Development of a Smart Power Meter for AMI Based on ZigBee Communication

Shang-Wen Luan Jen-Hao Teng Shun-Yu Chan* Lain-Chyr Hwang
Member IEEE
Department of Electrical Engineering,
I-Shou University,
Kaohsiung, Taiwan
*Department of Electrical Engineering,
Cheng-Shiu University,
Kaohsiung, Taiwan

Abstract: Many governments deploy ubiquitous IT project, which aims to combine the latest wireless network and wide-band technologies etc. to accomplish a ubiquitous wireless communication network. The ubiquitous wireless communication network can be utilized for the Advanced Metering Infrastructure (AMI). Therefore, this paper tries to use the new wireless communication technologies to design and implement a ZigBee-based smart power meter. An outage recording system is also designed and embedded into the smart meter. The microcontroller of Microchip dsPIC30F series is used to develop the proposed smart power meter. A ZigBee system is then deigned and integrated into the proposed power meter, and used to transmit the detailed power consumption data and outage event data to rear-end processing system. The proposed smart power meter cannot only be used for power consumption data collection but also for outage event data recording. The proposed system has great potential to be used to build the area-based AMI. Experimental results demonstrate the validity of the proposed system. Besides, the application of ZigBee communication in power area may, expectedly, lead to make a definite contribution to ubiquitous IT project.

Keywords: Ubiquitous IT Project, Wireless Network, Advanced Metering Infrastructure, Smart Power Meter, ZigBee

I. Introduction

Generally, distribution automation includes the functions of substation automation, feeder automation, automatic meter reading and automatic build-up of geographic information system and so on. Recently, the concept of smart grids which features higher utilization of power grid, demand reduction, and extensive usage of renewable energy source, is accepted and implemented all over the world. Smart grids are used to accomplish an advanced power system with automatic monitoring, diagnosing, and repairing functions. The installation of Advanced Metering Infrastructure (AMI) is looked upon as a bridge to the construction of smart grids; especially, while most of the power meters are still mechanical ones without digitization. An AMI consists of smart meter, communication technology, meter data management, and associated software and hardware. From the operational experiences of AMI in other countries, there are many advantages along with AMI; however, the construction of AMI is not easy due to the complicated communications between millions power meters [1-5].

In power engineering applications, the use of wireless technology can profit customers by integrating wireless network into AMI, outage event recording, and the like. There are many kinds of wireless network standards and ZigBee, a low-speed LR-WPAN (Low-Rate Wireless Area Personal Network) based on IEEE 802.15.4 standard, is one of them. ZigBee has been designed to have general-purpose protocol, and low-cost and low-power-consumption wireless communications standard by ZigBee Alliance. The ZigBee application profile includes home automation, industrial plant monitoring, commercial building automation, automatic meter reading, telecom services/m-commerce, wireless sensor networks, personal home and hospital care and so on [6-12]. Most of the power meters are still mechanical ones without digitization; therefore, the gathered data are inherently limited and man-power cost is enormous. If the power meters are digitized and combined with ZigBee networking, customers can transmit the power consumption data via ZigBee network to rear-end processing system. It cannot only save the man-power cost but also exhibit detailed power consumption information, and thus, providing the power company with comprehensive and complete data for further analysis.

This paper tries to design and implement a ZigBee-based smart power meter. A value-added function, the outage recording system is also designed. The microcontroller of Microchip dsPIC30F series is used to develop a smart power meter. A ZigBee system is then deigned and integrated into the proposed power meter, and used to transmit the detailed power consumption data and outage event data to rear-end processing system. Experimental results show the validity of the proposed system.

II. The Proposed Smart Power Meter

Fig. 1 shows the system architecture of the proposed ZigBee-based smart power meter and outage recording system. The full system can be divided into two parts: the ZigBee-based power meter and the rear-end processing system. Firstly, the voltage and current waveforms of loads are acquired by a data acquisition module and then converted to digital signal through the ADC module of MCU. The digital information are stored in the internal memory and used to carry on the power consumption calculation and outage event recording if necessary. The rear-end processing system is composed of a ZigBee coordinator and the software designed for the proposed smart power meter. The software of the proposed rear-end processing system is used to establish the power consumption and outage event database as well as to offer the inquiries of power consumption data and outage data recorded in the proposed smart power meter.

ZigBee network supports star, tree, and mesh topologies. In a star topology, the network is controlled by one single device called the ZigBee coordinator. The ZigBee coordinator is responsible for initiating and maintaining the devices on the network. All other devices, known as end devices, directly communicate with the ZigBee coordinator. In mesh and tree topologies, the ZigBee coordinator is responsible for starting the network and for choosing certain key network parameters, but the network may be extended through the use of ZigBee routers. In tree networks, routers move data and control messages through the network using a hierarchical routing strategy [11, 12]. The proposed smart power-meter and the rear-end processing system are equipped with a ZigBee device and a ZigBee coordinator, respectively. With the automatic networking characteristic of ZigBee, smart power meter serving as a node apparatus will communicate with the ZigBee coordinator of rear-end processing system and ZigBee network can then be constructed to accomplish the meter-reading function. After the ZigBee network was constructed, the rear-end processing system can send the request commands to the ZigBee coordinator and receive the power consumption data and outage event data from the power meter. Therefore, the automatic meter reading can be accomplished.

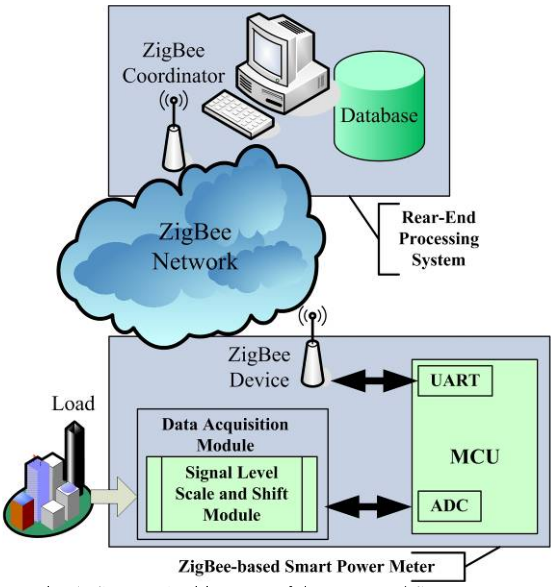

Fig. 1: System Architecture of the Proposed Smart Meter

The smart power meter is developed based on the MCU of Microchip dsPIC30F4011 [13-15]. The firmware designed in MCU can be divided into four parts: 1) power consumption calculation subroutine; 2) power consumption recording subroutine; 3) interruption calculation subroutine and 4) outage event recording subroutine. The firmware design in MCU can be used to calculate and record power consumption data and record five outage events with their interruption time, interruption durations and restoration time if an outage event occurred;. Visual Basic 2005 and Access 2003 are the tools used to design the human-machine interfaces of rear-end processing system. Four interfaces are designed in this paper; they are ZigBee-based real-time data acquisition for local AMI, customer information center, power consumption information center, and outage event information center. The detailed design concepts are similar to those proposed in [16]; however, they are not shown here due to limited space. The design and integration of ZigBee into the proposed smart power meter will be described in the next section.

III. ZIGBEE-BASED SMART POWER METER

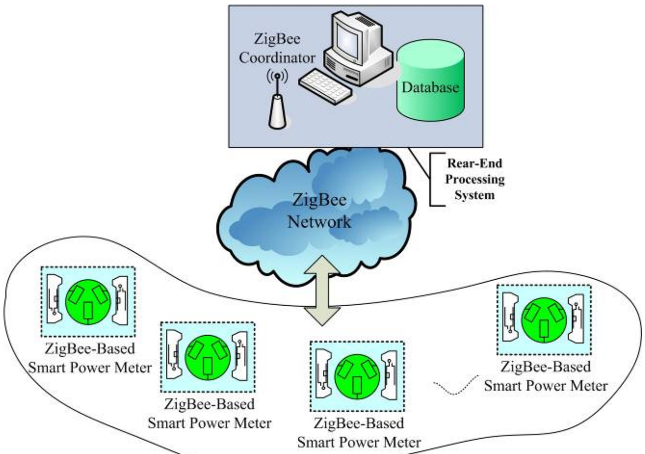

Fig. 2: The Concept of ZigBee-based Automatic Meter Reading System

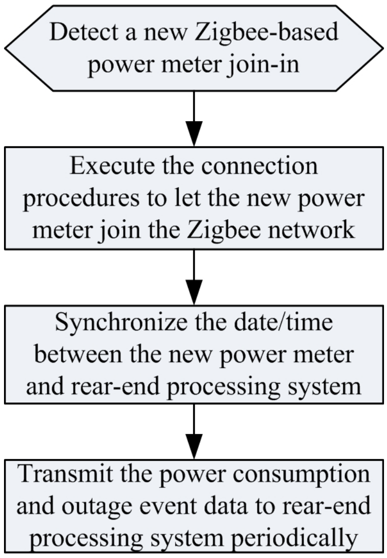

Fig. 3: The Flowchart for the ZigBee Network Construction and Data Transmission

In this paper, the smart power meter and rear-end processing system are equipped with a ZigBee device and a ZigBee coordinator, respectively. The star ZigBee network is employed; and therefore, ZigBee coordinator is responsible for initiating and maintaining the ZigBee devices of smart power meters. Then, the network for automatic meter reading can be constructed as the concept demonstrated in Fig. 2. Fig. 3 shows the flowchart of integration of ZigBee-based smart power meter into the ZigBee network and transmits the requested power consumption data and outage event data. From Fig. 3, it can be seen that while a new ZigBee-based smart power meter is detected by the ZigBee coordinator, the coordinator will execute the initialization and connection procedures to let the meter join the ZigBee network. The power meter will then execute the date/time synchronization; afterward, the power meter will have the correct time information and can transmit the power consumption and outage event data to rear-end processing system periodically. Fig. 4 shows the flowchart for date/time synchronization. From Fig. 4, it can be seen that the power meter transmits the date/time synchronization command from its ZigBee device to the ZigBee coordinator after the power meter join the network. If the whole command is received by the rear-end processing system, then the date/time data will be transmitted to the power meter via ZigBee coordinator and the date/time synchronization is then completed. If the data/time synchronization was accomplished successively, the procedure for power consumption data and outage event data transmission can be carried out periodically. Due to limited space, the flowcharts for power consumption data and outage event data transmission are not shown here.

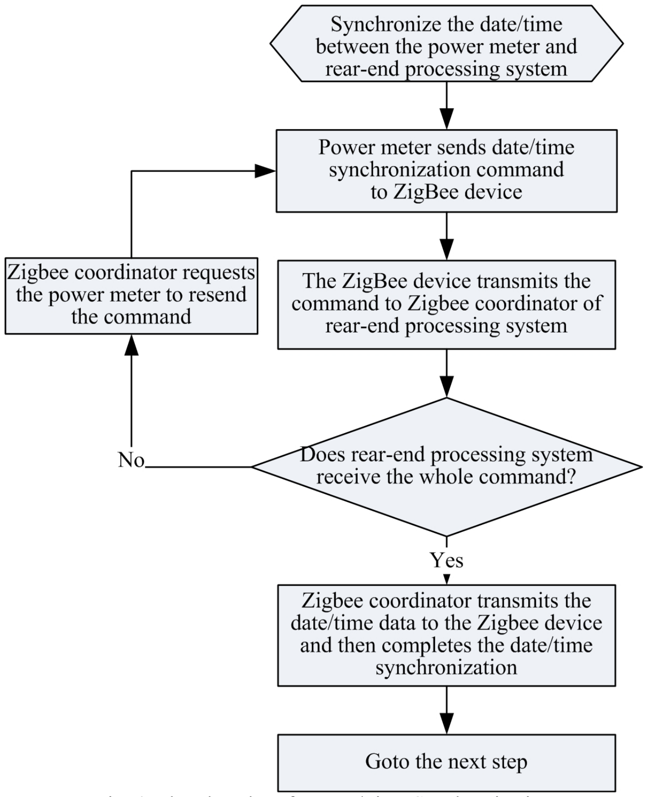

Fig. 4: The Flowchart for Date/Time Synchronization

In this paper, the data transmission format between power meter and rear-end processing system is shown in Table 1 and can be categorized into three groups. Group 1 represents real-time measured data of power meter consisting of power meter ID, measured date/time, voltage, current, frequency, power factor, and so on. Forty-one bytes is used to record the data of group 1. Group 2 stands for power consumption data including 41 bytes of real-time measured data and 17 bytes of power consumption data, thus, 58 bytes in total. Except for the bytes of real-time measured data, it is comprised by 4 bytes of real power consumption (kWh), 4 bytes of reactive power consumption (kVARh) and 9 bytes of recording data/time. Group 3 corresponds to outage event data with 97 bytes data length. The first 3 bytes is the number of outage events and the corresponding year information and the last 90 bytes store five outage event data. An outage event is recorded with 18 bytes, wherein, 5 bytes are used to store interruption time, 5 bytes for restoration time, 4 bytes for pre-outage real power (kW), and the other 4 bytes correspond to pre-outage reactive power (kVAR). Additionally, the above-mentioned three data groups can be distinguished according to the request commands wherein 0x04 request power meter to transmit its real-time power data, 0x05 request power meter to transmit its power consumption data, and 0x06 request power meter to transmit its outage event data.

IV. Experimental Results

A ZigBee-based smart power meter has been realized in this paper. Through the ZigBee network, the rear-end processing system used to acquire the power consumption and outage event data and store those data in rear-end database is also accomplished. In the experiments, an 800 Watt load is used for testing. In the development of ZigBee network applications, it is very important to make sure that the stacks for protocols between the ZigBee coordinator and ZigBee devices are precisely transmitted and received. Therefore, a ZENA wireless network analyzer [14, 15] is used to inspect and examine the correctness of data transmission between coordinator and devices. With the smart power meter being initialized, the connection procedures between ZigBee coordinator and ZigBee device will be executed to let the power meter join the ZigBee network. Afterward, the date/time synchronization will be carried out. Fig. 5 shows the data frames transmitted and received between ZigBee coordinator and ZigBee device for date/time synchronization. It can be clearly checked from Fig. 5 that the commands and data transmitted and received between ZigBee coordinator and ZigBee device. Fig. 6 shows the date/time synchronization interface of rear-end processing system and the date/time shown in smart power meter. As shown in Fig. 6, after the "OK" button in the smart power meter was pressed, the date/time synchronization will be completed.

Table 1: Data Transmission Format between Power Meter and Rear-end Processing System

Group 1: Real-time Measured Data (41 bytes)					
Power Meter ID	Date/Time	Voltage	Current	Power Factor	Frequency
16 bytes	9 bytes	4 bytes	4 bytes	4 bytes	4 bytes

Group 2: Power Consumption Data (58 bytes)								
Power Meter ID	Date/Time	Voltage	Current	Power Factor	Frequency	Date/Time for Power Consumption	Real Power (kWh)	Reactive Power (kVARh)
16 bytes	9 bytes	4 bytes	4 bytes	4 bytes	4 bytes	9 bytes	4 bytes	4 bytes

Group 3: Outage Event Data (93 bytes)					
No. of Event	Date/Time	Interruption Time	Restoration Time	Pre-outage Real Power (kW)	Pre-outage Reactive

<table>
<tr><td></td><td></td><td></td><td></td><td></td><td>Power (kVAR)</td></tr>
<tr><td>1 bytes</td><td>2 bytes</td><td>5 bytes x5</td><td>5 bytes x5</td><td>4 bytes x5</td><td>4 bytes x5</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="6">Commands Between Power Meter and Rear-end Processing System</td></tr>
<tr><td colspan="2">Request Power Meter to Transmit its Real-time Power Data (1 byte) = 0x04</td><td colspan="2">Request Power Meter to Transmit its Power Consumption Data = 0x05</td><td colspan="2">Request Power Meter to Transmit its Outage Event Data (1 byte) = 0x06</td></tr>
</table>

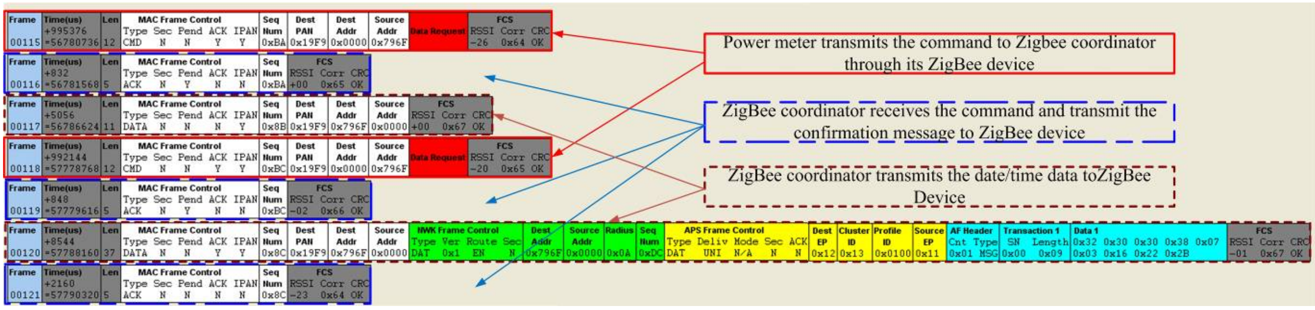

Fig. 5: Data Frames for Date/Time Synchronization

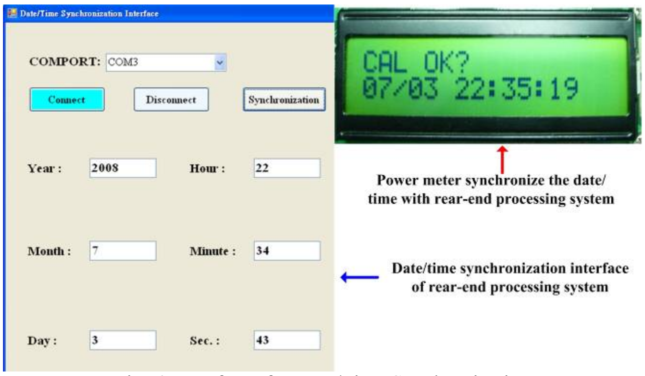

Fig. 6: Interfaces for Date/Time Synchronization

Afterward, the power meter has the correct date and time information and can transmit the power consumption and outage event data to rear-end processing system periodically. For example, if the rear-end processing system asks the power meter to transmit the real-time measured data, then the data frames as shown in Fig. 7 will be transmitted. Obviously, the command transmitted is 0x04. After the command was received by the power meter, the data frames as shown in Fig. 8 will be transmitted sequentially. From Fig. 8, it can be clearly seen that the power meter ID, date/time, voltage, current, power factor and frequency measured in the power meter are all transmitted precisely. Those data will be received by the rear-end processing systems and then stored in the rear-end database. The data frames for outage event data transmission are similar to those in Figs. 7 and 8; therefore, they are not shown here. Two outage events are simulated to test the outage event recording system. Fig. 9 shows the human-machine interface for real-time data acquisition. As illustrated in Fig. 9, the real-time measured data, power consumption data and outage event data are all displayed. Therefore, the proposed ZigBee-based smart power meter can be used for measuring real-time data, calculating power consumption data and recording outage event data successively, and also be used to transmit those data to rear-end processing system via ZigBee network precisely.

V. Conclusions

A ZigBee-based smart power meter was designed and implemented in this paper. The rear-end processing system used to acquire the power consumption and outage event data and store those data in rear-end database was also accomplished. Experimental results demonstrated the validity of the proposed system and showed that the proposed system can be effectively integrated into AMI. In addition, the proposed ZigBee-based smart power meter can be further extended and integrated into intelligent home automation; and therefore, a really "Ubiquitous" society can be created.

VI. Acknowledgements

This work was sponsored by National Science Council, Taiwan, under research grant NSC 96-2221-E-230-026-MY2。

VII. References

[1] "California Smart Grid Study," EPRI Aug. 2008
[2] "San Diego Smart Grid Study Final Report," SAIC Smart Grid Team, Oct. 2006
[3] Vojdani, A.; "Smart Integration," IEEE Power and Energy Magazine, Vol. 6, Issue 6, November-December 2008, pp. 71 – 79
[4] EU Smart Grids Framework "Electricity Networks of Future 2020 and beyond"
[5] Hart, D.G.; "Using AMI to Realize the Smart Grid," IEEE PES General Meeting, July 2008, pp.1 - 2
[6] Miaoqi Fang; Jian Wan; Xianghua Xu; Guangrong Wu; "System for Temperature Monitor in Substation with ZigBee Connectivity," IEEE International Conference on 11th Communication Technology, Nov. 2008, pp. 25 - 28
[7] Bo Chen; Mingguang Wu; Shuai Yao; Ni Binbin; "ZigBee Technology and its Application on Wireless Meter-reading System," IEEE International Conference on Industrial Informatics, Aug. 2006, pp. 1257 - 1260
[8] Yi-Hua Liu; Shun-Chung Wang; Po-Yen Chen; "Development of a Zigbee-based Electronics Ballast System," 6th IEEE International Conference on Industrial Informatics, July 2008, pp. 1556 - 1561
[9] Cao, Liting; Tian, Jingwen; Liu, Yanxia; "Remote Wireless Automatic Meter Reading System Based on Wireless Mesh Networks and Embedded Technology," Fifth IEEE International Symposium on Embedded Computing, Oct. 2008, pp. 192 - 197
[10] Liting Cao; Jingwen Tian; Yanxia Liu; "Remote Real Time Automatic Meter Reading System Based on Wireless Sensor Networks," 3rd International Conference on Innovative Computing Information and Control, June 2008, pp. 591 - 591
[11] "Wireless Medium Access Control (MAC) and Physical Layer (PHY)

Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs)," IEEE 802.15.4-2003, New York, October 2003.
[12] "ZigBee Specification," ZigBee Alliance, ZigBee Document 053474r17, January 2008.
[13] Microchip corporation, http://www.microchip.com/
[14] "PICDEM Z Demonstration Kit User's Guide" http://www.microchip.com", Microchip Technology Inc., 2007.
[15] "ZENA Wireless Network Analyzer User's Guide" http://www.microchip.com", Microchip Technology Inc., 2007
[16] Shun-Yu Chan, Shang-Wen Luan, Jen-Hao Teng, Ming-Chang Tsai, "Design and Implementation of a RFID-based Power Meter and Outage Recording System," IEEE International Conference on Sustainable Energy Technologies, Singapore, 2008.

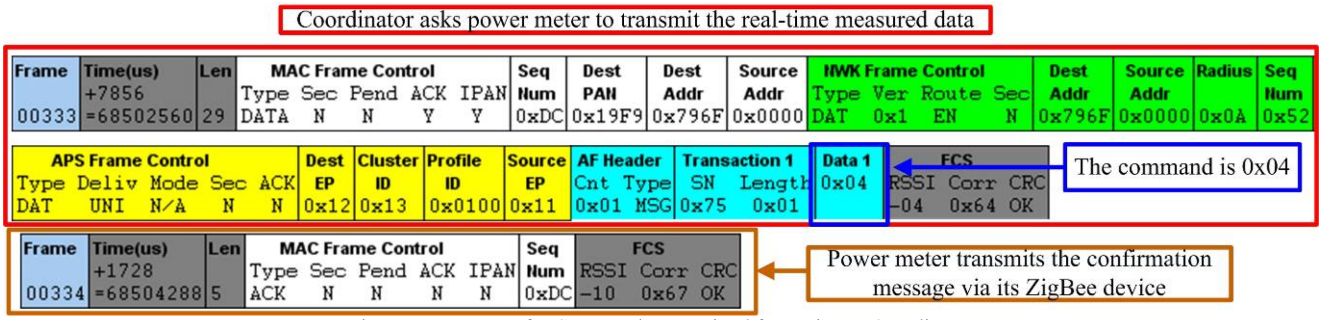

Fig. 7: Data Frames for Command Transmitted from ZigBee Coordinator

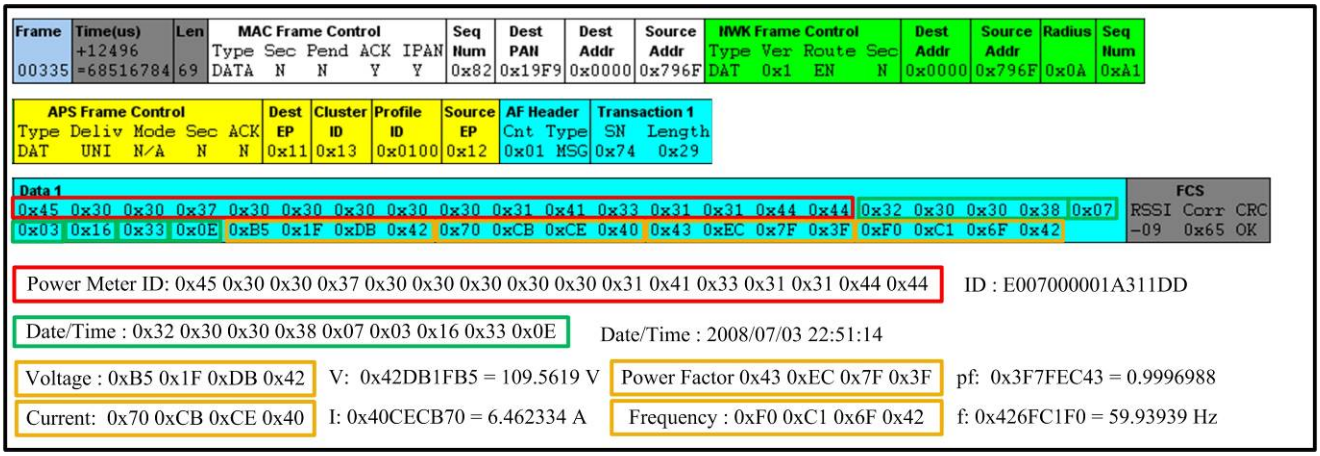

Fig. 8: Real-Time Measured Data Transmit from Power Meter to Rear-End Processing System

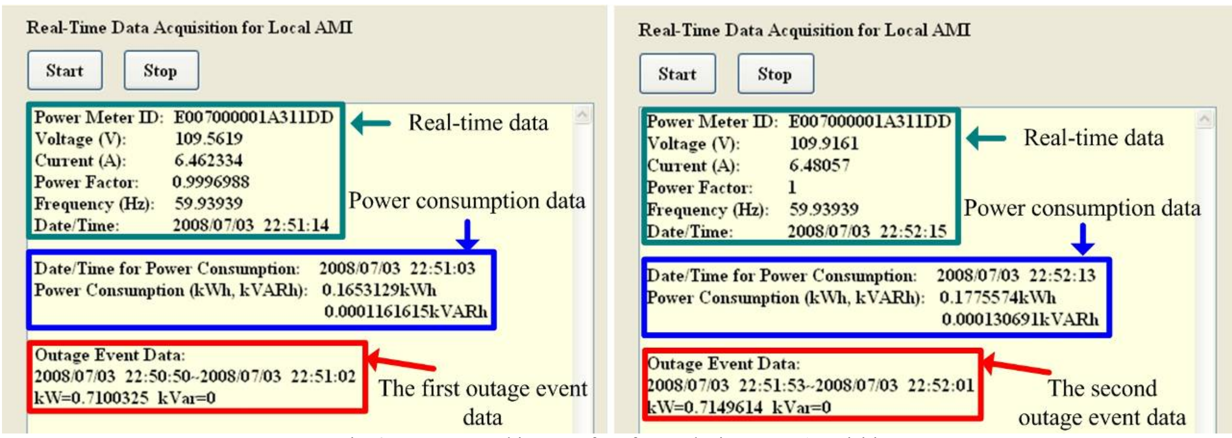

Fig. 9: Human-Machine Interface for Real-Time Data Acquisition