Design and Implementation of a DSP-Based Multi-Channel Power Measurement System

Jeong-Chay Jeon† and Hun Oh*

Abstract - In order to improve energy efficiency and solve power disturbances, power components measurement for both the supply and demand side of a power system must be implemented before appropriate action on the power problems can be taken. This paper presents a DSP (Digital Signal Processor)-based multi-channel (voltage 8-channel and current 10-channel) power measurement system that can simultaneously measure and analyze power components for both supply and demand. Voltage 8-channel and current 10-channel measurement is made through voltage and current sensors connected to the developed system, and power components such as reactive power, power factor and harmonics are calculated and measured by the DSP. The measured data are stored in a personal computer (PC) and a commercial program is then used for measurement data analysis and display. After voltage and current measurement accuracy revision using YOKOGAWA 2558, the developed system was tested using a programmable ac power source. The test results showed the accuracy of the developed system to be about 0.3 percent. Also, a simultaneous measurement field test of the developed system was implemented by application to the supply and demand side of the three-phase power system.

Keywords: digital signal processor (DSP), harmonics, multi-channel, power measurement

1. Introduction

As electric facilities and circuits of industrial plants and buildings become more and more complex, various problems including malfunction of control devices, data loss of computer systems and overheating of cables and transformers have been generated. Harmonic distortions due to the use of nonlinear loads such as computers, adjustable speed drives and electric furnaces bring about significant troubles in the electric power system [1]. Also, the concerns related to energy saving due to global warming and the decrease of energy resources has been on the rise in recent years. In particular, electric energy saving in industrial plants and buildings is of great concern in order to reduce goods production and equipments management cost.

These problems and concerns taken together have created the need for the measurement of power components such as active, reactive and apparent power, root-mean-square (rms) values of voltage and current, power factor, and power quality [2, 3]. There are many variants of power measurement available in the field ranging from hand-held instruments to portable monitors. These instruments have voltage 4-channel and current 5-channel and provide three-phase and four-wire metering. Therefore, they can measure individual power components of supply or demand of the three-phase four-wire power system. But, in order to effectively improve energy efficiency and solve power disturbances, measurement of power components for both the supply and the demand side of the power system must be implemented before appropriate action on power problems can be taken [4].

This paper presents the DSP-based multi-channel (voltage 8-channel and current 10-channel) power measurement system that can simultaneously measure power components for either the supply or the demand side of the power system. The DSP reads the digital voltage and current data from a multi-channel analog to a digital (A/D) converter and stores these values into data arrays in the memory. At this time, the DSP performs frequency analysis by Fourier conversion on each cycle of voltage and current using the 128-point radix 2 Fast Fourier Transform (FFT) algorithm in which the number of input points must be a multiple of 2, and calculates power (active, reactive and apparent power), power factor and so on.

Using YOKOGAWA 2558, which is used in standard calibration equipment, voltage and current measurement error revision work to improve measurement accuracy of the developed system was performed. The accuracy of active, reactive and apparent power measurement and harmonic analysis by the developed system was tested using a programmable ac power source (PACIFIC 345

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AMX). The test results indicated that accuracy is about 0.3 percent. In the field test of the developed system, the measurement of power components for all phases of the load and the source side in a three-phase power system was simultaneously implemented.

2. The system architecture and hardware

Fig. 1 presents the basic block diagram of the proposed multi-channel power measurement system. The proposed system largely consists of an analog signal input block with voltage 8-channel and current 10-channel measuring sensors, analogue to digital conversion (ADC) block converting analog signal into digital signal, digital signal processing block controlling circumference installations and performing operation function, programmable logic device (PLD) block performing system interface processing, memory block of static RAM (SRMA) and flash ROM (FROM), interface block to transfer the metering results to a personal computer via a serial link for display, and operation power source block supplying operation power of the proposed system. The proposed system was constructed on a single printed circuit board (PCB) as shown in Fig. 2.

2.1 Voltage and current signal input block

The voltage and current signal input block consists largely of the voltage and current input circuit, voltage follower circuit and low pass filter circuit. In the voltage signal input circuit, a voltage divider using a high precision resistor was designed in order to convert a voltage signal to a magnitude suitable for inputting the A/D converter channel.

In order to protect the system from surge and over-voltage, varistor TNR 20D751K and zener diode 1.5KE15 were used respectively. Also, in order to protect the system

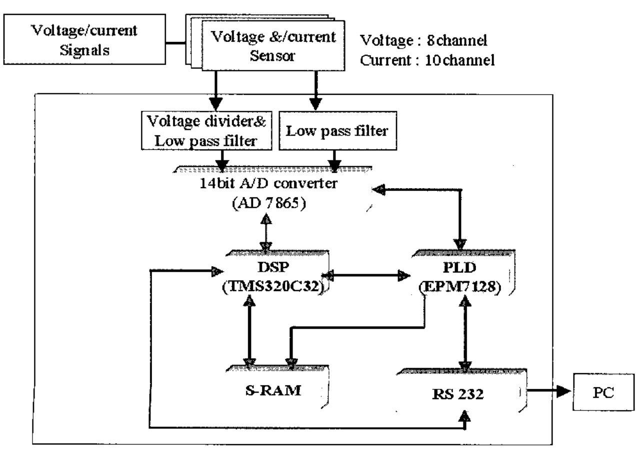


Fig. 1 Block diagram of the proposed system

from over-current, Raychem's poly switch fuse SMD 150 was used in the voltage and current signal input circuit. To reduce measurement error by the impedance of signal input circuit, the voltage follower circuit was used.

According to sampling theory, in order to determine sampling rate (or sampling frequency) in the ADC process, the highest frequency components of continuous signal must be limited. In this work, the band of interest is approximately DC to 3 kHz. Therefore, low pass filters (or anti-aliasing filters) to prevent voltage and current signal above 3 kHz were designed.

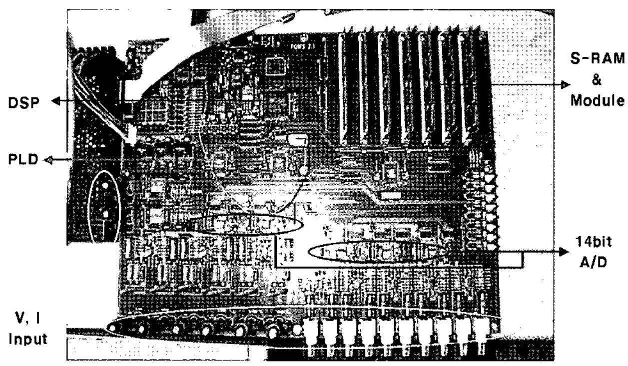


Fig. 2 Photograph of the developed system

2.2 ADC block

The voltage and current signal adjusted into signal suitable to ADC are simultaneously converted into digital signal. At this time, a sampling frequency of 7.68 kHz (i.e. 128 samples per cycle) is chosen so that the proposed system can measure up to the 64^{th} harmonic of 60 Hz. In order to simultaneously convert the analog signal of voltage 8 and current 10 channel into digital signal, the ADC circuit was designed by using an Analog Device 14 bit A/D converter AD 7865 having an analog input 4 channel of AC level and conversion start signal input ability. As well, in order to limit only the element in the event of element trouble occurring in the address and data bus of the ADC and guarantee security of the system in the case of any trouble, the proposed system used an 8 bit bi-directional buffer 74F245 between the DSP and A/D converter.

2.3 Digital signal processing and PLD block

The A/D converted data are transmitted to the TMS 320C32 DSP of the digital signal processing circuit. The TMS320C32 is a high-performance 32-bit floating-point DSP, and provides enhanced external memory interface with a 24-bit address bus, 32-bit data bus and faster in-structtion cycle time. For more details about the TMS 320C32 refer to [5].

In order to meet abnormal conditions such as operating error and power failure and save on measurement environment and processing states, EEPROM electrically erasable (EEPROM) 24LC32 was connected to the DSP. And a digital temperature sensor LM75CIM was used to revise temperature characteristics of OP-AMP by measuring the internal temperature of the system.

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 the operation speed of the DSP that is operated in the high frequency of 60 MHz.

2.4 Memory and others block

In order to save the data calculated by the DSP and quickly perform the processor program, the memory block was designed by connecting the 4Mbit S-RAM K6R4008 in serial and parallel. The memory block was set up in the system PCB using a 72pin SIMM socket. The program memory of the DSP was designed by using AMD's FROM 29F040.

The proposed system had serial ports using standard RS 232 protocol for interface with the 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 the PC, and Maxim's MAX232 for RS232C interface with a PC was used.

3. The system operation

The basic operation of the developed system was presented in the flowchart in Fig. 3. After the reset signal is inputted by RESET-IC DS 1233Z-6 and initialization of the DSP, the UART IC, the memory and ADC is performed, the developed system is operated according to the Mode_ process routine that performs ADC, MSR (Measurement) and COM (Communication) modes as shown in Fig. 4.

ADC_Mode chooses the measurement channel such as 1p1ch (single-phase and one channel), 1p2ch (single-phase and two channel), 3p1ch (three-phase and one channel) and 3p2ch (three-phase and two channel), and ADC operating conditions are inputted. After operating conditions of ADC channels are determined and the pertinent timer interrupt and the address to store ADC data are assigned, the timer interrupt is operated and voltage and current signal data are converted to digital data. Relevant interrupt is operated by ADC end signal and ADC raw data are stored in the memory.

MSR_Mode is consisted of five routines as shown in Fig. 5. First, the Cvt_Bit (Conversion Sign_Bit) routine converts 14bit ADC raw data to 32bit raw data that is suited to the DSP. In order to minimize calculation and conversion error, these raw data are converted to the magnitude of real data by the Cvt_Scale (Conversion Scale) routine. The Cvt_FFT (Conversion Fast Fourier Transform) routine calculates voltage and current harmonic order and magnitude by FFT on voltage and current data, Cvt_THD (Conversion Total Harmonic Distortion) routine calculates voltage and current THD. Finally, Cvt_Pwr (Conversion Power) routine calculates power factor and active, reactive and apparent power. In COM_Mode, the measured data can be collected

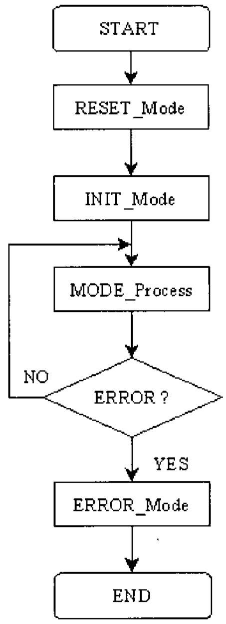


Fig. 3 Basic operation flowchart of the developed system

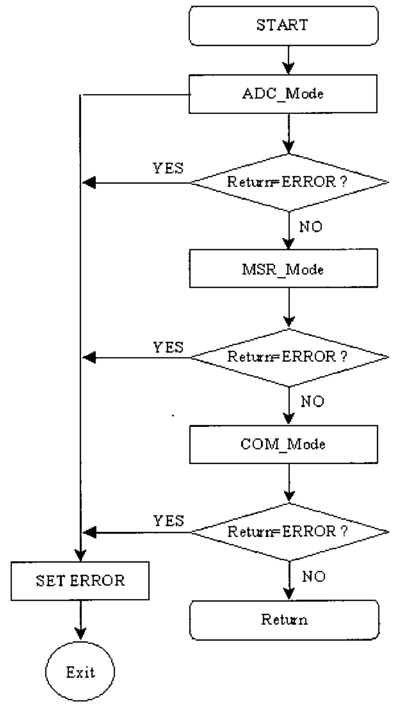


Fig. 4 MODE_Process routine flowchart

from the developed system by commanding it to output the data to the PC, and the data are stored and displayed on the PC.

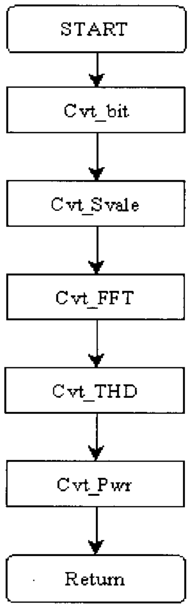


Fig. 5 MSR_mode routine flowchart

4. Revision of voltage and current measurement error

Voltage and current measurement error must be revised before the developed system is tested in a field. In order to confirm voltage and current measurement error on each voltage 8-channel and current 10-channel of the developed system, YOKOGAWA 2558, which is used as an ac voltage & current standard revision instrument, was used. The results of voltage and current measurement indicated that most of the errors in the developed system are due to gain error of the ADC rather than error by the voltage divider, voltage-follower and low-pass filter.

In order to revise voltage and current measurement error of the developed system, maximum values (Vpp-max and Ipp-max) on voltage and current rms values (Vrms and Irms) measured by the developed system were adjusted to theoretical maximum values.

Table 1 presents theoretical voltage and current rms and maximum values used to revise measurement errors of the system. Tables 2 and 3 present voltage and current values before and after error revision measured by the developed system. Fig. 6 and 7 representatively indicate voltage and current waveforms, which are measured by each channel of the system, before and after voltage and current measurement errors revision at 440Vrms and 180Irms respectively. Following measurement error revision of the developed system, voltage and current measurement values were coincided with theoretical maximum values in all channels of the proposed system as shown in Fig. 6 and 7.

Table 1 Voltage and current values used to revise measurement errors of the developed system

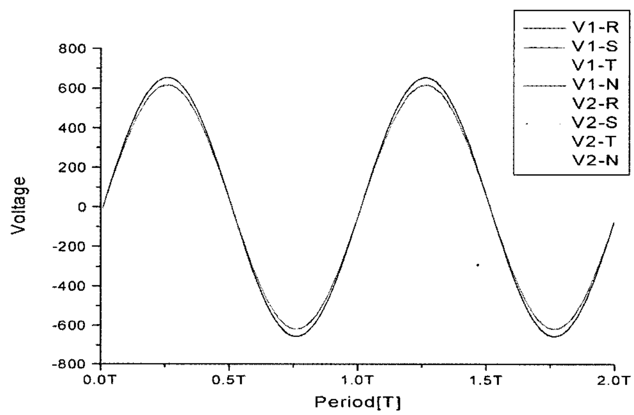
Standard Input-Voltage		Standard Input-Current	
Vrms [V]	Vpp-max [V]	Irms [A]	Ipp-max [A]
110	155.56	30	42.43
220	311.13	60	84.85
380	537.40	120	169.71
440	622.25	180	254.56

Table 2 Voltage values before and after errors revision

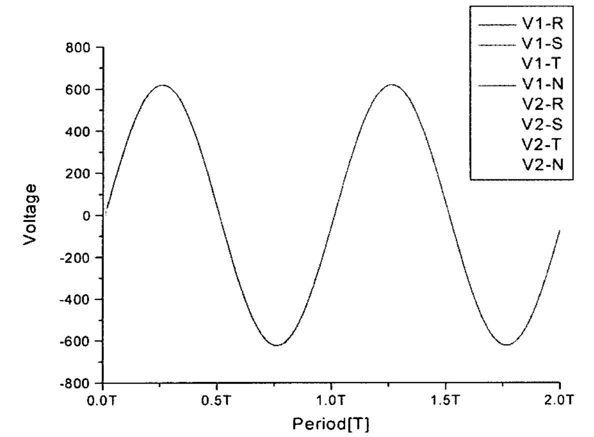
Channel	Vpp-max (440Vrms)		
	Standard Value [V]	Measured Value [V]	Value after Revision [V]
V1-R	622.25397	657.52302	622.259397
V1-S		657.08705	
V1-T		654.12249	
V1-N		655.51758	
V2-R		617.32701	
V2-S		617.76297	
V2-T		616.45508	
V2-N		616.97824	

Table 3 Current values before and after errors revision

Channel	Vpp-max (440Vrms)		
	Standard Value [A]	Measured Value [A]	Value after Revision [A]
I1-R	254.55844	276.61140	254.55844
I1-S		275.14640	
I1-T		273.55960	
I1-N		275.14640	
I1-G		257.69040	
I2-R		257.73740	
I2-S		255.61520	
I1-T		256.95800	
I1-N		256.95800	
I1-G		253.54000	

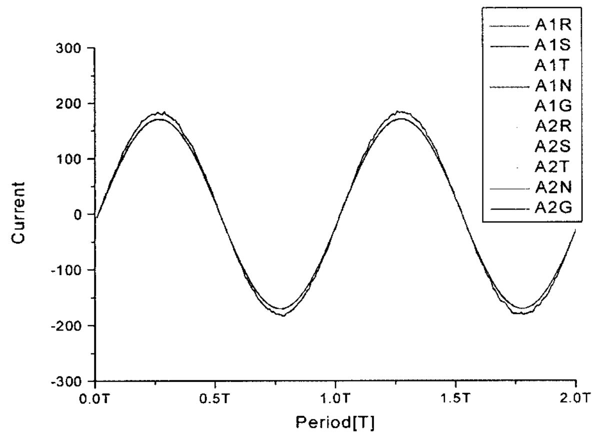


(a) Before

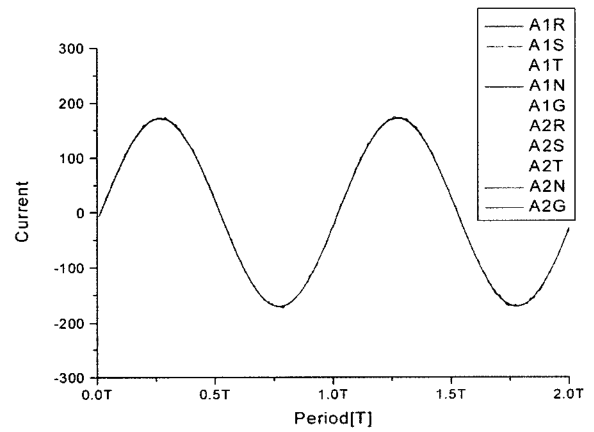


(b) After

Fig. 6 Voltage revision at 440Vrms



(a) Before



(b) After

Fig. 7 Current revision at 180Arms

5. Test and results

First, accuracy of power (active, reactive and apparent power) measurement and harmonic analysis by the developed system were tested. Then, the test system, which is consisted of programmable ac power source (PACIFIC 345AMX) and load, was constructed. Programmable ac power source can produce voltage with arbitrary magnitude and frequency. Test results indicated that the developed system yielded less than 0.3 % error in all cases.

In order to verify that the developed system can simultaneously measure power components for both the supply and demand side of the power system, the developed system was connected with load and source sides of the three-phase power system as shown in Fig. 8. The power system of Fig. 8 used a 100 HP DC motor to produce automobile soundproofing material, and a capacitor bank was used to compensate reactive power. In points 1 and 2 (supply and demand side) of Fig. 8, power components such as current waveforms, reactive power and harmonic current spectrum will show different values or pattern because of reactive power compensation and harmonic current reduction by capacitor and inductor. Therefore, in order to effectively prevent power disturbances and improve energy efficiency, simultaneous measurement of power components for both the supply and the demand side of the power system by the proposed method is required.

In Fig. 8, power components such as voltage and current waveforms, reactive power and harmonic current spectrum are simultaneously measured by the developed system and are expressed by the Microcal^{TM} Origin program (version 6.0) installed in the PC. Fig. 9 shows the field test scene of the developed system.

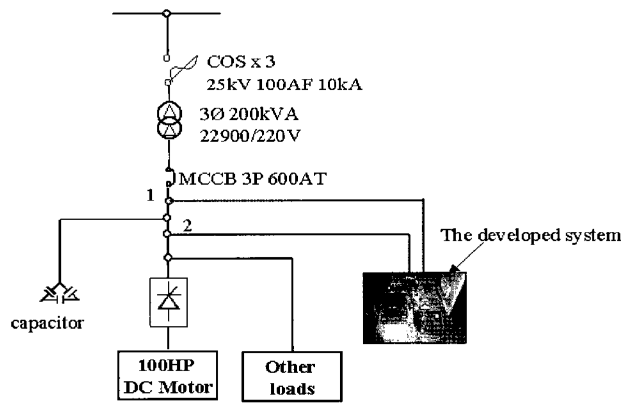


Fig. 8 Wiring diagram for field test of the developed system

Fig. 9 Field test scene

Fig. 10 and 11 indicate three-phase voltage and current waveforms of source and load (points 1 and 2 of Fig. 8 respectively). In Fig. 10, the voltage waveforms for points 1 and 2 of Fig. 8 were similar to the sine wave. But the current waveforms for points 1 and 2 of Fig. 8 presented different waveforms from each other. The current waveforms for point 2 were distorted because of harmonic currents due to the DC motor drive and other loads, and the current waveforms for point 1 were similar to the sine wave because of the reduction of harmonic current by the capacitor and the inductor.

Fig. 12 illustrates variation of the apparent power magnitude for a phase (R phase) of points 1 and 2 according to operating conditions of the DC motor and capacitor in Fig. 8. In Fig. 12, it was confirmed by simultaneous measurement using the developed system that the apparent power magnitude for points 1 and 2 differ from each other according to operating conditions of the DC motor and open and close status of the capacitor.

Fig. 13 indicates the current harmonic magnitude spectrum for points 1 and 2 of Fig. 8. In Fig. 13, the harmonic spectrum for points 1 and 2 are simultaneously confirmed by the developed system. In the case of 5^{th} harmonic currents of Fig. 13, it was confirmed that the harmonic current for point 1 shows a decrease compared with the harmonic current for point 2 because of reduction of harmonic current by the capacitor and inductor.

As the results of the field test, it was certificated that measurement of power components for all phases of load and source side using the developed system can be simultaneously implemented and the developed system can be effectively applied to measure power components of the power system in order to solve power disturbances. Consequently, the proposed multi-channel power measurement system can be applied to meet specific requirements such as several point power monitoring or analysis.

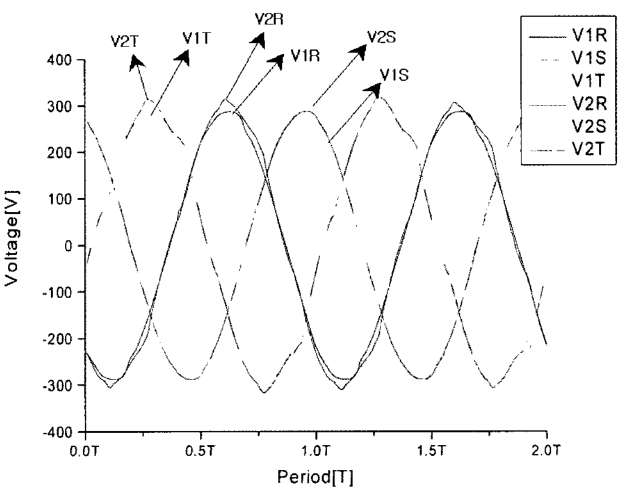


Fig. 10 Voltage waveforms

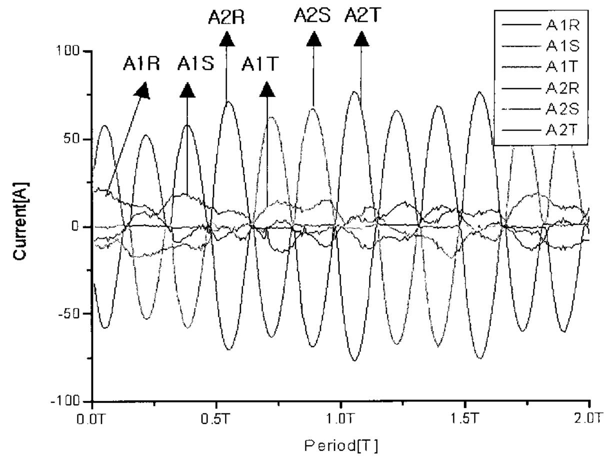


Fig. 11 Current waveforms

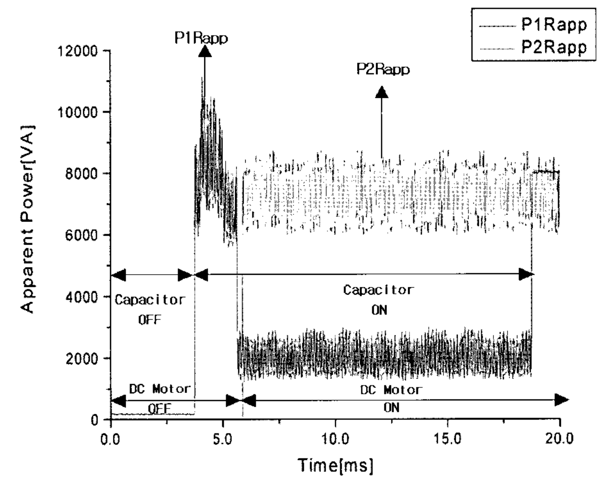


Fig. 12 Apparent power

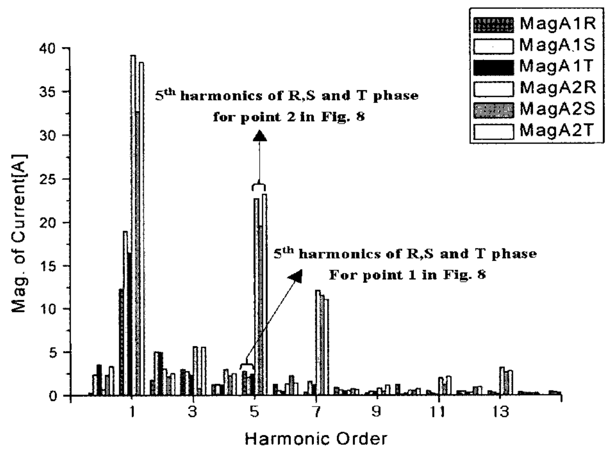


Fig. 13 Harmonic magnitude spectrum

5. Conclusion

In this work, the DSP-based multi-channel (voltage 8-channel and current 10-channel) power measurement system to simultaneously analyze power components and harmonics in several points of a power system was 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 programmable ac power source with that calculated by the developed system. All the test results indicated that the measurement error is less than 0.3 percent. For the field test, the developed system was connected with the load and source side of the three- phase power system in which the capacitor and inductor to improve power factor were installed. The result of the field test indicated that the measurements of power components for all phases of load and source side were simultaneously implemented.

As the results of the field test, it was certificated that the measurements of power components such as voltage and current waveforms, reactive power and harmonics for all phases of the load and source side using the developed system can be simultaneously implemented and the proposed system can be effectively applied to measure power components of the power system in order to solve power disturbances.

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