development of an Experimental Tool to Measure Power Quantities

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Abstract. The development of an experimental flexible measurement system, DSP-based, to be used in a low voltage distribution grid is presented. The metering system, a key element in the liberalized electricity market, is developed for measuring and analyzing electrical power quantities under sinusoidal, nonsinusoidal, balanced or unbalanced conditions. Various issues involved in selecting a DSP, adopting the hardware architecture and developing software for the application are discussed.

Keywords. Power measurement, power quality, digital signal processor (DSP), Component Object Module (COM) Client.

1) Introduction

Power quality and reliability of electrical energy are growing concerns in today's technical world, for both power providers and users alike. The electrical energy distribution system is subject to important changes [4] and along with these, the notion 'Power Quality' becomes a very important issue. A key reasons for the increasing importance is the rapid spread of the use of equipment sensitive to power system disturbances. especially information and communication technology equipment, the widespread use of non-linearly behaving power electronic converters and the deregulation of the electricity market. The latter makes the quality of the power a key element in the contracts with a market value.

The measurement of electrical power quantities relevant for the quality of energy supplied and development of definitions to determine the value of electricity need to be performed. These quantities can be a valuable tool in assessing Power Quality.

In order to address these problems, the new IEEE Trial-Use Standard 1459 lists a set of definitions developed to give guidance with respect to the electrical quantities to be measured and processed. To investigate the usefulness of the new IEEE Standard, the proposed definitions were implemented and applied to some case studies in real life measurements.

In this paper, the development of a tool capable of measuring power-related quantities based on power definition from IEEE Trial Std. 1459 is described. The general structure of the platform is explained alongside a more detailed discussion of the power measurement functions, hardware and software architecture and the comparison between them.

2) General structure of the system

The system consists of current and voltage sensors connected to analog/digital (A/D) converters, a Digital Signal Processor (DSP) and a PC.

The number of current and voltage modules varies, allowing the implementation of single phase as well as polyphase multi-wire power measurements. For instance, single-phase power measurements require one voltage and one current sensor while for three phases systems, 3 or 4 voltage and current sensors are needed, depending on whether or not a neutral conductor is available (figure1). An insulation barrier using optocouplers, protecting both equipment and operators from hazardous mains voltages is used.



Figure 1: System architecture of the power measurement system

After transformation, the input AC voltage and current are digitized by a 12 bits A/D converter. The digital voltage and current signals are then transmitted to a DSP, for further processing. In the DSP sampled data are transformed to the frequency domain, using an FFT-algorithm and then with this information, the power definitions discussed in [1] are calculated.

The system must be able to calculate the power accurately up to the 64^{th} harmonic. The sampling frequency was chosen to be $f_s = 6400$ Hz or 128 samples per 50 Hz cycle. Finally, the PC can control, monitor, store and perform activities and results.

In order to obtain the high performance, software plays also a key role in the design concept.

3) Experimental setups

The system must have sufficient processing power to meet the computational requirements of the real-time measurement implementation. The DSP based environment has to be easy to implement, flexible and cost-effective. In addition, it should have a good user-interface. Therefore, two laboratory setups are outlined below.

A. First setup

For development purposes, a dSPACETM DSP real-time embedded control system is used [10]. The hardware includes the DS1102 single processor board system which is based on the Texas Instruments TMS320C31 third generation floating-point Digital Signal Processor (DSP). It operates at a clock frequency of 60 MHz and is the main processing unit. The acquisition system is based on 12-bit A/D converters (TI ADS7818), consecutively read by a high-speed serial port.

A standard PC serves as host for the software development environment, consisting of MATLAB, Simulink, Real-Time Workshop, and the dSPACE tools Real-Time Interface and ControlDesk.

Simulink is a graphical interface for modeling and constructing block diagrams via drag & drop operations. The Real-Time Workshop (RTW) generates C-code from block diagrams and the Real-Time Interface (RTI) addresses the TI compiler and downloads the program to the DSP. For reasons of flexibility and computation-time some of routines, e.g. FFT algorithm, are written in C. There is no DSP overhead due to the use of Direct Memory Access (DMA) and interrupts.

As stated before, for the user interface dSPACE tool ControlDesk was selected. This software tool allows parameter changing and data recording during experiments in real-time mode.

B. Second setup

From the hardware point of view the changes are related to the digital signal processor (DSP) platform, the converters and sensors modules being the same as in the previous implementation.

A photo of a prototype of the system is shown in figure 2. This picture shows the sensor modules and the serial communication link to the DSP.

The second setup uses a 150 MHz Texas Instruments (TI) TMS320C6711 DSP based Starter Kit (DSK) providing a suitable software tool called Code Composer Studio (CCStudio).



Figure 2: Hardware setup of the prototype.

The implementation for calculating the power according to the new IEEE Trial Std. 1459, is structured in two parts. A Microsoft Visual C++ Component Object Module (COM) Client application to control and analyze data (e.g. sampling frequency, active power, reactive power, total harmonic distortion) and a DSP target application where the 'C' programming language is used (e.g. to process mathintensive algorithm in real-time as FFT). The following main components can be distinguished.

1) COM Client

To be more transparent and not to interfere with the source code of the target application every time when a change is needed, a Microsoft Visual C++ COM Client application is developed. For a three-phase system, it is possible to choose the number of conductors: three or four, depending on whether or not a neutral conductor is used (figure 3).

This information constitutes the input data for DSP target application and may be transfered between the COM Client (PC) and DSP devices without stopping the target application.

A Real-Time Data Exchange (RTDX) module is used. Similarly, the data computed by the DSP can be analyzed and visualized on the host, using this COM Client, the transfer being achieved also via RTDX.

IEEE Trial-Use Standard 1459	_ 🗆 ×		
Please select an option:			
Power Measurements for:	Ωκ[
One phase			
C Three phases	Cancel		
Three wires			
O Four wires			
Sampling frequency [Hz]: 6400			

Figure 3. Visual C++ COM Client

2) DSP target application

TI's DSP/BIOS real-time kernel included in Code Composer StudioTI, is used. The data from the A/D converters are consecutively read by a high-speed serial port (McBSP1) of the 'C6711'. As soon as a frame of 128 samples from each converter i.e. voltage and current is obtained, the program begins to process the data using the appropriate mathematical techniques: FFT and other algorithms to calculate the electrical quantities. To implement this step, the threads as Hardware and Software interrupts (HWI, SWI) performed in CCStudio DSP/BIOS module are used. For the DSP, the algorithm is entirely written in the 'C' programming language.

4) Evaluation of the power measurements

The IEEE Trial-Use Standard 1459-2000 proposes a set of definitions for electrical quantities when voltages and currents are distorted. In this section first, the theoretical background of the definition for the measurement of electric power quantities is discussed and then, to evaluate the power measurements and the accuracy of the system using the proposed method, two examples are presented.

A. Power quantities measurement

While the background of the definition can be found in [1], a brief summary is given below.

The method is to separate the main results in two components; the 50 Hz, or fundamental part and the non-50 Hz part.

This approach can be observed for the most important quantities, being normalized as indicators of power quality.

For example, the corresponding rms values squared of current and voltage are as follows:

$$U^{2} = U_{1}^{2} + U_{H}^{2}; \quad I^{2} = I_{1}^{2} + I_{H}^{2}$$
(1)

For three-phase systems, the recommended apparent power in the standard is the effective apparent power:

$$S_e = 3U_e I_e \tag{2}$$

where U_e and I_e are the equivalent voltage and current. In case of the three-wire system, the expressions of the equivalent voltage and current are

$$U_{e} = \sqrt{\frac{U_{uv}^{2} + U_{vw}^{2} + U_{wu}^{2}}{9}}$$
(3)

$$I_{e} = \sqrt{\frac{I_{u}^{2} + I_{v}^{2} + I_{w}^{2}}{3}}$$
(4)

where U_{uw} , U_{vw} , U_{vu} are the phase-to-phase voltages and I_u , I_v , I_w are the line currents, with u, v, w representing the phases. Equation (1) can be applied to the effective voltage and current as well. Substitution in (2) gives

$$S_{e}^{2} = 9V_{e}^{2}I_{e}^{2} = 9(U_{e1}^{2} + U_{eH}^{2})(I_{e1}^{2} + I_{eH}^{2})$$
(5)

$$S_{e}^{2} = S_{e1}^{2} + S_{eN}^{2}$$
(6)

$$S_{eN}^{2} = S_{eI}^{2} [THD_{eI}^{2} + THD_{eU}^{2} + (THD_{eI}THD_{eU})^{2}]$$
(7)

where S_{el} is the 50 Hz apparent power and S_{eN} , is the nonfundamental apparent power. The latter is according to [1] an evaluator of harmonic pollution delivered or absorbed by a load. THD_{el} and THD_{eU} terms in (7) are the equivalent total harmonics of the current and voltage.

$$\text{THD}_{\text{el}} = \frac{I_{\text{eH}}}{I_{\text{el}}}$$
(8)

$$THD_{eU} = \frac{U_{eH}}{U_{el}}$$
(9)

In order to illustrate the measurement of quantities (1)-(9) defined above and also other quantities, two examples are presented. The main relevant results are listed and discussed in the following section.

B. Measurement - single phase

Figure 4. shows a single-phase rectifier with a resistive/inductive load.



Figure 4. Circuit diagram single-phase system with rectifier load

The values of the rms, fundamental and total harmonic voltage and current are:

U = 212 .76 V I = 2.99 A U₁ = 212 .69 V I₁ = 2.88 A U_H = 4.45 V I_H = 0.85 A THD_U = 2.09 % THD_I = 29.05 %

Table 1 summarizes the most important quantities measured and figure 5 shows the harmonic spectrum of the current for a single-phase system with rectifier R-L-load.

Table 1 lists the basic powers: apparent, active and nonactive. The columns are divided into the combined powers, the 50 Hz (fundamental powers), and non-50 Hz components (nonfundamental powers). The last two rows give the indices: power factor and harmonic pollution factor

Table I. Results for single-phase system rectifier load

Quantity	Combined	50Hz powers (fundamental)	Non-50 Hz powers (nonfundamental)
Apparent [VA]	S = 636.15	$S_1 = 612.54$	$S_{\rm N} = 171.74$ $S_{\rm H} = 3.72$
Active [W]	P = 599.49	P ₁ = 599.07	$P_{\rm H} = 0.378$
Nonactive [VAr]	N = 212.84	Q ₁ = 167.75	$\begin{array}{c} D_{\rm I} = 177.97 \\ D_{\rm U} = 12.83 \\ D_{\rm H} = 3.70 \end{array}$
Power factor	PF = 0.92	$PF_1 = 0.96$	-
Harmonic pollution	-	-	$S_N / S_1 = 0.284$





Figure 5. Harmonic spectrum of current single-phase system rectifier load

C. Measurement - three-phases

The circuit used, is presented in figure 6. It consist of a three-phase bridge rectifier with a resistive/inductive load. Equivalent voltage, current and total harmonics of the current and voltage using (3),(4), (8) and (9) are:

$U_{e} = 23.948 V$	$I_e = 1.7669 \text{ A}$
U $_{e1} = 23.944$ V	$I_{e1} = 1.699 \text{ A}$
$U_{eH} = 0.477 V$	$I_{eH} = 0.483 \text{ A}$
THD _{eU} = 1.992 %	$THD_{eI} = 28.4 \%$

Computations lead to the results summarized in Table 2.

D. Power measurement accuracy

The accuracy of the power measurement is calculated, taking into account the performance of the voltage/current sensors and the algorithm.

As stated before, one voltage and one current sensor are required for single-phase power measurements. Sensors performances is closely related to various errors and nonlinearities of the 12-bit ADS7818P A/D converter. The effective number of bits (ENOB) of the A/D converter is 11,0 [10]. The standard deviation σ of the voltage measurement (range: \pm 650 V) is 0.19 V and of the current measurement (range: \pm 27 A) is 7.8 mA [4].

In case of single-phase systems, the results are verified using a power analyzer PM3000A, an instrument capable of quantifying many of the traditional electrical quantities that were measured or calculated.

Table II. Values three-phase three-wire rectifier load

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Quantity	Combined	50 Hz powers	Non-50 Hz powers
		(fundamental)	(nonfundamental)
		(Tundamentar)	(nonrundamentar)
Effective Apparent Power [VA]	$S_e = 126.949$	$S_{e1} = 122.087$	$S_{eN} = 34.793$
			$S_{eH} = 0.691$
Active Power [W]	P = 101.911	$P_1 = 102.150$	$P_{\rm H} = -0.239$
Nonactive Power [Var]	N = 75.697	$Q_1 = 66.863$	$D_I = 34.701$
		-	$D_{\rm U} = 2.432$
			$D_{\rm H} = 0.648$
Effective Power Factor	$PF_{e} = 0.802$	$PF_{1e} = 0.836$	
Line use	-	-	$S_{eN} / S_{e1} = 0.284$



Figure 6. Circuit diagram, three-phases, three-wire system with a rectifier load

Table 3 lists main quantities and the errors between measured and calculated values by the system architecture described above (figure 1) and the power analyzer (case – rectifier load). It has to be mentioned that the sampling frequency is not synchronized with the 50 Hz grid frequency causing the "picket-fence" errors [4] and also another source of errors being the accuracy in reading data from the power analyzer. Comparison of the calculated by the system architecture and measured by the power analyzer values yielded less that 2% error in all cases.

Table III. Accuracy of the power measurement single-phase system rectifier load

Electrical	Value measured	Value	Error
Quantities	and calculated by	measured	[%]
	the system	with power	
	architecture.	analyzer	
		-	
Voltage [V]	212.76	212.8	0.18
Current [A]	2.99	2.95	1.35
Active [W]	599.49	589.1	1.74
Apparent [VA]	636.15	627.76	1.33
Nonactive [VAr]	212.841	216.89	1.9

5) Comparison of the systems

Some features related to software environment for both platform are shown next.

A. Matlab/Simulink/ControlDesk

Advantages

- flexibility to implement the algorithm
- easy to display and simulate the results

Drawbacks

- slow environment
- high cost

Application

- teaching
- B. Code Composer Studio/Visual C++

Advantages

- very high speed
- windows debugger interface
- simple to write software code for TI DSPs
- cost effective solution

Drawbacks

• requires knowledge of C language and windows architecture

Application

• research

The hardware performances of the selected DSPs are compared in table 4.

The experimental results show that the first system is both slow and expensive, while the second setup is more suitable for measurement techniques, from both hardware and software architecture aspects.

Table IV. Performance comparison of selected DSPs

Mftr.	Type & speed (MHz)	MIPS	MFLOPS
Texas	TMS320C31-60	30	60
Instruments	TMS320F240-20	20	-
	TMS320C6711-150	1,200	900

These conclusions led to the further development and use of the second TMS320C6711 DSP platform.

6) Conclusions

The development of an experimental flexible measurement system, DSP-based, to be used in measuring and analyzing electrical power quantities under sinusoidal, nonsinusoidal, balanced or unbalanced condition is discussed. The definitions proposed in the new IEEE Standard 1459-2000 are implemented.

The experiments showed the second system proposed to be more suitable for the measurement techniques, being a cost-effective solution as well. The new development platform is capable of implementing more extended and computation time intensive algorithm. Given the power of the system, there are many application possible, as the control of an active power filter-to-handle harmonic components, representing clearly an additional advantage.

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