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Implementation of a Web-based Instrument System Integrating Power Quality Monitoring into Smart Meter

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ABSTRACT: In this paper, a web-based single phase smart meter system is built utilizing multiple microprocessors.The meter structure consists of four units to implement the instrumentation and measurement of electric energy, power parameters, and power quality. It provides the users with the real-time information by displaying it on the meter, web pages and mobile phone, which is updated at regular intervals. Finally, a prototype was built up, and the tested results validate the feasibility of the smart meter system.

KEYWORDS: Smart Meter, Advanced Metering Infrastructure, Power Quality, Web-based Instrumentation andMeasurement

I.INTRODUCTION

To reduce power consumption and increase electric network operation efficiency, information technology and intelligent appliances have been increasingly employed in smart grid to regulate a user's loading [1-3]. And the fundamental of a smart grid is Advanced Metering Infrastructure (AMI), whose kernel is the smart meter.
Besides, high-tech industry is under rapid development, and a great number of precise instruments and power quality sensitive devices are widely adopted in the modern power network. Various high-efficient power converters are also increasingly used for electric power energy conversion in different facility. The non-linear characteristics of this kind of loads have caused power quality distortion, such as harmonics, spike, notch, and etc. [4-6]. So power quality needs to be continuously monitored for the successful operation of all equipment's in a smart grid.
The effective solution of power quality problem depends on the accurate realization of on-line power quality characteristics. Since the smart meter is capable of power information acquisition and bidirectional communication [7-9], it can be used for remote power quality monitoring. In this paper, a prototype smart meter is built from a power IC (ADE7953), three different microprocessors (TMS320-F2407A, TMS320-F2812, and MSP430), signal conversion devices, and different communication modules. The functions of the system include electric power energy consumption recording, billing, and different power quality indices monitoring. Using the proposed system, one can easily understand the real time information of a user's load including electric power consumption and power quality which are transmitted and updated through the smart meter's communication network and client-server structure. The test results validate the feasibility of the prototype smart meter system.

II.POWER PARAMETERS AND POWER QUALITY INDICES

A. Definition Formula of Power Parameter:

In this paper, the on-line signal is sampled, and different power parameters and power quality indices are computed from the sampled data by the following definition formula:

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(1) RMS

The RMS value of voltage or current is calculated by Equation 1

$$RMS = \sqrt{\frac{1}{N}\sum_{n=1}^{N} f^2[n]} \qquad (1)$$

Where N be the total sample points and f[n] is the n-th sample value of f(t).

(2) Real Power

Real power is defined as work within unit period (T) and the calculation equation is as follows:

$$P = \frac{1}{nT}\int_0^{nT} p(t)dt = VI \quad (2)$$

Where p(t) is the product of voltage (v (t)) and current (i (t)), V andI are the RMS value of v(t) and i (t) respectively.

(3) Reactive Power

Conventionally, reactive power is defined as the average power within unit period, which is delivered to but not consumed by a circuit or device. It can be derived by the instantaneous reactive power q(t) as follows:

$$Q = \frac{1}{nT}\int_0^{nT} q(t)dt = VI \times \sin(\theta) \qquad (3)$$

Where, θ is the phase difference between voltage and current under purely sinusoidal condition.

(4) Electric Power Energy

Electric power energy is derived by accumulating real power, and it can be digitally computed as below:

$$E = \sum_{n=1}^{\infty} p(nT_s) \times T_s \qquad (4)$$

Where, T_S is as the sampling period of p(t).

B. Definition Formula of Voltage Variation:

According to IEEE Std.1159-2010, voltage variation can be classified into three categories:

1. Voltage rise (swell)
2. Voltage drop (sag) and
3. Complete loss of voltage (interruption).Their rms value ranges are 1.1~1.8 pu (swell), 0.1~0.9 pu (sag), under 0.1 pu (interruption) respectively. And each category can be divided into three types according to the event duration: (1) instantaneous (0.5 ~ 30 cycles), (2) momentary (30 ~ 180 cycles), or (3)

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temporary (30 ~ 180 cycles). For the real-time measurement of voltage variation, the following rms-value calculation method is used in this paper [10].

$$V_k = \sqrt{\frac{1}{M}\sum_{m=k-M+1}^{k} v_m^2} \tag{5}$$

$$V_{k+1} = \sqrt{\frac{1}{M}\sum_{m=k-M+2}^{k+1} v_m^2}$$

$$= \sqrt{\frac{1}{M}\left[\left(\sum_{m=k-M+1}^{k} v_j^2\right) - v_{k-M+1}^2 + v_{k+1}^2\right]}$$

$$= \sqrt{\frac{1}{M}\left[MV_k^2 + v_{k+1}^2 - v_{k+1-M}^2\right]} \tag{6}$$

Where V_m is the m-th voltage sample point and V_k is the k-th voltage RMS-value at k-th sampling instant.

C. Definition Formula of Voltage Flicker:

To quantify voltage flicker severity, different definitions have been proposed, and the index of equivalent 10-Hzcomponent, ΔV_{10}, is selected to describe the level of voltage flicker in this paper. The definition formula of ΔV_{10} is as follows:

$$\Delta V_{10} = \sqrt{\sum_i \left(\alpha_i \times \Delta V_i\right)^2} \tag{7}$$

Where α_i is the flicker sensitivity factor and ΔV_i is two times of the voltage flicker amplitude V_{fi} at the frequency of f_i in the range from 0.1 Hz to 30 Hz.

D. Definition Formula of Harmonics:

Harmonics is caused by nonlinear load operation in power system, and a distorted voltage can be expressed as follow:

$$v_L(t) = \sum_{j=1}^{N} \sqrt{2} V_{Lj} \times \sin\left(j \times \omega t + \varphi_j\right) \tag{8}$$

Where, V_{Lj} andψ_j are the RMS value and the phase angle of j-th order voltage harmonic respectively. To quantify voltage harmonic distortion, Total Voltage Harmonic Distortion Factor (THD_v) is defined as follow:

$$THD_v = \frac{\sqrt{\sum_{j=2}^{N}\left(V_{Lj}^2\right)}}{V_L} \tag{9}$$

Where V_L is the rms value of the fundamental voltage.

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III.SMART METER SYSTEM STRUCTURE

The proposed smart meter system comprises three major sections shown as Figure1: Digital Power Meter Unit (DPMU), Metering Interface Unit (MIU), and Data Management Unit (DMU). In the DPMU, the raw voltage and current signals are separately sampled and analyzed for electric power energy consumption and power quality measurements. The real-time accumulative electric energy information is stored into EEPROM module and then delivered to MIU through the Dual Port RAM (DPR) modules, DPR1 and DPR2, which are the buffers among different microprocessors, and the on-line power quality conditions are also measured and transferred at different instants. Both the electric energy and power quality information are passed to DMU which consists of Data Center and client-server platform.

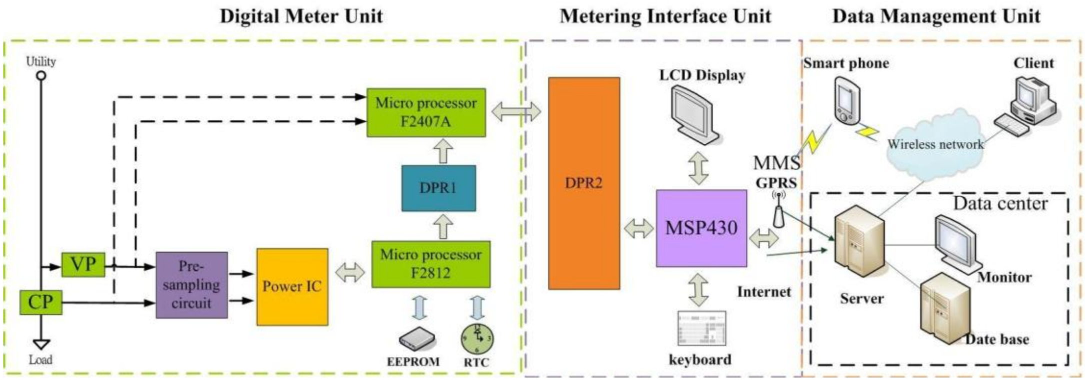

Figure 1: Simplified structure of the smart meter system

To implement various functions of the smart meter system, Figure 2 shows the flowchart of the software main programs. Firstly, all microprocessors are initialized and then the microprocessor, TMS320-F2812, starts to sample the electric power signals from the output of the power IC, ADE7953. And the power energy consumption is calculated and stored to the memory device, EEPROM, at a fixed time interval of 7.5 seconds. Besides, different power parameters, such as real power, reactiveare temporally stored into DPR1 and then transferred to DPR2 by the microprocessor, TMS320-T2407A. Finally, the Metering Interface Unit (MIU) will upload the power information in DPR2 to DMU through the Internet or to the user’s mobile phone by the wireless communication of GPRS module. Similarly, the raw voltage and current signals will be sampled and analyzed periodically to collect power quality information including harmonics every 15 seconds and voltage flicker every one minute. The individual operation of DPMU, MIU, and DMU is described as follows:

A. Digital Power Meter Unit:

From Figure 1, we can see the hardware structure of dual-core microprocessor, including TMS320-F2812 and TMS320-F2407A. The power system voltage and current signals are respectively attenuated and isolated by Voltage Probe (VP) and Current Probe (CP) and the output signals of VP and CP are then inputted to a pre-sampling circuit of the power IC (ADE7953) which is used to measure the power parameters including real power, reactive power, power factor, rms voltage and rms current. All of these power parameter information are then processed by the microprocessor, TMS320-F2812, according to the flow chart shown in Figure 3. Similarly, Figure 1 also illustrates that the output signals of VP and CP are sampled and analyzed by the microprocessor, TMS320-F2407A, for power quality analysis including harmonics and voltage flicker, and Figure 4 shows the process for DPMU to collect power quality information including harmonics and voltage flicker.

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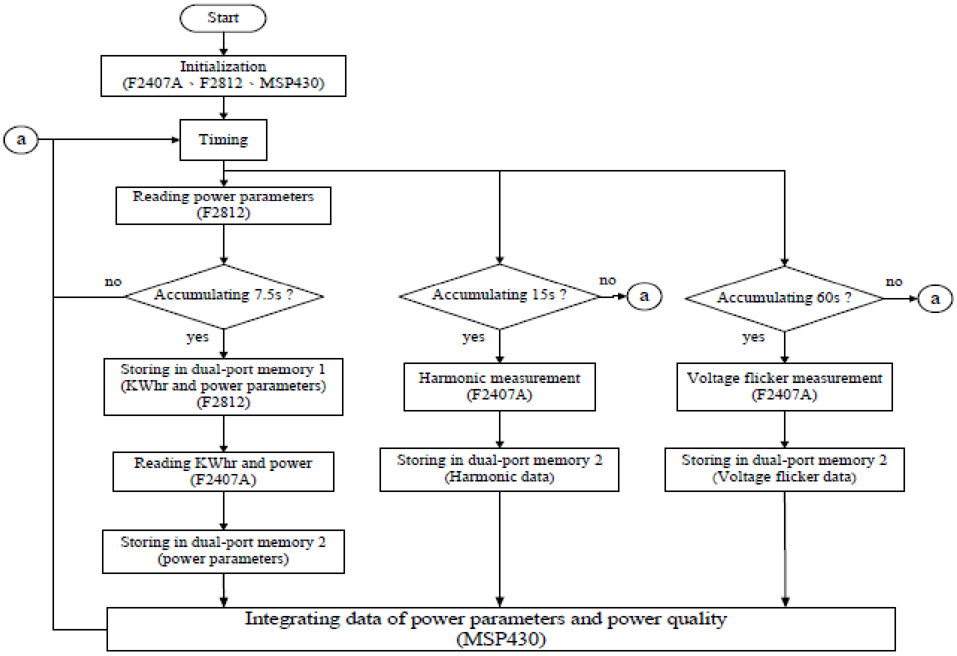

Figure 2: Flow chart of the main program for the smart meter system

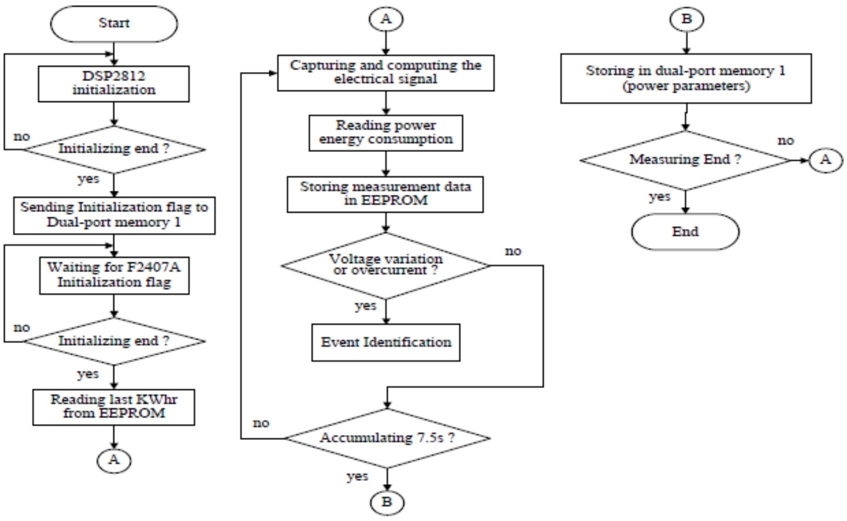

Figure 3: Flow chart for DPMU to collect power parameters and voltage variation information

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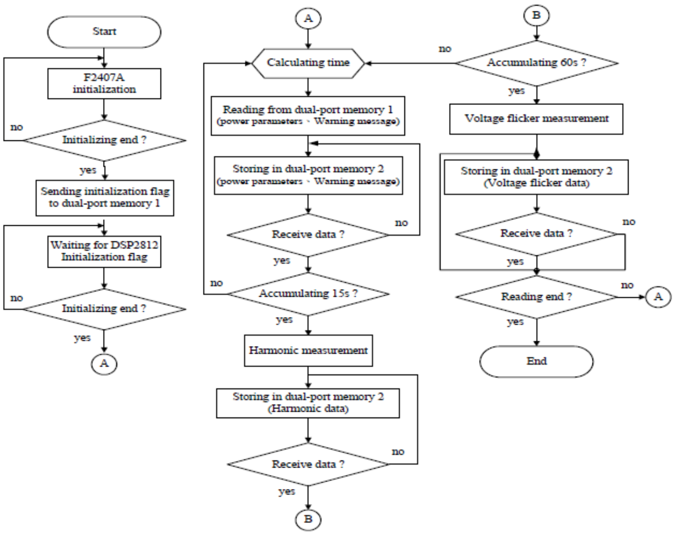

Figure 4: Flow chart for DPMU to collect harmonics and voltage flicker information

B. Metering Interface Unit:

The microprocessor, MSP430, is the kernel of the module.It receives the power parameters and power quality measurement results from DPMU as shown in Figure 1. Meanwhile, all data are displayed and refreshed on the LCD monitor at different time period of 7.5 seconds, 15 seconds, or 60 seconds. Different power parameters and power quality indices can be also selected and displayed on LCD monitor according to user's demand. Besides, MIU will upload all power and power quality information to DMU through Internet and in case of an emergent event, such as overload or voltage sag, the relevant information will be automatically sent to a particular cellular phone through GPRS module. The flow chart for above data processing is shown in Figure 5.

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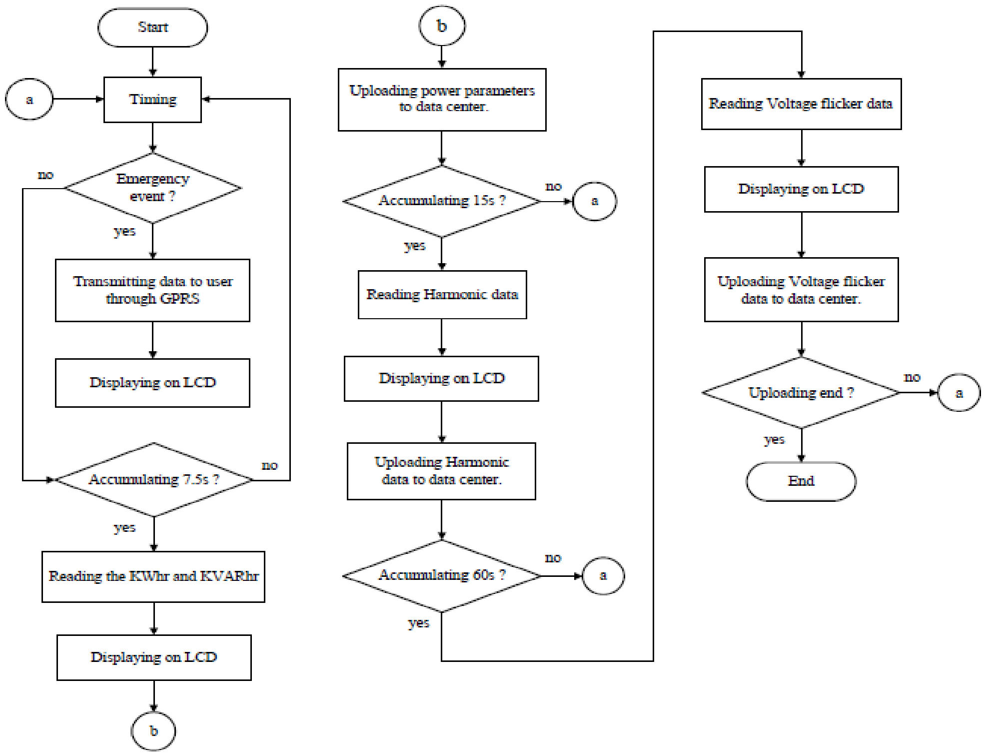

Figure 5: Flow chart for MIU to display power parameters and power quality information on the LCD monitors and transfer data to DMU

IV.TEST RESULTS

To validate the functions and the feasibility of the proposed smart meter system, a series of tests were respectively performed in the laboratory for electric power parameters and power quality measurements, and the results are described as follows.

A. Metering Measurement Performance:

Firstly a commercial digital power meter, Voltech PM100, and the proposed prototype metering system are used to measure the power parameters for the same load, a projector with the specifications of 110V and 240W, and the results are shown as Table 1. We can see that the accuracy of the proposed system is acceptable since the respective error compared with the corresponding data by PM100 is within 1.5%.

Parameter	Measurement Results by Different Meters		
	PM1 00	DSP Calculation	Error (%)
V_{rms}	115.00	114.97	0.03
I_{rms}	1.91	1.92	-0.52
S	219.30	220.72	-0.66
P	218.10	217.10	0.46
PF	0.995	0.984	1.11

Table 1: Power Parameter Measurement Comparison

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B. Electric Power Parameters Measurement:

Figure 6 shows the test results on the LCD display for a low voltage user's load, including rms voltage and current (V_{rms} and I_{rms}), apparent power (S), real power (P), reactive power (Q), power factor (PF), electric energy and billing. The spinning disc symbol is used to simulate the operation of a classical mechanic watt-hour meter, and the spinning speed is proportional to the real power consumption.

Figure 6: Typical test results for electric power parameters measurement by the proposed smart meter prototype for a power line in laboratory

C. Power Quality Measurement:

An autotransformer is used to simulate voltage variation events, such as voltage sag or swell. Figure 7 shows the typical test result for a voltage sag disturbance, it can be seen that the voltage amplitude and duration are respectively equal to 64% and 0.827 seconds. In addition, MIU sent an alarm message to the user's cellular phone through GPRS module since the variation exceeded a preset level in the case shown in Figure 8, the sag severity was 96.52% (voltage amplitude was 3.48%) for a duration of 0.755 seconds. For the other power quality disturbances including voltage flicker and harmonics, a power circuit supplying nonlinear loads such as PC, projector, and etc. was monitored, and the typical test results were shown in Figure 9 and Figure 10.

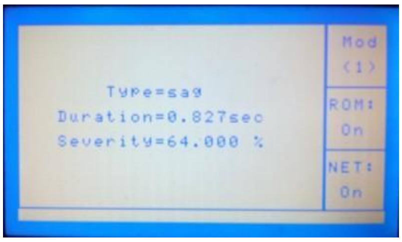

Figure 7: Voltage sag event measurement result by the proposed smart meter system in power quality monitoring mode

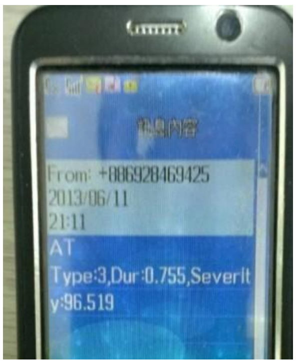

Figure 8: Typical alarm message sent to the user's cellular phone through GPRS mode

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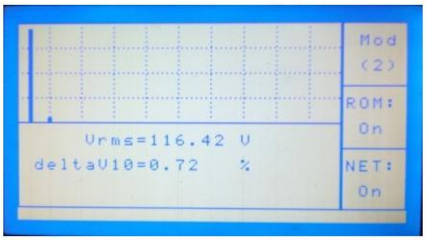

Figure 9: Voltage flicker measurement result by the proposed smart meter system in power quality monitoring mode

Figure 10: Harmonics measurement result by the proposed smart meter system in power quality monitoring mode

D. Utility Power Failure:

The proposed smart meter can not only provide power quality and power parameters information, but also it will record and display utility power failure information on the MIU LCD. This function can help user understand when a power failure event occurred, and Figure 11 shows a typical utility power failure event that happened at 11:30 am, 17 June 2013.

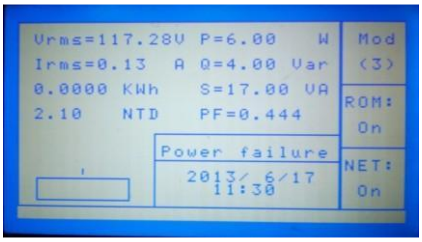

Figure 11: A typical utility power failure event on the MIU LCD display

E.Web Pages for Power Information:

As power parameters and power quality indices are uploaded to DMU by MIU, they will be stored to database and displayed on different web pages immediately. The typical test results are shown from Figure 12 to Figure 17 for differenttrends of RMS voltage, voltage flicker (V_{rms} and ΔV_{10}), harmonic (THD_V), and power parameters (V_{rms}, I_{rms}, S, P, Q, PF, and power energy).

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Figure 12: Web page showing voltage flicker trend

Figure 13: Web page showing voltage harmonics trend

V.CONCLUSIONS

Smart meter is the kernel of Advanced Metering Infrastructure (AMI) which is the key factor for a successful smart grid. Besides, power quality needs to be guaranteed for a modern power system. Therefore, a smart meter system with power quality monitoring function is proposed in this paper. The meter system is built using multiple low-cost microprocessors to increase its feasibility. A single phase prototype meter system was built, and the desired functions were tested in the laboratory. The important results include: (1) The smart meter is successfully implemented with a power IC (ADE7953) and three different microprocessors (TMS320-F2407A, TMS320-F2812, and MSP430), and a mini data management unit is also constructed using client-server mode, (2) The performance of the smart meter is proved from the laboratory test results, (3) Users can easily understand the real-time information about the electric power consumption, emergent power circuit event, and power quality variation through browsers with Internet connection.

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