A Low Cost Smart Meter Network for a Smart Utility

Gianluca Aurilio, Daniele Gallo, Carmine Landi, Mario Luiso
1Department of Industrial and Information Engineering
Second University of Naples
Via Roma 29, 81031 Aversa (CE), Italy
mario.luiso@unina2.it

Giorgio Graditi
ENEA Portici Research Centre
P. E. Fermi, 1 - 80055 Portici (Naples) - Italy
giorgio.graditi@enea.it

Abstract—As the electric transmission and distribution networks gain smartness from the use of renewable energies and latest measurement and communication technologies, also the utilities become smart. In a modern utility several energy sources are present and energy efficiency has to be guaranteed. Therefore, in order to be a smart utility, it has to be equipped with a measurement and control network to efficiently manage the various energy sources and loads. In this paper a low cost solution for the real-time energy management in a smart grid is presented. It provides several power meters, that continuously monitor connected loads communicating with a Data Concentrator via Power Line bus. Through the implemented web server the users can remotely control their consumption using a web browser. To prevent external attacks, a low computational cost protection software, based on Advanced Encryption Standard Code, was implemented. The paper illustrates the hardware architecture, discusses the adopted communication protocol solutions and is completed with an example of energy monitoring for a smart utility.

Keywords—Smart Grid; Smart Meter; Power Quality; Power Line Communication; Cyber Security

I. INTRODUCTION

As the electric transmission and distribution networks gain smartness from the use of renewable energies and latest measurement and communication technologies, also the utilities become smart. In a modern utility several energy sources are present and energy efficiency has to be guaranteed. Therefore, in order to be a smart utility, it has to be equipped with a measurement and control network to efficiently manage the various energy sources and loads ([1]-[7]). The key element of such a measurement and control network could be a smart meter. Smart Meters are electronic measurement devices used by utilities to communicate information for billing customers and operating their electric systems. The benefits of Smart Metering installations are numerous for many different stakeholders of the systems. The benefits for utility customers are: a better access and data to manage energy use, a more accurate and timely billing, an improved and increased rate options, an improved outage restoration and the monitoring of Power Quality data. For the Customer Service and Field Operations are: a reduced cost of metering reading, an elimination of handheld meter reading equipment, a reduced call center transactions, a monitoring data for improved efficiency, reliability of service, losses, and loading ([8]-[12]).

So in this paper a low cost solution for the real-time energy management in a smart grid is presented. It provides several power meters, that continuously monitor connected loads communicating with a Data Concentrator via Power Line bus. Through the implemented web server the users can remotely control their consumption using a web browser [14]. To prevent external attacks, a low computational cost protection software, based on Advanced Encryption Standard Code, was implemented. The paper illustrates the hardware architecture, discusses the adopted communication protocol solutions and is completed with an example of energy monitoring for a smart utility.

The paper is organized as follows. In Section II the main communication technologies are presented. In Section III a measurement network architecture is proposed and in Section IV the cyber security and the adopted communication protocol is shown. Finally in Section V some preliminary experimental results are shown.

II. MAIN COMMUNICATION TECHNOLOGIES

Smart Meters are varied in technology and design but operate through a simple overall process. The Smart Meters collect data locally and transmit them via a Local Area Network (LAN) to a Data Concentrator. Then data are transmitted via a Wide Area Network (WAN) to the utility central collection point for processing and use by business applications. Two solutions could be adopted for a smart meter network implementation: Radio Frequency (RF) and Power Line Communication (PLC). Factors that impact on the selection of the technology include evaluation of existing infrastructure, legal aspects, functionality and technical requirements [15].

A. Radio Frequency – RF

Smart Meter measurements and other data are transmitted by wireless radio from the meter to a Data Concentrator. Advantages include acceptable latency, large bandwidth and the coverage of long distances. Disadvantages include terrain and distance challenges for rural areas, proprietary communications and multiple collection points.
B. Power Line Communication - PLC

Smart Meter measurements and other data can be transmitted across the utility power lines from the meter to a Data Concentrator. Advantages include the exploitation of existing utility infrastructure, in terms of poles and wires, improved cost effectiveness for rural lines, more effective in challenging terrains, and the capability to work over long distances. Disadvantages include long data transmit time, small bandwidth and throughput and higher cost in urban and suburban locations [16].

C. Radio Frequency Vs. Power Line Communication

In the proposed architecture the PLC technology is chosen. It is more secure against external manipulation. In fact, since the PLC is a “wired technology”, in order to perform an external attack a user has to be able to physically connect to the network. The network proposed in this paper is a Smart Utility that needs a low energy consumption, a low bit rate, being low the amount of data transmitted over the network and the possibility of using an existing infrastructure. These considerations led us to choose the PLC technology.

III. MEASUREMENT NETWORK ARCHITECTURE

The architecture of the proposed measurement and control network is shown in Fig. 1. It is composed by: N Smart Meters to monitor N loads, N PLC modems to interface each smart meter with the power line and one Data Concentrator with its PLC device to receive, store and process the data of the grid.

A. Smart Meter

The hardware of the Smart Meter consists of the following blocks: i) voltage and current transducers section, ii) a microcontroller (STM32F407VG) [17] to acquire and process the signals, iii) a local graphic interface display iv) a memory section to locally store measurement results.

Each meter (Fig. 2) acquires continuously voltage and current through a transduction and conditioning section. The measured quantities are: Voltage and Current Root Mean Square Value (RMSv and RMSi), Frequency (f), Active Energy (eA), Reactive Energy (eR), Active Power (P), Reactive Power (Q), Power Factor (PF), Voltage and Current Total Harmonic Distortion (THDV and THDI). These data are transmitted across the utility power lines from each meter to a Data Concentrator that makes decisions based on the consumption strategy adopted by the user ([18], [19]). Equations from (1) to (5) show the adopted mathematical formulas for the evaluation of the cited quantities.

\[
\begin{align*}
RMS_v &= \sqrt{\frac{1}{N} \sum_{k=1}^{N} v_k^2} \\
RMS_i &= \sqrt{\frac{1}{N} \sum_{k=1}^{N} i_k^2} \\
P &= \frac{1}{N} \sum_{k=1}^{N} v_k i_k \\
Q &= Q_{con} = \left( \frac{1}{N} \sum_{k=1}^{N} v_k \cdot i_k \right) \\
A &= RMS_v \cdot RMS_i \\
PF &= \frac{P}{A} \\
THD_v &= \sqrt{\frac{\sum_{k=1}^{M} v_k^2}{V_{\text{rms}}^2}} \\
THD_i &= \sqrt{\frac{\sum_{k=1}^{M} i_k^2}{I_{\text{rms}}^2}}
\end{align*}
\]

B. PLC Interface

The architecture of the Smart Meter network includes a master data aggregator and several slave microcontrollers. As shown in Fig. 1, each meter transfers data to concentrator through power line communication transceiver modules that are designed to send and receive serial data over the power line network. The communication interface between microcontroller and the power line transceiver is the RS232. The PLC power line communication modem (Fig. 3) consists of a motherboard and a UART-RS232 daughter board. This module has both physical and logic addresses. In a network, both physical and logic addresses can be used to address different nodes in the network.
This power line module can be connected directly to a microcontroller through the 3.3 V TTL UART interface. It works on 230Vac/50Hz, 110Vac/60Hz and 0-400Vdc power line through a FSK (Frequency Shift Keying) modulation used in physical layer with Carrier frequency of 262 kHz/144 kHz. The maximum data rate is 30 kbps, the maximum transmission distance is 90 m and the support nodes number is 65535. Module data packets are broadcasted through power lines. Logic address is composed of two parts: domain and nodes. For example, the logic address (10:200) means that the domain value is 10 and the node value is 200. Module data packets can only be received and processed by modules in the same domain [20].

C. Data Concentrator

The role of Data Concentrator is to receive the meter data from one or multiple Smart Meters, to verify and store the data and to deliver data subsets to the utility applications such as billing, outage management, etc. The Data Concentrator can check the power profile and energy consumption of each load and so it can disconnect a single load or to decide its time of use [21]. Furthermore the user can monitor, remotely through the web server and locally through the Data Concentrator display, the household loads and check the amount of the bills.

The Data Concentrator was realized with Raspberry Pi (Fig. 4) that is a System-on-a-chip (SoC) Broadcom BCM2835, which incorporates a processor ARM1176JZF-S 700 MHz, GPU Video Core IV, memory of 512 MB [22]. It works with SD card which hosts an operating system based on Linux kernel or RISC OS. In particular, we installed the Raspbian operating system, that is a version of the Debian on Linux kernel or RISC OS. In particular, we installed the Raspbian Operating System (DBMS MySQL) where storing data. 

The decision to use Python as programming language was taken for two reasons. The first is the presence of Python in the Raspberry Pi as a Personal Computer (PC) development language within Raspbian operating system; the second is the possibility to connect Python application directly to MySQL database. Another important aspect is the possibility to consult the concentrator data in the local network through the use of the browser using a PHP script with a direct connection to MySQL database.

IV. CYBER SECURITY AND COMMUNICATION PROTOCOL

The sensitivity of the data type and the reliability of the control within a network Smart Grid require security as a key requirement. To maintain the steady operation for smart power grid, huge measurement devices must be distributed generally among the power grid. This increase exposes more to the external attacks that can alter the load through the web server. It can create several problems, for example the disconnection of a load or the increase of the amount of billing modifying the time of use of a specific load. For these reasons, it becomes fundamental to develop techniques to improve cyber security of the communication network.

A. Cyber Security

The encryption algorithm chosen is The Advanced Encryption Standard (AES–128 bit). The AES is a specification for the encryption of electronic data established by the U.S. National Institute of Standards and Technology (NIST) in 2001. AES is based on a design principle known as a substitution-permutation network and is fast in both software and hardware [23].

B. Communication and Synchronous measurements

Each meter transmits the data according to the follow format:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Type</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID</td>
<td>int 4 Byte</td>
<td>-</td>
<td>Node identifier with 4 field</td>
</tr>
<tr>
<td>RMSV</td>
<td>float 4 Byte</td>
<td>V</td>
<td>Voltage Root Mean Square</td>
</tr>
<tr>
<td>RSHI</td>
<td>float 4 Byte</td>
<td>A</td>
<td>Current Root Mean Square</td>
</tr>
<tr>
<td>fS</td>
<td>float 4 Byte</td>
<td>Hz</td>
<td>Voltage Frequency</td>
</tr>
<tr>
<td>eA</td>
<td>float 4 Byte</td>
<td>Wh</td>
<td>Active Energy</td>
</tr>
<tr>
<td>eR</td>
<td>float 4 Byte</td>
<td>VARh</td>
<td>Reactive Energy</td>
</tr>
<tr>
<td>P</td>
<td>float 4 Byte</td>
<td>W</td>
<td>Active Power</td>
</tr>
<tr>
<td>Q</td>
<td>float 4 Byte</td>
<td>VAR</td>
<td>Reactive Power</td>
</tr>
<tr>
<td>PF</td>
<td>float 4 Byte</td>
<td>-</td>
<td>Power Factor</td>
</tr>
<tr>
<td>THDV</td>
<td>float 4 Byte</td>
<td>%</td>
<td>Voltage Total Harmonic Distortion</td>
</tr>
<tr>
<td>THDH</td>
<td>float 4 Byte</td>
<td>%</td>
<td>Current Total Harmonic Distortion</td>
</tr>
</tbody>
</table>

The data format is composed by: an “ID” field that is the identifier of the node in the local network; the 10 parameters described in section III. As shown in Table I, the identifier is composed by 4 byte of integer type and the other parameters are composed by 4 byte of float type. The total size of the data pack is 44 byte. Since the data are encrypted with the AES-128, the final size of the package is 64 byte.

The synchronous measurements can be reached with broadcast communication through the PLC-UART modem. The data can be acquired from Data Concentrator into two steps. In the first step the Data Concentrator broadcasts the request of the data at the time $t_0$, putting on the bus the char “*”. Each meter, belonging to the same domain, receives the request and store the data in the local memory update at time $t_0 + t_w$ where $t_w$ is the delay time. In the second step each meter sends in sequential mode the stored data to Data Concentrator which stores these data into database.

![Image of Data Concentrator Raspberry Pi model B.](Fig. 4)
The Data Concentrator provides the opportunity to examine the Smart Meters individually and it provides an intuitive interface where the user, via web server, can choose to query all nodes or a single node.

V. EXPERIMENTAL RESULTS

In order to experimentally validate the designed measurement network architecture, the block scheme represented in Fig. 5 is realized. It is composed by two Smart Meter to monitor two loads and a Data Concentrator. The Smart Meter’s PLC Modems are programmed whit address 1:2 and 1:3, while the Data Concentrator PLC Modem is programmed whit address 1:1. As loads we have connected two PCs. The implemented HTTP web server into Data Concentrator contains information regarding the power profile, the Energy consumption, and several Power Quality parameters ([24], [25]). The physical realization is shown in Fig. 6. In this figure is presented the Raspberry pi board with its display on the right and a Smart Meter with its display on the left.

The microcontrollers of the Smart Meters are programmed to acquire 5 periods of the 50 Hz voltage and current with two simultaneous analog to digital converters with resolution of 12 bits and a sample frequency of 10 kHz. With this configuration, the microcontroller processes 1000 samples of each signal and transfers the results to the display. When arriving the request from Data Concentrator, the microcontroller encrypts in AES-128 the last data and sends the data through PLC Modem. In Fig. 7 the Smart Meter display is shown. Each Smart Meter displays the list of parameters of the Table I and the acquired voltage and current waveforms.

A screenshot of the Local Data Concentrator Interface is shown in Fig. 8. This interface reports the parameters of the first load. In Fig. 9 is shown the remote response of the Data Concentrator that measures the parameters each four seconds.

In Fig. 10 we can see the view of the web site implementation written in PHP language. The user, through this interface, can brow into 4 pages: Home Page, Broadcast Page, Single Page and History Page. The user can choose to query all Smart Meters of the local network in broadcast or manual modality. In the History Page it is possible to query the database as shown in Fig. 11. In particular, the user can choose the Smart Meter, the time period and the parameter he wants to view. In Fig. 12 an example response is shown. In particular we can see the distribution of the Voltage, Current, Active Power, Reactive Power and Apparent Power.

VI. CONCLUSION

In this paper a low cost solution for the real-time energy management in a smart grid is presented. It provides several power meters, that continuously monitor connected loads communicating with a Data Concentrator via Power Line bus. Through the implemented web server the users can remotely control their consumption using a web browser. To prevent external attacks, a low computational cost protection software, based on Advanced Encryption Standard Code, was implemented. Experimental results are shown. From them it stems that the proposed Smart Meter network can be easily installed in a home and in an industrial grid with the possibility to monitoring the various loads through a local friendly user interface or the remote web server. In the future, in order to realize a complete smart utility, it will be equipped with a measurement and control network to efficiently manage the various energy sources and loads.
Fig. 8. The local Friendly User Interface of the Data Concentrator.

Fig. 9. A screenshot of the remote response of the Data Concentrator.

Fig. 10. The Home Page of the PHP interface.

Fig. 11. The History Page of the PHP interface.

Fig. 12. Example monitoring power profile.

VII. REFERENCES


