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Developing Harmonic Power Analyzer based on IEEE 1459-2010 Standard

P. Wattanayingcharoen, A. Detchrat, S. Chitwong

Abstract—**This paper describes the developing harmonic power analyzer based on IEEE 1459-2010. This instrument use the power definitions present in IEEE standard, the instrument use ARM Cortex-M3 high performance 32bits microcontroller to calculate electric power from isolated current and voltage transducers, and compare the experimental results with commercial instrument.**

Index Terms—**Harmonic analyzer, IEEE 1459-2010, power measurement**

I. Introduction

In present, power system and power quality have been concerned about harmonic pollution generated by modern electronic devices such as adjustable speed drivers, controlled rectifier and clusters of personal computer[1]. The voltage and current distortion of waveform can cause malfunctions or damage on load.

The quality in power system is the most important for all equipment. Therefore, power quality monitoring system and/or harmonics analysis and identification are among the important factors to improve quality of power system. Presently, however, the definitions for active, reactive, and apparent power currently used are based on the knowledge that ignores harmonics component, as long as the current and voltage waveforms are nearly sinusoidal. At present, IEEE standard 1459 is the only available standard that gives some guidelines for designing instrument for measuring power and energy, suggesting quantities that should be measured for revenue purpose, engineering, economic decisions and major harmonic polluters individuation.

Nowadays, harmonic analyzers are manufactured based on the principle of Fast Fourier Transform (FFT) technique, which is capable to extract both magnitude and frequency of electrical signals. This technique is used in high performance instrument thus cost of the instrument is very high.

This paper proposes the Developing single phase Harmonic Power Analyzer based on IEEE 1459-2010 Standard. Instead of using FFT technique which are used in high performance instruments, we will using Kalman technique which will present more accurated and detailed results. The comparasion of both techniques are shown later in this document

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P.Wattanayingcharoen is Master degree student in Instrumentation Engineering Faculty of Engineering King Mongkut's Institute of Technology Ladkrabang. E-mail address : pwatta@gmail.com

A. Detchrat is Master degree student in Instrumentation Engineering Faculty of Engineering King Mongkut's Institute of Technology Ladkrabang. E-mail address : aeketrang.na@gmail.com

S. Chitwong is Asst. Prof. in Engineering Faculty of Engineering King Mongkut's Institute of Technology Ladkrabang. E-mail address : kcsakrey@kmitl.ac.th

II. Theoretical Overview

A. IEEE standard 1459-2010

As present in first section, tradition instruments used knowledge in 1940s. The waveform is prone to significant errors when the current and voltage are distorted. User must be careful when using this instrument since the accuracy and information obtained from instrument does not include harmonic component, until in January 2000 IEEE announce first Trial used standard IEEE 1459-2000 define the power measurement under sinusoidal, nonsinusoidal, balance and unbalance conditions. 10 years after publication, in March 2010, the review was introduced and published in standard IEEE 1459-2010, with some important changes and corrections.

The standard defines the power measurement when the voltage and current are not sinusoidal, when the load is unbalanced or voltage is asymmetric and when the energy dissipated. The key concept of standard for power resolution is the separation fundamental component of voltage and current from all of harmonics component. This improves the quality of measurement of instrument and traditional power monitor system. The standard definitions for single phase and three phase system are present in Table I and II,

TABLE I
IEEE 1459-2010 QUANTITIES WITH NONSINNUSOIDAL SINGLE PHASE SYSTEM

Quantity	Combined	Fundamental	Nonfundamental
Apparent $[VA]$	S	S_1	S_N, S_H
Active $[W]$	P	P_1	P_H
Nonactive $[VAR]$	N	Q_1	D_1, D_V D_H
Line utilization	$PF = P / S$	$PF_1 = P_1 / S_1$	-
Harmonic pollution	-	-	S_N / S_1

TABLE II
IEEE 1459-2010 QUANTITIES WITH NONSINNUSOIDAL THREE PHASE SYSTEM

Quantity	Combined	Fundamental	Nonfundamental
Apparent $[VA]$	S_e	S_e, S_1^+ S_{U1}	S_{eN}, S_{eH}
Active $[W]$	P	P_1^+	P_H
Nonactive $[VAR]$	N	Q_1^+	D_{e1}, D_{eV} D_{eH}
Line utilization	$PF = P / S_e$	$PF_1^+ = P_1^+ / S_1^+$	-
Harmonic pollution	-	-	S_{eN} / S_{e1}
Load unbalance	-	S_{U1} / S_1^+	-

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In this paper, we focus on single phase non sinusoidal system. And basic power component definitions for single phase system, the representation can be used.

$$v = \sqrt{2}V_1 \sin(\omega t - \alpha_1) + \sqrt{2}\sum_{h\neq 1} V_h \sin(h\omega t - \alpha_h) \quad (1)$$

$$i = \sqrt{2}I_1 \sin(\omega t - \beta_1) + \sqrt{2}\sum_{h\neq 1} I_h \sin(h\omega t - \beta_h) \quad (2)$$

Where h is the harmonics order and 1 is fundamental component. Through this the RMS values of voltage and current are.

$$V_{RMS} = \sqrt{V_1^2 + \sum_{h\neq 1} V_h^2} = \sqrt{V_1^2 + V_h^2} \quad (3)$$

$$I_{RMS} = \sqrt{I_1^2 + \sum_{h\neq 1} I_h^2} = \sqrt{I_1^2 + I_h^2} \quad (4)$$

The active power is defined as

$$P = P_1 + P_H \quad (5)$$

The fundamental active power P_1 is defined as

$$P_1 = V_1 I_1 \cos\theta_{1'} \quad (6)$$

And P_H is the harmonics active power

$$P_H = \sum_{h\neq 1} V_H I_H \cos\theta_{h'} \quad (7)$$

The fundamental reactive power is defined as

$$Q_1 = V_1 I_1 \sin\theta_{1'} \quad (8)$$

The apparent power is defined as

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

The fundamental apparent power is defined as

$$S_1 = V_1 I_1 \quad (10)$$

From the energy flow point of view, the fundamental apparent, active and reactive power components are the highest interest point. The nonfundamental power determined by the distortion of voltages and currents which is defined as

$$S_N = \sqrt{S^2 + S_1^2} \quad (11)$$

The nonactive power N can now be defined as

$$N = \sqrt{S^2 - P^2} \quad (12)$$

The current distortion power D_I, voltage distortion power D_V, and the harmonic apparent power S_H are defined as

$$D_I = V_1 I_H,\ D_V = V_H I_1,\ S_H = V_H I_H \quad (13)$$

Displacement power factor is defined as

$$PF_1 = P_1 / S_1 \quad (14)$$

And power factor is defined as

$$PF = P / S \quad (15)$$

The harmonic pollution HP is defined as the ratio of the nonfundamental apparent power S_N to the fundamental apparent power

$$HP = S_N / S_1 \quad (16)$$

The last value, Total Harmonic Distortion (THD) based on fundamental and harmonic RMS value, the voltage total harmonic distortion (THD_V) and current total harmonic distortion (THD_I) are defined as

$$THD_V = V_H / V_1,\quad THD_I = I_H / I_1 \quad (17)$$

IEEE Standard 1459-2010 computations were implemented by software using a discrete form, and using the Kalman filter to obtain the harmonic components of the signal.

The Kalman filter can be implemented by [6] are define as follow

$$\hat{x}_{k+1|k} = \Phi_k \hat{x}_{k|k-1} + K_k (y_k - F_k \hat{x}_{k|k-1}) \quad (18)$$

where $\hat{x}_{k+1|k}$ denotes the estimate of the state vector x_{k+1}, evaluated at the time t_k. The Kalman gain K_k is

$$K_k = \Phi_k P_{k|k-1} F_k^T (F_k P_{k|k-1} F_k^T + R_k)^{-1} \quad (19)$$

where

$$P_{k+1|k} = \Phi_k P_{k|k-1} \Phi_k^T - K_k F_k P_{k|k-1} \Phi_k^T + \Gamma_k Q_k \Gamma_k^T \quad (20)$$

represents the covariance of the estimation error.

Other variables in the filtering equations are related to a dynamic system that represents the signals to be filtered, that is,

$$x_{k+1} = \Phi_k x_k + v_k \quad (21)$$

$$y_k = F_k x_k + v_k \quad (22)$$

$$\dim x_k = n\times 1, \dim y_k = r\times 1, \dim \gamma_k = p\times 1 \quad (23)$$

where γ_k and v_k are uncorrelated Gaussian white-noise sequences with means and covariances as follow

$$E\{\gamma_i\} = 0, E\{\gamma_i \gamma_i^T\} = Q_i \delta_{ij} \quad (24)$$

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$$E\left\{v_i\right\} = 0, E\left\{v_i v_j^T\right\} = R_i \delta_{ij} \tag{25}$$

$$E\left\{\gamma_i v_j^T\right\} = 0, E\left\{\gamma_i x_j^T\right\} = 0, E\left\{v_i x_j^T\right\} = 0 \forall i, j \tag{26}$$

where $E\{\cdot\}$ denotes the expectation operator and δ_{ij} denotes the Kronecker delta function.

The model that describes a signal S_k with n harmonic is described in what follows. Consider a signal S_k with n harmonic components, i.e.,

$$S_k \sum_{i=1}^{n} A_{i_k} \sin\left(i\omega_k t_k + \theta_{i_k}\right) \tag{27}$$

where A_{i_k}, $i\omega_k$ and θ_k are the amplitude, angular frequency and phase of each harmonic component i at the time instant t_k. This signal can be modeled in state-space as follows:

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{2n-1} \\ x_{2n} \end{bmatrix}_{k+1} = \begin{pmatrix} M_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & M_n \end{pmatrix}_k \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{2n-1} \\ x_{2n} \end{bmatrix}_k + \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \vdots \\ \gamma_{2n-1} \\ \gamma_{2n} \end{bmatrix}_k \tag{28}$$

$$y_k = \begin{bmatrix} 1 & 0 & \cdots & 1 & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{2n-1} \\ x_{2n} \end{bmatrix}_k + v_k \tag{29}$$

where

$$M_1 = \begin{bmatrix} \cos\left(i\omega_k T_s\right) & \sin\left(i\omega_k T_s\right) \\ -\sin\left(i\omega_k T_s\right) & \cos\left(i\omega_k T_s\right) \end{bmatrix} \tag{30}$$

$$x_{(2i-1)_k} = A_{i_k} \sin\left(i\omega_k t_k + \theta_{i_k}\right) \tag{31}$$

and

$$x_{2i_k} = A_{i_k} \cos\left(i\omega_k t_k + \theta_{i_K}\right) \tag{32}$$

T_s is a constant sampling frequency.

Components of positive sequence are obtained by

$$v_{d_k}^{+} = \frac{1}{3} v_{a_k}^{f} - \frac{1}{6}\left(v_{b_k}^{f} + v_{c_k}^{f}\right) + \frac{\sqrt{3}}{6} S_{90}\left(v_{b_k}^{f} - v_{c_k}^{f}\right) \tag{33}$$

$$v_{b_k}^{+} = v_{a_k}^{+} - v_{c_k}^{+} \tag{34}$$

$$v_{c_k}^{+} = \frac{1}{3} v_{c_k}^{f} - \frac{1}{6}\left(v_{a_k}^{f} + v_{b_k}^{f}\right) + \frac{\sqrt{3}}{6} S_{90}\left(v_{a_k}^{f} - v_{b_k}^{f}\right) \tag{35}$$

where $S_{90} = e^{j90^\circ}$ defines the 90º phase-shift operator. These 90º shifted values are obtained by the Kalman filter, without the use of additional filters to shift the fundamental signal.

III. Instrument Design

Conceptually, a microcontroller (uC) is like a personal computer (PC) that most of us use every day. However, a uC is difference from a PC in the sense that in uC everything is built in a single chip, while a PC may consist of a many components. uC are generally used to control stand-alone automatic systems such as digital cameras, and smart phones.

ARM Cortec-M3 is based on ARMv7-M architecture which is not the same as ARM7. ARM7 uC are based on ARMv4 architecture. Basically, ARM Cortex-M3 has been designed to improve and overcome several limitations of ARM7. Thus the core processor in this work is used ARM Cortex-M3 high performance 32 bit microprocessor, the main reasons for chosen this processor described below.

- ARM Cortex-M3 offers the best compromise. It is comparable to 16-bits uC in terms of price and feature in a single chip, and it offers superior performance to 8/16-bits systems.
- Low power consumption.
- High speed and high performance processor for implement of algorithm.
- Support high level language such as C, thus software development can implement faster than low level language and can implement complexities algorithm.

The input of A/D are the isolated voltage and current transducers (LV-25P and MI5) since using input voltage and current are better than using step down transformer. Moreover, we also measure the input by using high sampling rate which generated from microcontroller since it will give us the accuracy of the instrument is more acceptable.

Software module in ARM Cortex-M3 includes Signal component extractor. Prediction estimation and IEEE 1459-2010 modules are implemented by C language. Kalman Filter is used in Signal component extraction and prediction , estimation modules. Signal component extraction is used for extracting fundamental and harmonics component that prepare for calculating power component. Prediction and estimation module is using for predicting and estimating input power component to ensure that input are more accurate than before calculating the power component in IEEE 1459-2010 in last block diagram in ARM Cortex-M3 chip.

In Fig. 1 the diagram is shown software and hardware diagram that implemented in the developed instrument.

IV. Experiment Results

Testing environment for the developed instrument is shown in Fig. 2. The testing equipment includes commercial instrument and developed instrument to measure power component obtain from load, diode D1 is used for clipping input signal to unbalanced condition.

Voltage, current and all of power definition in standard have been implemented in the instrument and compare with commercial instrument in unbalanced condition that obtain from testing environment are shown in TABLE III – V. Fig. 3, Shown a photograph of the developed instrument

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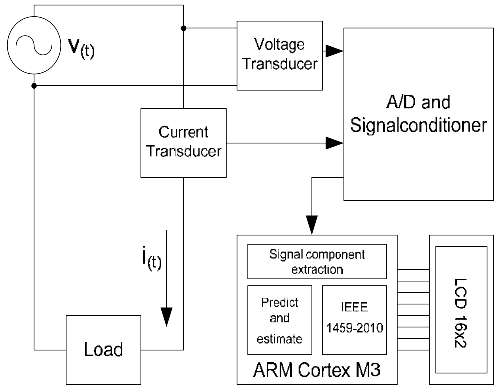

Fig. 1. Shown block diagram of developed instrument.

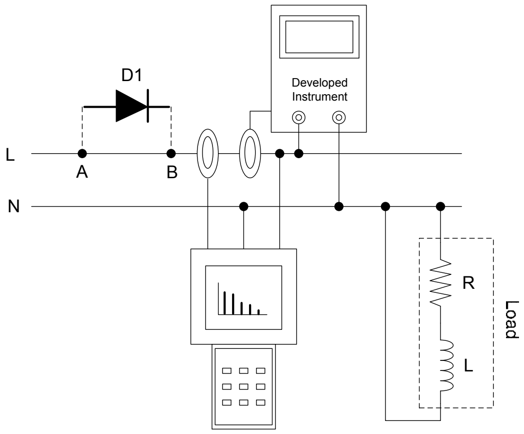

Fig. 2. Shown the experimental circuit diagram.

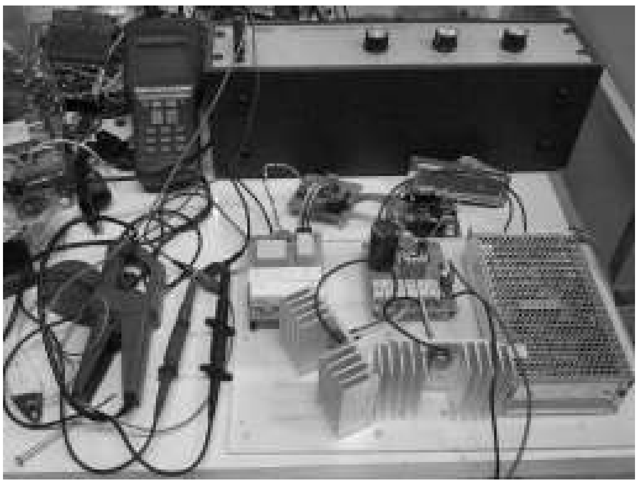

Fig. 3. Shown a photograph of the developed instrument and used in this paper.

TABLE III
HARMONICS COMPONENT FROM EXPERIMENT RESULT COMPARE WITH TRADITIONAL INSTRUMENT

Harmonic	Current (Ampere)		
	Instrument	Fluke 41B	%error
1	0.58	0.56	3.57
3	0.52	0.52	0
5	0.44	0.44	0
7	0.34	0.34	0
9	0.23	0.23	0
11	0.13	0.13	0
13	0.50	0.51	1.96

TABLE IV
EXPERIMENT RESULT IN NONSINUSOIDAL CONDITION FROM DEVELOPED INSTRUMENT

Quantity	Combined	Fundamental	Nonfundamental
Apparent [*VA*]	S=295.32	S_I=187.64	S_N=228.06 S_H=1.79
Active [*W*]	P=173.21	P_I=173.17	P_H=0.12
Nonactive [*VAR*]	N=239.36	Q_I=72.30	D_I=226.41 D_I=1.44 D_H=1.92
Line utilization	PF=0.58	PF_I=0.92	-
Harmonic pollution	-	-	S_N/S_I=1.21

TABLE V
EXPERIMENT RESULT IN NONSINUSOIDAL CONDITION FROM COMMERCIAL INSTRUMENT

Quantity	Combined	Fundamental	Nonfundamental
Apparent [*VA*]	S=294.11	-	-
Active [*W*]	P=172.92	-	-
Nonactive [*VAR*]	N=243.67	-	-
Line utilization	PF=0.58	-	-
Harmonic pollution	-	-	-

V. CONCLUSION

In this paper it has been shown the Developing Harmonic Power Analyzer based on IEEE 1459-2010 Standard for single phase power system from experimental results in section IV. Notices IEEE standard provides more details than traditional instrument in term of harmonics component.

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