A Practical Approach to Smart Grids: New Energy Residential Gateways on PLC

Antonio Cuevas[1], Jaime Caffarel[1], Carmen Lastres[1], Rocío Martínez[1], Asunción Santamaría[1]
[1]Centro de Domótica Integral (CeDInt-UPM): Technical University of Madrid, Spain
{acuevas, jcaffarel, clastres, rocio, asun}@cedint.upm.es

Abstract— ***The successful deployment of Smart Grids needs simple, flexible and inexpensive solutions. This paper presents a functional Energy Residential Gateway using X10 protocol on PLC which provides a practical implementation of Energy Management (EM), Dynamic Pricing (DP) and Demand Response (DR) services in the home environment.***

Keywords- Smart Grids, Residential Gateways, Demand Response, Dynamic Princing, X10, A-10, Extended X10.

I. INTRODUCTION

The demand for electrical energy is increasing globally [1] [2]. Predictions on electrical energy needs, based on the current electrical energy models, envisage that the global energy consumption on Earth by 2050 will be double that of current consumption [1].

The implementation of Smart Grids is a necessity to achieve the objectives of energy efficiency that are a “must” for the future.

The key challenge faced by Smart Grid technologies is an efficient management of power grids. The electrical network infrastructure must be controlled, allowing Smart Metering services. Users will become an active part of distributed energy generation, by means of in-building renewable energies. So, the new generation Smart Grids will be decentralized networks. Smart Grids will also allow Demand Response (DR) and Dynamic Pricing (DP) services. These services are needed to control consumption depending on variations in the energy supply conditions established by the utility company.

The use of PLC for in-house electrical power management networks is one of the best options because the availability of the transmission media in every building. The ubiquity of the in-house, low-power grid facilitates the inclusion of devices into the network (electrical appliances and multimedia devices).

The X10 data transmission protocol is designed to send simple control frames between devices connected to the network. X10 on PLC is easy to use and inexpensive (there are several manufacturers of X10 control modules, and X10-PLC devices are commercially available at relatively low prices).

The X10 transmission protocol was designed to control home electrical devices. It has a limited range: 256 devices can be installed in houses of up to 185 m2. But this is not a limitation in most European countries, where the average house is 130 m2 [3]. Although the number of electrical appliances and devices in a house has increased considerably over recent decades [4], the average number of controllable electric devices remains less than 256. On the other hand, the basic command set of the X10 protocol is simple (switch on/off, set parameter or status request), but it is enough to meet the requirements of DR and DP Services.

DR Service allows energy consumption to be distributed during the day. The connection/disconnection of appliances and electrical devices can be automatically controlled depending on the power-supply conditions coming from the utility company.

The X10 command set includes on/off switching, light intensity regulation functions, transmission of sensor information data, transmission of state request commands or transmission of actuation functions. This paper presents an inexpensive and fully-functional system offering DR and DP services with the X10 protocol on PLC.

Residential Gateways are absolutely necessary to build Smart Grids. Residential Gateways are the interface between the house and the utility. The Home Area Network (HAN) connects the home nodes (electric devices and appliances) to the Residential Gateway. Users can program automatic activation/deactivation of devices in order to save as much energy as possible. But energy management can also be carried out using Ambient Intelligent Software Routines included in the Residential Gateway (the user’s actuation is not needed in these cases). Residential Gateways show instant and average electrical consumption.

DR allows the in-house electric power demand to be controlled as a response to a warning signal coming from the utility. DR services are suitable to [5]:

- Avoid Peak Clipping: drop in demand at critical periods.
- Allow Load Shifting: redistribution of the electric power demand based on energy prices.
- Valley filling: growth of the electric power demand at low-priced periods.

These three services are carried out under different pricing polices:

- Dynamic Pricing (DP) [6]: when the rate depends on Critical Peak Clipping (CPP), Time Of Use (TOU) and Real Time Pricing (RTP) [7].

- Demand Adjustments resulting from Incentive-based programs: classified as remote control and non-remote control.

This paper presents the implementation of a Residential Gateway for Energy Efficiency in Houses and its main characteristics. Section II presents the hardware and software architecture and the provided services. Section III presents the system performance analysis when implemented in a real environment. Finally, the conclusions are presented in Section IV.

II. Energy Residential Gateway (ERG)

The Energy Residential Gateway (ERG) presented in this paper has been designed to meet the following requirements:

- Easy to use: Home Area Network (HAN) devices can be controlled by means of a user-friendly graphical interface (Graphical User Interface - GUI) based on Qt libraries [8].
- Innovative services for efficiency: A new set of EM, DR and DP services addressed to customers and utilities are implemented in the ERG.
- Flexibility: The ERG is open to integrate ambient intelligence DR&DP algorithms aimed at saving energy automatically and flat the Power Demand Tracking without user interaction.
- Economical and plug-and-play solution: HAN reconfiguration (such as the inclusion of new devices) is carried out using software discovery routines. No changes in the physical network topology are needed because of the use of PLC.

A. ERG connection to the Smart Grid Architecture

The ERG is a part of a new Smart Grid model that includes a Utility Smart Grid Manager (USGM). USGM manages the communication of messages between the Utility transformer substation and each house/building.

The core of the Smart Grid is the Utility Management Platform (UMP). UMP manages elements, processes and services related to distributed generation systems, utility power and final user devices.

Communications between USGM and the ERG are established through an Internet connection provided by an Internet Service Provider (ISP).

Figure 1 shows the Smart Grid, with the ERG, in terms of communication:

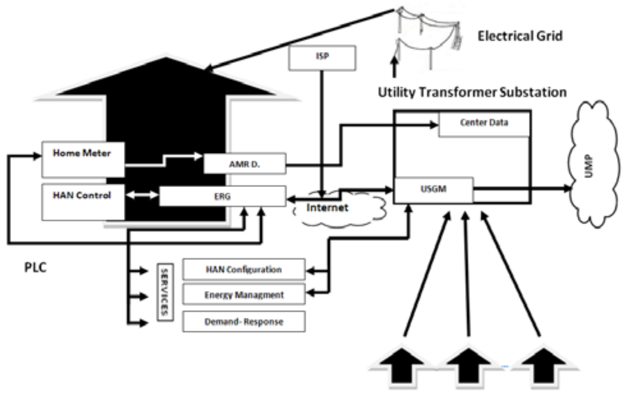

Figure 1- Smart Grids Architecture

Figure 2 shows the HAN. The ERG controls devices and interacts with home energy meters through X10, extended X10 and A-10 protocols, using PLC.

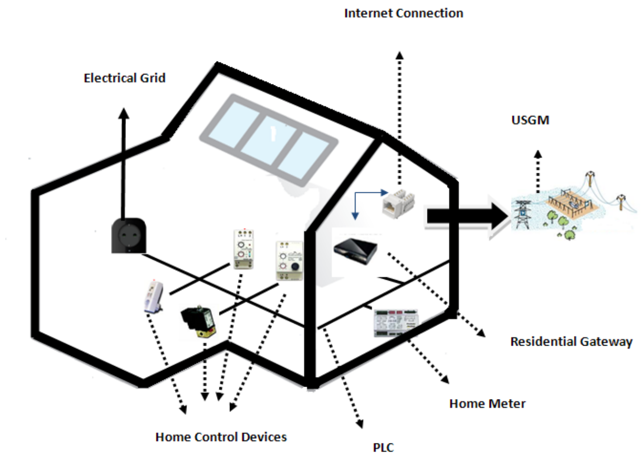

Figure 2- HAN Architecture

The ERG information exchange with the in-house energy meter uses an extended version of the X10 protocol. The Extended-X10 protocol has been designed to provide customers EM, DR and DP services. The extension of data frames consists of the definition of the ***Databyte Request*** Field values (see Table 1). These values allow information exchange between the ERG and home energy meters.

	Home Meter X10 Extended Protocol					
	House Code	***Ext. Code***	***Unit Code***	***Databyte Request***	***Type + Function***	***Data***
Size	**4 bits**	**5 bits**	**4 bits**	**8 bits**	**8bits**	**4 bytes**
Type	"A"-"P"	11000	"1"-"16"	**00000000: Voltage 00000001: Current 00000010: Power 00000011: Energy**	**11000001: Data Request 11000011: Data Reception**	**Meter Value**

Table 1- Home Meter X10 Extended Protocol

B. *ERG Hardware and Software Architecture*

The ERG has been implemented using an ARM926 microprocessor and its associated control peripherals.

Figure 3 shows the ARM926 Kit-Development Board used to implement ERG:

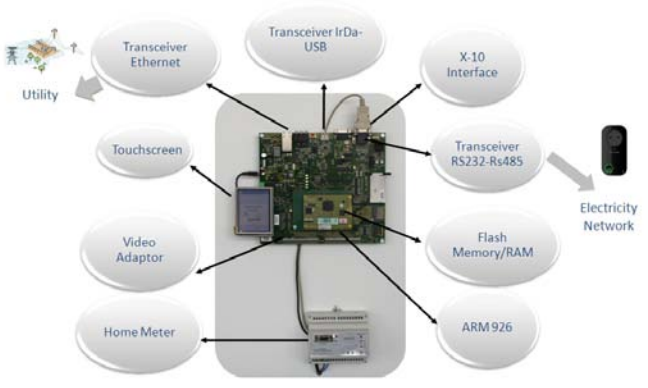

Figure 3- Hardware architecture of the ERG

A touchscreen provides the GUI for user interaction. A video adaptor is also implemented to show the GUI on a television. In this case, menu navigation is carried out with the TV remote control.

Flash and RAM memories are integrated into the ERG to store the HAN device database and the HAN energy/power measurements.

An RS232 transceiver enables the communication between the ERG and the X10 Interface.

An Ethernet transceiver allows the information exchange between the ERG and the utility as regards the EM, DR and DP services.

An IrDa transceiver enables the communication between the ERG and the TV remote control.

The communication and metering functions of the ERG are implemented by two external devices: an X10/RS232 Interface that performs the conversion of ERG frames into X10/A-10 frames (and vice versa) and the Home Meter which sends information on the HAN power and energy consumption when it receives a request from the ERG.

In terms of Software Architecture, the ERG is made up of five functional modules, each one with a specific functionality:

- Control Module: for the management and configuration of the HAN. It establishes the communication with the Home Meter and HAN nodes.
- Graphical User Interface (GUI) Module: consists of graphical elements such as windows, menus, radio buttons, check boxes and icons that provide the tools for users to interact with the ERG. It is presented as a friendly and intuitive interface in which each button corresponds to a type of service provided by the ERG. This GUI is presented either on a touchscreen or a TV screen. The extension of GUI to mobile devices is under development.
- Settings Module: sets the system date and time.
- Energy Management Module: provides HAN control, monitoring of house energy consumption, events schedule and information on user-Utility contract details (flat rates, hourly rates, etc).
- DR & DP Module: manages any Demand Response or Dynamic Pricing event received at the ERG from the Utility.

Figure 4 shows the relationships between these five functional modules:

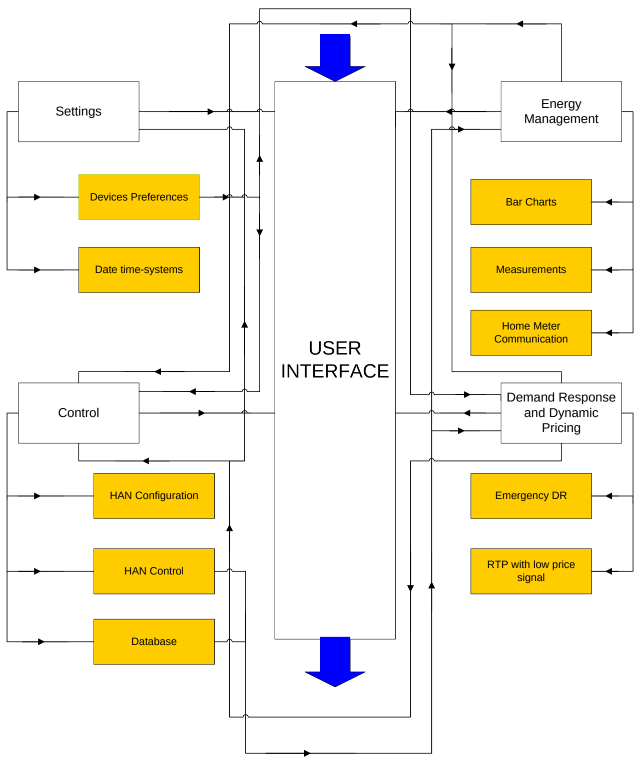

Figure 4- Software Functional Modules Connections

C. *Services Provided by the ERG*

Three kinds of services are provides by the ERG:

- *HAN Configuration and Control Services*

Users can pre-configure the HAN by registering devices in a database stored in the FLASH Memory of the ERG. HAN Configuration services include the creation of new devices in the database and the modification of device's status.

Up to 256 devices can be managed by the ERG. Functions available are on/off switching (for lights, appliances and electrical loads) and dimming (for lights and blinds).

- *Energy Management Services*

These services allow the user to control energy consumption in an efficient and economic way. They can be classified as follows:

- Monitor Energy/Power Consumption: shows the user real-time detailed information on how much energy is being consumed. Current power and energy consumption (W and kWh, respectively) are shown. The cost of the energy consumed during last month in single or dual tariff mode is also shown in €/$. ERG provides the last hour/day bar charts energy consumption as shown in Figure 5.

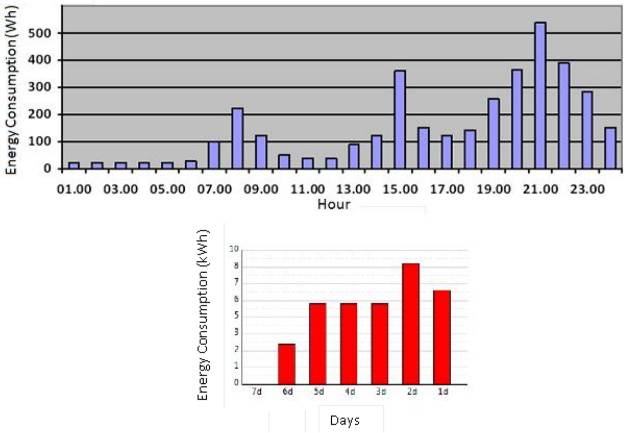

Figure 5- Bar Charts of Energy Consumption

- Communication: the ERG sends the hourly electric energy consumption to the USGM. When a request for instant power consumption is received from the USGM, the ERG sends a real-time response.
- Events scheduling: allows the user to schedule electric loads on/off switching and dimming.
- Customer information service: the ERG shows the user-Utility contract details. Log files containing messages exchanged between the USGM and the ERG can be viewed by the users. Finally, alert messages and warnings related to contingencies on power supply can also be displayed.

- *Demand Response and Dynamic Pricing Services*

ERG DR&DP services focus on peak clipping and valley filling, accordingly to demand adjustment criteria [9].

USGM sends a DR message to ERG to decrease power demand at peak hours. USGM messages contain maximum electric power available at a given moment. If the user accepts this power reduction, ERG disconnects electric loads (HAN devices) following a user- preference table to keep the house electric energy consumption under the required threshold.

For valley filling, the ERG is ready to switch on or dim HAN devices when a low-price RTP message is received from the USGM.

In both scenarios, the ERG automatically discovers those HAN devices that can be switched or dimmed.

The algorithm process of these two services is shown in Figure 6.

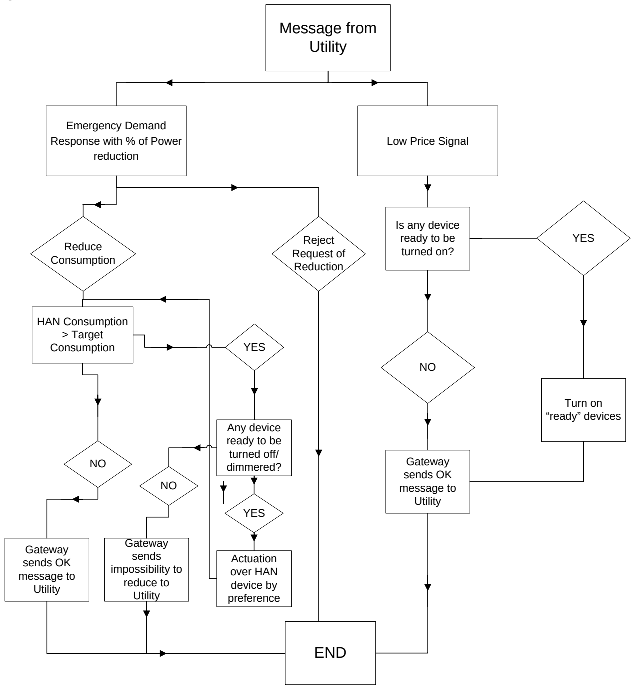

Figure 6- ERG Algorithm for DR&DP services

Data frames of DR&DP transmission and reception information between the ERG and the USGM are included in Table 2:

DR&DP Services	**(ERG<->USGM) Frames**			
	Type Number	***Hour***	***Date***	***Other***
Emergency DR	1	HH::mm	DD/MM/YYY	% Reduction
Low price Signal	2	HH::mm	DD/MM/YYY	--

Table 2- Data Frames of DR&DP

III. ANALYSIS OF RESPONSE TIMES

The ERG presented has been successfully installed in the Energy Efficiency Show Room at the Center for Energy Efficiency and Smart Buildings of Technical University of Madrid (CeDInt-UPM) (See Figure 7a and 7b).

(a) *(b)*

Figure 7- (a) ERG Demonstrator. (b) CeDInt Facility

This facility is equipped with an X10/A-10 phase coupler filters in the electrical network to avoid an X10/A-10 interference, and four X10/A-10 appliance modules to provide control services. The electrical devices and appliances installed in this show-room are a washing machine, a PC display, six LED lamps with dimming capabilities and a motorized venetian blind. Thus, the show-room has a HAN architecture similar to that shown in Figure 2.

The ERG has been tested to measure response times. These must be short enough to meet the requirements of EM, DR and DP services. Performance tests show the following results:

- The ERG is able to switch/dim the aforementioned HAN devices. The average response time (t_{son_off}) is 1.5 seconds. t_{son_off} is the time for the user request and the device response.
- Communication between ERG and the Home Meter has been checked. The ERG requests for power/energy information using the Extended X-10 protocol are answered by the Home Meter. The average response time (t_{pr}) is 4 seconds. t_{pr} is the time for request and response.
- An USGM simulator has been implemented to send Emergency DR Messages from the Utility to the house. The ERG average response time to an Emergency DR message has been calculated as follows:

$$t_{eDR}= (n+1)(t_{pr} + t_{c1}) + n(t_{on\_off})+ p(t_{c2}) \quad (1)$$

Where:

n = numbers of HAN devices that must be switched off/ dimmed to attain the percentage of power reduction.

p = numbers of HAN devices registered in the database.

t_{pr} = average response time of the home meter for an energy/power request.

t_{on_off} = average response time of HAN device to implement a Switch off/ Dim order.

t_{c1} = time for checking whether HAN Consumption is higher than the Target Consumption.

t_{c2} = time for checking the status (on/off/disable/enable) of a HAN device.

t_{c1} and t_{c2} depends on the access time to the database and therefore are negligible compared to t_{pr} and t_{on_off} and can be set out in the following expression:

$$300\, t_{c1} = 300\, t_{c2} = 0.5 \text{ sec.} \quad (2)$$

Table 3 shows the average response time for an Emergency DR depending on n and p values.

	Average Response Time for an Emergency DR					
	n= 2 p=20	***n= 6 p=20***	***n= 8 p=20***	***n = 12 p= 20***	***n= 16 p=20***	***n= 20 p= 20***
Time (sec.)	15.36	37.43	**48.46**	70.52	92.59	114.65

Table 3- Average Response Time for an Emergency DR

- Low-priced RTP Messages from the USGM to the ERG have been simulated. The average response time in this case is calculated as follows:

$$t_{RTP}= r(t_{off\_on}) + p(t_{c3}) \quad (3)$$

Where:

r = numbers of HAN devices that must be switched on.

p = numbers of HAN devices registered in the database.

t_{off_on} = average response time of the HAN device for a Switch on/ Dim order.

t_{c3} = time for checking the status (on/off/disable/enable) of a HAN device.

As previously stated, t_{c3} can be approached according to expression (2).

Table 4 shows the average response time for a RTP signal from the USGM depending on r and p.

	Average Response Time for a RTP low priced signal					
	r= 1 p=20	***r= 4 p=25***	***r= 8 p=30***	***r = 10 p= 40***	***r= 12 p=40***	***r= 16 p= 50***
Time (sec.)	1.82	6.40	**12.48**	15.64	18.64	24.80

Table 4-Average Response Time from a RTP low priced signal

As regards the performance-test results, the following conclusions are drawn:

- All the services mentioned in Section II operate satisfactorily in the test-room.
- The typical EU house has n=8, p=30 and r=8 (highlighted in bold in Tables 3 and Table 4). Therefore, the response of the HAN devices is fast enough to meet the requirements of DR, DP and HAN control services.

IV. CONCLUSIONS

The ERG allows HAN configuration, control, energy management and innovative Demand Response and Dynamic Pricing services using X10 technology on PLC. The ERG has been designed not only as a part of a Smart Grid, but as an intelligent device with a user-friendly interface (GUI). The GUI helps to reduce energy consumption. The ERG can be easily extended to provide access through the use of mobile devices (i-Phone, Android and Symbian). Ambient intelligence procedures are also easy to integrate.

X10 has advantages such as simplicity, ubiquity and low installation cost. X10 on PLC is an interesting choice to design a fully-functional home network with DP and DR services.

The response of the HAN devices is fast enough to meet the requirements of DR, DP and HAN control services in the residential environment. Performance tests demonstrate the feasibility of Smart Grids. The ERG contributes to avoiding peak clipping and valley filling whenever contingencies happen in the electricity distribution network.

Finally, with the aim of providing access to the ERG from everywhere, a server module is under development. It will be accessed from any mobile device with an Internet connection. In this case, a server-based solution is chosen instead of a native application. Server-based solutions are not limited to a single mobile platform (e.g. Android, Symbian or iPhone) and provide more flexibility allowing access to the ERG server from every platform with an Internet browser.

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