XIX IMEKO World Congress
Fundamental and Applied Metrology
September 6–11, 2009, Lisbon, Portugal

DSP BASED POWER ANALYZING SYSTEM FOR ONSITE MEASUREMENTS

W.M.S. Wijesinghe [1] *and Young Tae Park* [2]

[1]University of Science and Technology, Daejeon, South Korea, wije@kriss.re.kr
[2]Korea Research Institute of Standards and Science, Daejeon, South Korea, pyt@kriss.re.kr

Abstract – A three-phase power analyzing system based on digital signal processing (DSP) has been developed as a traveling standard for onsite power calibration. The design and operation is described for a sampling wattmeter capable of measuring power parameters of sinusoidal signal with frequencies of 50 to 60 Hz and measuring harmonics of nonsinusoidal signals up to 3 kHz. The system is utilized with digital-to-analog converts synchronized with each other. Software has been developed to calculate power parameters using the digital signal processing technique. The calibration system is traceable to national standard systems with an accuracy of 0.05% and allows the calibration of industrial power measurement systems.

Keywords : signal processing, power, harmonics,

1. INTRODUCTION

In the area of energy maintenance, precise power measurement is very important for reducing power losses that directly affect the economy of any country. All industries try to minimize power losses, while maintaining their power measurement traceability. Therefore, the capabilities of power testing and calibration have grown, and the demand on national metrology institutes (NMIs) to provide such services has increased. To provide such facilities to the changing needs of the industry for electrical measurements, Korea Research Institute of Standards and Science (KRISS) power laboratory is conducting a research program to accommodate power parameters such as active and reactive power, power factor and harmonics. Industrial research laboratories that require traceability to the National Standards Laboratory have the option to perform the calibration in their laboratories. In order to provide on-site calibration facilities, KRISS requires a high-precision traveling standard

The important factors of the power standards are determination of the active power, apparent power and power factor, which minimizes the reactive power and the errors of those factors should be minimized for the power standard and its precise measurement. In the past two decades, sampling methods have been employed for the measurement of ac voltage, current and power. A number of research and development works were published treating the dual-channel sampling method in both the theoretical and practical aspects [1,2]. The dual-channel sampling technique is applied whenever to electrical parameters are sampled, in the case of voltage and current, for the measurement of power, harmonics, phase angle etc. Therefore, the DSP-based sampling method can be used for measuring ac voltage, current and power to develop the traveling standard. The designed sampling wattmeter generates power data in real time with a fixed sampling rate, and then the developed software calculates the root mean square (rms) values of voltage and current waveforms, power parameters and harmonics of the waveforms.

2. MEASURING SYSTEM

The sampling wattmeter system consists mainly of three-phase voltage and current input sections, a channel connector, a data acquisition (DAQ) card and a computer used for control and data calculation. The channel connector consists of six analog channels, and the input voltages of the channels are limited to the 0–10 V range. The block diagram of the three-phase power measuring system is shown in Fig. 1.

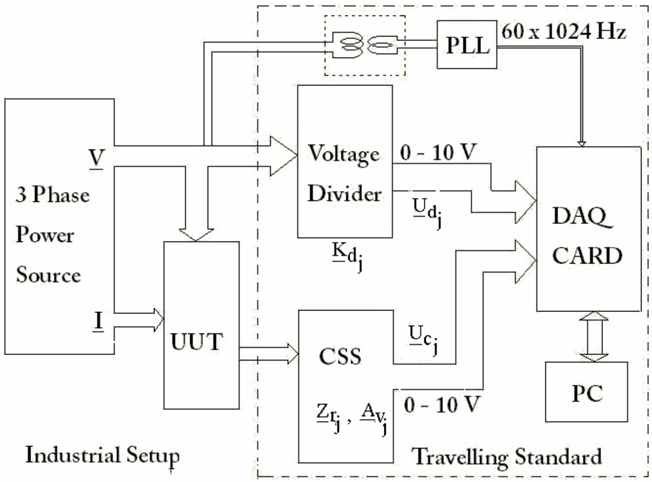

Fig. 1. Layout of the measuring system.

When sampling the current and voltage waveforms as shown in Fig. 2, a single channel of the DAQ system takes N samples within the space of a sampling interval T_s. In an ideal situation, an integer number of periods nT, n =1 in Fig. 2 should be equal to an equally spaced total sampling time, that is:

$$nT = NT_s \quad (1)$$

However, in the synchronous sampling technique equality (1) is not fulfilled, and it gives an error:

$$\delta t = NT_s - nT \quad (2)$$

This is called a truncation error and can be minimized using a phase-locked loop (PLL) circuit that synchronizes all channels with the running frequency of 60 × 1024 Hz providing equality for equation (1). The PLL circuit was developed within the laboratory and fixed with other components utilized in the system

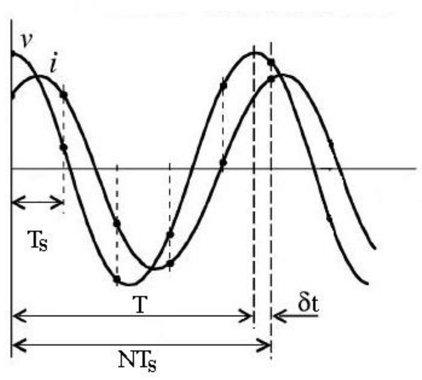

Fig. 2. Synchronous sampling.

The current shunt setup (CSS) utilized for the acquisition of the current signal consists of three current shunts and instrumentation amplifiers. The current input terminals are connected to the three 0.2 Ω standard current shunts attached to instrumentation amplifiers, and the range of their output is 1–10 V for nominal input currents of 1, 2 and 5 A. The shunts, together with their output amplifiers, are calibrated by injecting a known ac current into them and measuring the output voltage of the amplifiers.

The voltage input section consists of three resistive voltage dividers for higher voltages, and the output of each divider is designed for 1 and 5 V for nominal input voltages of 120 and 240 V. The six analog inputs of the DAQ system were used as sampling voltmeters. Initially the system was calibrated according to the procedure laid down in the manufacturer's manual and the results were found to be within the specification. All the channels are triggered using an external PLL signal, while the sampling data are updated in real time. The sampling rate is 1024 samples per cycle and for better accuracy 40 cycles count for the average. Meanwhile, the sampled data are stored in the computer memory to calculate power parameters and harmonic analysis.

3. SIGNAL PROCESSING

Fast Fourier transform (FFT) function is used to calculate discrete Fourier transform (DFT) for signal processing of current and voltage waveforms. The real and imaginary parts of the DFT, *DFTRe* and *DFTIm*, are calculated first for each sample and then amplitudes are calculated for fundamental frequency and harmonics frequencies. The rms values of the waveforms and harmonics amplitudes, H_j, can be calculated as:

$$rms = \sqrt{V_{DC}^2 + \sum_{j=1}^{M} H_j^2} \quad (3)$$

and

$$H_j^2 = \frac{1}{2} K_j^2 \left\{ \left(DFT\,\mathrm{Re}_j \right)^2 + \left(DFT\,\mathrm{Im}_j \right)^2 \right\} \quad (4)$$

Where, K_j is frequency response correction for the j_{th} harmonic of the total M harmonics and more details can be found in [3].

The voltage $\underline{V}$, current $\underline{I}$, and the phase angle between them are the quantities of interest that calculate the active and reactive power. The quantities can be expressed in terms of $\underline{U}_{dj}$ and $\underline{U}_{cj}$, combined with the voltage divider ratio, $\underline{K}_d$ parameter, CSS gain ratio, $\underline{A}_v$, and CSS impedance, $\underline{Z}_r$, for the j^{th} harmonics, as shown in Fig. 1. After digitizing, the analog input voltages of the DAQ may be expressed as complex numbers, since the FFT calculates the real and imaginary parts of the DFT for the fundamental and its harmonics. Therefore, $\underline{U}_{dj}$ and $\underline{U}_{cj}$ are complex numbers and U_{dj} is rms amplitude of the jth harmonics, where j = 1 to M and M is taken as 50 in the data processing. The voltage divider and the CSS parameters are also complex numbers since they can be expressed using their relative ratio and phase errors. Then, the main power parameters of the j^{th} harmonics can be written as follows. The active power is:

$$P_j = \frac{1}{4} U_{d_j}^2 \,\mathrm{Re}\,\underline{Y}_j \quad (5)$$

and the reactive Power is:

$$Q_j = \frac{1}{4} U_{d_j}^2 \,\mathrm{Im}\,\underline{Y}_j \quad (6)$$

where

$$\underline{Y}_j = \left\{ \left(\underline{K}_{d_j} + \frac{1}{\underline{Z}_{r_j} \underline{A}_{v_j}} \frac{\underline{U}_{c_j}}{\underline{U}_{d_j}} \right)^2 - \left(\underline{K}_{d_j} - \frac{1}{\underline{Z}_{r_j} \underline{A}_{v_j}} \frac{\underline{U}_{c_j}}{\underline{U}_{d_j}} \right)^2 \right\} \quad (7)$$

The output of $\underline{Y}_j$ is a complex number, and it can be solved very easily within the developed software. Reference [4] provides some details of equations (5)–(7). The program has two modes, 'Normal' and 'Harmonics,' for power and other parameters to be measured. In the 'Normal' mode j = 1 and the system measures the sinusoidal power. In the 'Harmonics' mode equations (5) and (6) calculate power for every set of harmonics and the total active and reactive power are given by the summation of P_j and Q_j. The imaginary-real ratio of the DFT of each channel provides the phase angle between harmonics, whereas the imaginary real ratio of $\underline{Y}_1$ calculates the phase angle between voltage and current channels.

In data processing, special attention has been given to compensate the amplitude and phase errors introduced by the system. The errors of the voltage divider and CSS were both corrected directly through vector calculations and the program provided an option to feed the data. The DAQ card also contributed to the errors in gain and phase, and the gain error can be corrected by multiplying the rms and harmonics amplitudes by the gain error correction factor of the DAQ card, which is determined from the experiments. During the experiments it was found that there is a certain time delay between two channels of the DAQ card, although the channels are synchronized with each other; this may be attributed to phase jitter between channels, and a phase error occurs when the power parameters are calculated. The procedure is not as straightforward as other corrections and needs to be reconstructed the waveforms of the current signal. The real and imaginary components, *DFTRe* and *DFRIm* of the current are further corrected by taking into account the difference in time delay between the current and the voltage channels of the acquisition system. More details can be found in [1].

The software was developed using LabView for the three-phase power calibration system, as shown in Fig. 3. The number of samples per period and the sampling rates were fixed in the program and the phase selection single- or three-phase operations were set before running the program. Common electrical parameters such as rms voltage and current, active, reactive and apparent power, and total harmonic distortion (THD) were calculated according to procedures mentioned and displayed above.

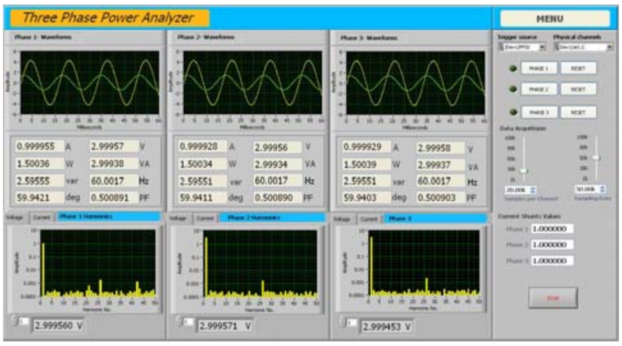

Fig. 3. Screen printout of the power and harmonic calibration software.

The data updates are in real time, and the system is a plug-and-play solution for onsite power analyses and measurements.

4. RESULTS AND EVALUATION

The accuracy of the traveling sampling wattmeter was evaluated using a high-precision power analyzer Model LMG 500, a product of Zimmer Electronics Systems, GmbH. The phases of the system were tested, a single phase at a time, using an electrical power source, Fluke 6100A, which generates stable voltage, and current in both sinusoidal and nonsinusoidal conditions. The results were obtained for the voltage range 0–240 V and the current range, 0–5 A. Tests were performed at 60 Hz for power factors of 0.2 to 1 leading and lagging. Typical test results, for voltage, current and power measurements are shown in Tables 1.1 and 1.2 for both the sinusoidal and nonsinusoidal waveforms. The errors shown in the tables referred to the full-scale measurements values of the current and voltage ranges. The errors in power measurement for the distorted waveforms were less than 0.05% for both the leading and lagging power factors.

Table 1.1 Voltage, current and power measurements under sinusoidal test conditions.

Voltage (V)		Current (A)		Power (W) V= 240 V, I = 1 A		
Val.	Error %	Val.	Error %	PF*	Error %	
					Active	Reactive
120	0.02	1	-0.01	1	0.01	-
210	0.02	2	-0.03	0.9	0.01	0.03
220	0.01	3	-0.03	0.7	-0.01	0.04
230	0.01	4	-0.02	0.5	-0.03	0.05
240	-0.01	5	-0.01	0.3	-0.05	0.03

Table 1.2 Voltage, current and power measurements under nonsinusoidal test conditions

	Voltage Harmonics (V)		Current Harmonics (A)		Har. Power (W) V = 240 V, I = 5 A, THD =10%	
Har. No.	Ref. Val.	Mea. Val.	Ref. Val.	Mea. Val.	PF*	Err.%
1	240.006	240.009	5.0007	4.9997	0.9	0.01
3	1.0004	0.9998	1.0001	0.9992	0.7	-0.01
5	0.5002	0.4999	0.5002	0.4996	0.5	0.05
7	0.5001	0.4999	0.4999	0.4998	0.3	-0.05

*Power factor lead and lag, Val.: Value, Ref.: Reference, Mea. : Measured , Har. : Harmonics.

Harmonics power measurements were also carried out by varying the THD percentage within 1%–20% of fundamental. The results agreed within the same level of accuracy mentioned in Table 1.2.

As described in the signal processing section, the errors were compensated for within the calculation. The values which made uncertainty contributions to the system were mainly dependent on the phase and ratio errors of the DAQ card, voltage divider and CSS. The uncertainty of the ratio error for both the voltage divider and CSS was within 10 ppm, and the phase error uncertainty was less than 20 μrad. These values were very low compared to the DAQ card gain correction and phase error uncertainties between two channels; they were 25 ppm and 50 μrad, respectively. The overall uncertainty calculation revealed that the rms value uncertainty was within 50 ppm for the sinusoidal and 100 ppm for the nonsinusoidal waveforms. The power measurement uncertainties were less than 100 and 200 μw/VA for the sinusoidal and nonsinusoidal waveforms respectively. During the power measurements, it was noticed that the readability of the DAQ card in real time data acquisition caused higher uncertainties in the power measurements.

5. CONCLUSION

The desired objective of a computer-based power analyzing system is to analyze three-phase power systems on site, thus fulfilling an industrial demand. The designed system can be used as a traveling standard with an accuracy of up to 0.05%. Furthermore, the software is more flexible and many reference quantities can be calculated, particularly those needed for harmonics measurements. Most of the components in a measuring system are commercially available. Therefore, the system can be constructed easily with low cost compared to commercial power analyzers. The system is very important, in particular, for power industries to analyze their systems.

Further improvements are planned for the future, in particular replacement of the voltage divider and CSS systems. A high-precision voltage transformer (VT) can be used as a divider to obtain high stability of the voltage signal, and the CSS setup would be replaced by a current transformer (CT). The replacement is very useful, in particular for reducing the size of the traveling standard, and it is important for the future of the system. Furthermore, by introducing a current transformer the current range can be extended up to 50 A very easily. In terms of reducing the level of uncertainty, the overall stability of the system needs to be upgraded. The modern DAQ card is a good choice for improving the level of accuracy of the system. The calibration of the system with a reference standard will also reduce the level of uncertainty. Currently, the reference system for harmonics is developing; we hope to conduct in future a direct comparison to obtain further reduction of the level of uncertainty.

REFERENCES

[1]. U Pogliano, " Use of integrative analog-to-digital converters for high precision measurement of electric power," *IEEE Trans. Instrument Meas*., vol 50, no. 5, pp 1315-1318, Oct 2001.

[2]. Endre Toth, A. M. R. Franco and R.M. Debatin, " Power and Energy Referance System, Applying dual-Channel sampling", *IEEE Trans. Instr. Meas.*, vol. 54, no 1 Feb. 2005.

[3]. U. Pogliano, " Precision measurement of AC voltage below 20 Hz at IEN, " *IEEE Trans. Instrum. Meas*., vol 46, pp. 369-372, Apr. 1997.

[4]. Gunther Rammn, Harald Moser and Andreas, " A New scheme for Generating and Measuring Active, Reactive and Apparent Power at Power Frequencies with Uncertainties of 2.5 x 10^{-6}.

S. Wijesinghe was born in Sri Lanka in 1967 and he received the B.Sc. and M. Sc. in Physics from the Universty of Sri Jayewardenepura Sri Lanka and University Science Malaysia in 1996 and 2003 respectively. He has been employing as a Research Officer at the Industrial Technology Institute since 1997.

He joined Korea Research Institute of Standards and Science (KRISS) under the University of Science and Technology (UST) as a PhD student in 2007. His research interests are in development of power standards and high precision measurement system for harmonics and harmonics power measurements.

Young Tae Park was born in South Korea in 1952. He received the Ph.D. degree in electrical appliances and electricity material from Chung-nam University, Daejeon in 1983.

He joined the Korea Research Institute of Standards and Science (KRISS),Daejeon, where he has been working on low frequency power electrical energy standards since 1983. At present he is a principal researcher in the division of physical metrology, KRISS.