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IEEE 1459-2010 규격의 정의를 이용한 다중 입력 채널을 갖는 전력 감시 시스템

전정채[1], 오 훈[2*]
[1]한국전기안전공사, [2]원광대학교 전기공학과

Power Monitoring System with Multiple Input Channels Using the Definition of IEEE Standard 1459-2010

Jeong-Chay Jeon[1] and Hun Oh[2*]
[1]**Korea Electrical Safety Corporation**
[2]**Department of Electrical Engineering, WonKwang University**

요 약 본 논문에서는 전력 시스템의 전원 및 부하 측을 동시에 감시가 가능한 다 채널(전압 8채널, 전류 10채널) 전력 측정 시스템을 개발하였다. 제안된 시스템은 전력품질과 관련된 규정인 IEEE 1459-2010의 정의를 사용하여 전력 성분을 계산하는 신호처리 알고리즘을 기반으로 TMS320C42 DSP를 이용하여 개발하였다. 개발된 시스템은 표준 전원 공급 장치를 이용하여 그 성능 시험을 실시하였고, 그 결과 측정오차는 0.2% 이하로 나타났다. 또한 제안된 시스템을 3상 4선식 전력시스템에 설치하여 실증 시험을 실시하여 그 성능을 입증하였다. 제안된 시스템은 상업 및 산업용 전력 시스템에 적용하여 동시에 다 채널로 전력을 측정 및 분석함으로써 전력품질과 관련된 다양한 문제를 줄일 수 있을 것이다.

Abstract This paper develops power measurement system with multiple sensor input channels (voltage-8 channels and current-10 channels) that simultaneously can monitor power components for both supply and load side of power system. The hardware implementation of the proposed system is based on TMS320C42 DSP and signal processing program algorithm to calculate power components use the definition of IEEE Standard 1459-2010 related power quality. The performance of the developed system is tested by using standard ac power source device, and the test results showed that accuracy of the developed system is less than 0.2 %. Also, field test of the proposed system in the three-phase and four-wire power system was implemented. Simultaneous multiple channel measurement and analysis of power components in commercial and industrial electrical power system using the proposed system will be necessary to reduce power quality problems.

Key Words : DSP, IEEE, multiple channels, power component, Simultaneous measurement

1. Introduction

Power quality (PQ) including harmonics, voltage dips, brief interruptions, transients, power factor, and unbalance can cause problems of the operation of the supplied equipment [1]. Especially, electrical harmonics caused by nonlinear loads such as inverters, rectifiers and DC power supplies produce malfunction of control devices, data loss of computer systems and overheating of cable and transformer in today's electrical power system [2].

Many standards and guidelines related power quality

This work was supported by research program 2012 of Wonkwang University in Korea
*Corresponding Author : Hun Oh(WonKwang Univ.)
Tel: +82-10-2520-9990 email: ohhun@wku.ac.kr
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were developed. In order to deal with power quality, the International Electro-technical Commission (IEC) has developed IEC 61000 series called Electromagnetic Compatibility (EMC) Standards and the Institute of Electrical and Electronic Engineers (IEEE) has published IEEE 1159 that defined categories and typical characteristics of power system electromagnetic phenomena. Some of the other organizations have developed their own standards such as ANSI, NEMA [3,4].

These concerns about PQ created the needs of the measurement of power components such as active, reactive and apparent power, root-mean-square (RMS) values of voltage and current, power factor and PQ [2,3]. Especially, commercial and industrial companies more need the PQ monitoring system to reduce product quality problems, process down, computer equipment disturbance, and other equipment failures by PQ. These systems have many advantages for both end uses and utility companies [5].

There are many variants of power measurement available in the field ranging from hand-held instruments to portable monitors. These instruments or monitors have voltage 4-channel and current 5-channel and provide three-phase and four-wire metering. Therefore, they can measure power components of only one side that is supply or demand side of three-phase and four-wire power system.

But, some applications require simultaneous power components measurement and monitoring for both supply (or source) and load (or demand) side of power system should be implemented in order to effectively improve energy efficiency and solve problems related PQ [4].

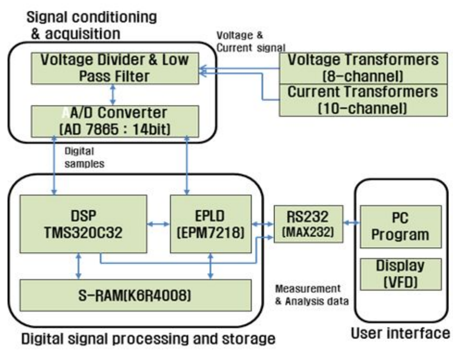
This paper presents a power monitoring system that simultaneously can measure power components with multi-channel (voltage-8 channel and current-10 channel) input sensors for supply and demand side of power system. The proposed system use a floating point digital signal processor (DSP) TMS320C32 and 14bit analog to digital (A/D) converter AD 7865 that simultaneously convert analog signals into digital signals. In order to measure electrical power components, definitions of [6,7] and related standard IEEE 1459-2010 are used [8-13]. The system can measure the current and voltage values including harmonic content, the active, reactive, and apparent power, the power factor, the voltage and current harmonic, the total harmonic distortion (THD) and so on.

Accuracy of the voltage and current measurement, active and apparent power measurement, harmonic analysis by the developed system has been tested by using standard ac power source FLUKE™6100A. The test results show that accuracy of measurement is less than 0.2 percent. In the field test of the developed system, the power components measurement for all phases of load and source side in three-phase power system was simultaneously implemented.

2. System Implementation

2.1 System Design & Implementation

Fig. 1 shows the basic structure of the proposed system. The proposed system is largely divided into three subsystems of signal conditioning and acquisition subsystem excluding voltage and current sensors (voltage-8channel and current-10 channel); digital signal processing and storage subsystem; and the user interface system.



[Fig. 1] Basic structure of the proposed system

Voltage measurement is done by probe-type voltage sensors (accuracy: 0.0 5%) and current measurement is done by clamp-type current sensors. In the input signal conditioning and acquisition subsystem, voltage divider using a high precision resistor (accuracy: 0. 1 %) and low pass filters to prevent voltage and current signal above 3 kHz were designed. Sampling frequency of 7.68 kHz (128 samples per cycle) is chosen so that the proposed system could measure up to 50^{th} harmonic of 60 Hz. This system allows signals with maximum rated voltage 750 V.

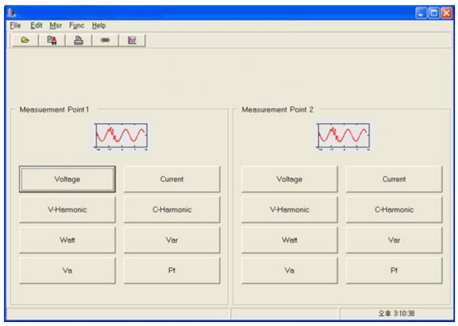
In order to simultaneously convert the analog signals of voltage 8 and current 10 channels into digital signals, A/D circuit was designed by using Analog Devices 14bit A/D converter AD 7865 having analog input 4 channel of AC level and conversion start signal input ability. This device can simultaneously convert analog signals into digital signals.

After operating conditions of A/D channels are determined and the pertinent timer interrupt and the address to store A/D data are assigned, the timer interrupt is operated and voltage and current signal data are converted to digital data. Relevant interrupt is operated by A/D end signal and A/D raw data are stored in the memory. 14bit A/D raw data convert into 32bit raw data that is suited to the DSP. In order to minimize calculation and conversion error, these raw data are converted to magnitude of real data.

Digital samples are transferred to digital signal processing and storage subsystem. The proposed system adopts The TMS320C32 is high-performance 32-bit floating-point DSP for signal processing. The interface circuit between the DSP and the external digital elements such as the A/D converter, memory and others was designed by using Altera's erasable/programmable logic device (EPLD) EMP7128 so that the interface circuit can keep up with operation speed of the DSP that is operated in the high frequency of 60 MHz.

In order to save the data calculated by the DSP and quickly perform processor program, the memory block was designed by connecting 4Mbit S-RAM K6R4008 in serial and parallel. The program memory of the DSP was designed by using AMD's FROM 29F040. In order to meet abnormal conditions such as operating error and power failure and save measurement environment and processing states electrically erasable PROM (EEPROM) 24LC32 was connected to the DSP.

User interface subsystem using personal computer (PC) program and display device vacuum fluorescent device (VFD) can provide users with access to the monitoring and analyzed data. The proposed system had serial ports using standard RS 232 protocol for interface with PC. Universal asynchronous receiver/transmitter (UART) IC PC16550 as the serial and parallel conversion element of data for transmission and reception of data between the developed system and PC, and Maxim's MAX232 for RS232C interface with PC was used. Finally, PC program to confirm data measured the proposed system is developed as shown in Fig. 2.



[Fig. 2] Front panel of the developed PC program for viewing data and graphs.

2.2 Signal Processing

IEEE 1459 definitions or expressions of [5-7] are used in the developed system to calculate the power components such as power factor and active, reactive and apparent power. For single-phase non-sinusoidal system, The RMS (root mean square) values of voltages and currents including harmonics are

$$V_{RMS} = \sqrt{V_1^2 + \sum_{h \neq 1}^{M} V_h^2} \tag{1}$$

and

$$I_{RMS} = \sqrt{I_1^2 + \sum_{h \neq 1}^{M} I_h^2} \tag{2}$$

where is the harmonics order, M is the highest harmonic, and V_h and I_h are respectively the voltage and current RMS values of the hth harmonics of the fundamental frequency.

Calculating of power components of system having nonlinear load is somewhat more complicated than if the current were sinusoidal. Because of harmonic distortion of current or voltage the calculation of power components (apparent, active, reactive power) is very difficult. The total active power could be presented as a sum of components related to the fundamental and other harmonics:

$$P = P_1 + P_h = \sum_{h=1}^{M} V_{RMS_h} I_{RMS_h} COS(\theta_h) \tag{3}$$

Where P_1 is the fundamental active power, while P_h comprises the sum of all higher components and is referred to as harmonic active power, $\theta_h$is the phase angle between V_h and I_h.

The total reactive power to be calculated as:

$$\begin{aligned} Q &= Q_1 + Q_2 \\ &= \sqrt{\sum_{h=1}^{M} [V_{RMS\ h} I_{RMS\ h} SIN(\theta_h)]^2} \\ &= \sqrt{Q_1^2 + \sum_{h=2}^{M} Q_h^2} \end{aligned} \tag{4}$$

Equation 4 eliminates the situation where the value of the total reactive power Q is less than the value of the fundamental component Q_1. The apparent power S is calculated as a product of RMS values of voltage and current:

$$S = I_{RMS} * V_{RMS} = \sqrt{\sum_{h=1}^{M} V_{RMS_h}^2} * \sqrt{\sum_{h=1}^{M} I_{RMS_h}^2} \tag{5}$$

The power factor (PF) of a load or system is generally accepted as the ration of the active power to the apparent power:

$$PF = \frac{Q}{S} \tag{6}$$

The total voltage harmonic distortion is defined as

$$V_{THD} = \frac{\sum_{h=2}^{M} V_{RMS_h}^2}{V_1} \tag{7}$$

Also, the total current harmonic distortion is defined as

$$V_{THD} = \frac{\sum_{h=2}^{M} V_{RMS\ h}^2}{V_1} \tag{8}$$

According to IEEE 1459-2010, in three-phase systems with unbalanced and non-sinusoidal conditions, the voltage and currents in each phase could by using (1) and (2). In this case, three current phasors are not shifted exactly 120° with respect to each other. And the all power components are the sum of the power phase.

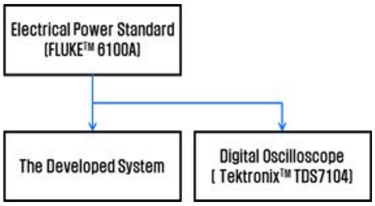
The calculation of power components (P,Q,S)defined above are is based on sampled instance of voltage and current. Fast Fourier Transform (FFT) of the sampled waveform calculates voltage and current harmonic order and magnitude, and total voltage and current harmonic distortion (V_{THD} and I_{THD}).

3. Experiment results

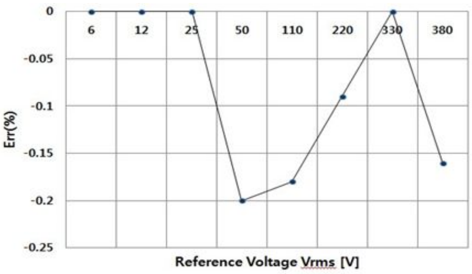
3.1 Accuracy Evaluation

To reduce error due to the voltage divider, the voltage-follower, the low-pass filter and gain of ADC, software revision of the development system was performed. The accuracy of power (active, reactive and apparent power) and harmonic measurement was tested by comparing reference data supplied by the electrical power standard system (FLUKE 6100A) with data measured by the developed system as shown in Fig. 3.

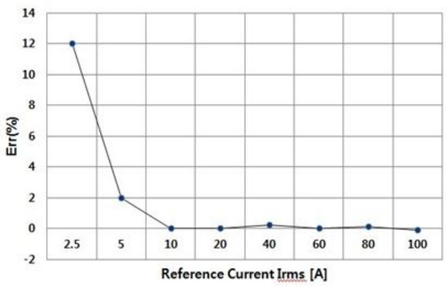
Fig. 4 shows the voltage measurement error (%) for different of reference input voltage by power standard instrument. The error is less than 0.2 %. The current measurement error is less than 0.2 % excluding error (%) below 10 A as seen in Fig. 5.



[Fig. 3] The accuracy test method



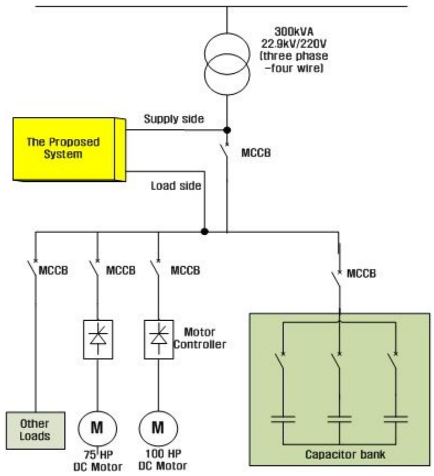
[Fig. 4] Voltage measurement error (%)



[Fig. 5] Current measurement error (%)

3.2 Field Test for Power Components Monitoring

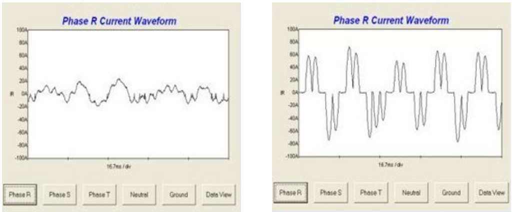
In order to verify simultaneous power components monitoring using multiple sensors, the developed system was connected with load and supply side of three-phase power system as shown in Fig. 6. The power system used 75 HP and 100 HP DC motors, an extruding machine, an air blower, and other loads in order to produce the automobile soundproofing material, and the capacitor bank for compensation of reactive power and suppression of harmonics was installed. The power system, in order to effectively prevent power disturbances and improve energy efficiency, needs simultaneous measurement of power components for both supply and load side (or demand side) of power system by the proposed method.



[Fig. 6] Wiring diagram for field test of the proposed system

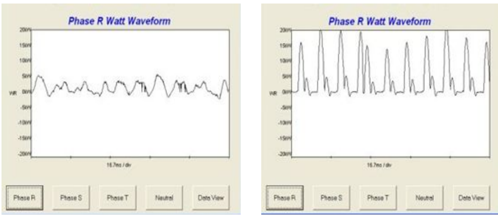
Fig. 7 shows the results to analyze current waveforms of supply and load side monitored by the proposed system. In the test results, variation of current waveform by the capacitor bank installed in the power system can be simultaneously confirmed. Fig. 8 and 9 indicate the experimental result of simultaneous active and reactive power monitoring. Improvement of power factor by the capacitor bank can be easily confirmed by monitoring power components like as active, reactive and apparent power of supply side and load side. Fig. 10 and 11 demonstrate current harmonic spectrum and voltage harmonic data measured by the proposed system respectively.

In this test, the effectiveness of the capacitor bank is easily confirmed by comparing harmonic spectrum and data of supply side with harmonic spectrum and data load side. All the tests appear to confirm the effectiveness of the proposed solution for simultaneous power components measurement for both supply and load side of the power system.



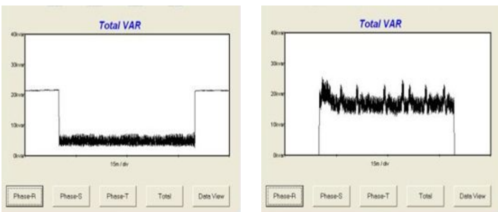
(a) (b)

[Fig. 7] Simultaneous current waveform monitoring results: (a) Supply side (b) Load side



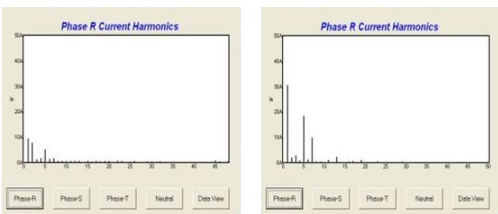
(a) (b)

[Fig. 8] Simultaneous active power monitoring results (16.7ms/div): (a) Supply side (b) Load side



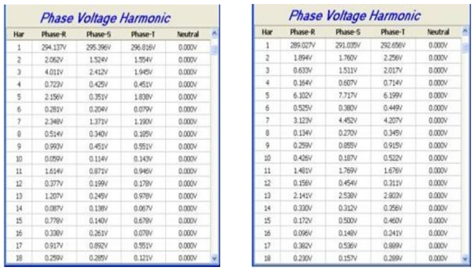
(a) (b)

[Fig. 9] Simultaneous reactive power monitoring results (15minute /div): (a) Supply side (b) Load side



(a) (b)

[Fig. 10] Simultaneous current harmonic spectrum monitoring results (a) Supply side (b) Load side



Phase Voltage Harmonic

Har	Phase-R	Phase-S	Phase-T	Neutral
1	294.137V	295.396V	296.816V	0.000V
2	2.062V	1.524V	1.554V	0.000V
3	4.011V	2.412V	1.945V	0.000V
4	0.723V	0.425V	0.451V	0.000V
5	2.156V	0.351V	1.838V	0.000V
6	0.281V	0.204V	0.079V	0.000V
7	2.348V	1.371V	1.190V	0.000V
8	0.514V	0.340V	0.185V	0.000V
9	0.993V	0.451V	0.551V	0.000V
10	0.059V	0.114V	0.143V	0.000V
11	1.614V	0.871V	0.946V	0.000V
12	0.377V	0.199V	0.178V	0.000V
13	1.207V	0.245V	0.978V	0.000V
14	0.087V	0.138V	0.067V	0.000V
15	0.778V	0.140V	0.678V	0.000V
16	0.338V	0.261V	0.078V	0.000V
17	0.917V	0.892V	0.551V	0.000V
18	0.259V	0.285V	0.121V	0.000V

Phase Voltage Harmonic

Har	Phase-R	Phase-S	Phase-T	Neutral
1	289.027V	291.035V	292.656V	0.000V
2	1.894V	1.760V	2.256V	0.000V
3	0.633V	1.511V	2.017V	0.000V
4	0.164V	0.607V	0.714V	0.000V
5	6.102V	7.717V	6.199V	0.000V
6	0.525V	0.380V	0.449V	0.000V
7	3.123V	4.452V	4.207V	0.000V
8	0.134V	0.270V	0.345V	0.000V
9	0.259V	0.855V	0.915V	0.000V
10	0.426V	0.187V	0.522V	0.000V
11	1.481V	1.769V	1.676V	0.000V
12	0.156V	0.454V	0.311V	0.000V
13	2.141V	2.538V	2.803V	0.000V
14	0.330V	0.312V	0.356V	0.000V
15	0.172V	0.500V	0.460V	0.000V
16	0.096V	0.148V	0.241V	0.000V
17	0.382V	0.536V	0.889V	0.000V
18	0.230V	0.157V	0.289V	0.000V

(a) (b)

[Fig. 11] Simultaneous current harmonic data monitoring results: (a) Supply side (b) Load side

4. Conclusions

The power monitoring system with multiple sensor channels (voltage-8 channels and current-10 channels) to simultaneously analyze power components and harmonics in several points of power system has been designed and implemented. Voltage and current measurement errors of the developed system were revised, and accuracy of power (active, reactive and apparent power) and harmonic measurement was tested by comparing power components outputted in the standard ac power source with that calculated by the developed system. All the test results show that the measurement error is less than 0.2 %. For field test, the developed system was connected with load (or demand) and supply (or source) side of three-phase power system that the capacitor and inductor to improve power factor were installed.

As the results of field test, it was certificated that monitoring of power components for all phases of load and source side using the developed system with multiple sensor input can be simultaneously implemented and the developed system can be effectively applied to measure power components of power system in order to solve power disturbances. Consequently, the proposed power monitoring system can be applied to meet the specific requirement such as several point power monitoring or analysis. Future work to reduce the measurement error and minimize the proposed system will be need.

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Jeong-Chay Jeon [Regular member]

- Feb. 1999 : Wonkwang Univ., Electrical Engineering, MS
- Mar. 2000 ~ current : Electrical Safety Research Institute, senior researcher

<Research Interests>
Measurement and control system, Power quality, intelligent control and embedded systems

Hun Oh [Regular member]

- Aug. 1993 : WonKwang Univ., M.S
- Aug. 1997 : WonKwang Univ., Ph.D
- Oct. 2011 ~ current : WonKwang Univ., Professor

<Research Interests>
Photovoltaic Power Generating System, Renewable energy