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A multi-agent system providing demand response services from residential consumers

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ABSTRACT

High share of distributed energy resources (DER) into power systems can significantly modify the net demand profile. Error forecasts of intermittent generation of renewable energy sources (RES) along with the current inelastic behavior of the consumption can provoke considerable network operational issues, such as frequency fluctuations and voltage imbalances. Increasing the noncontrollable DER penetration in network operation requires increased flexible and dispatchable generation capacity for balancing RES generation intermittency. Demand response mechanisms can be an efficient and less costly alternative for handling the grid issues posed by high RES penetration. The aim of this paper is to demonstrate enabling Information and Communication Technologies (ICT) and operational tools for distributed demand management mechanism that allows consumers to participate in grid support without affecting their level of satisfaction. An actual household environment called Mas Roig and located in Llagostera, Spain is used to demonstrate and assess the ICT based demand response mechanism. The results of the implementation are presented and evaluated providing useful insights for a mass deployment of such mechanisms.

1. Introduction

The past few years are characterized by an explosive growth in the development and installation of distributed energy resources (DER) resulting in operation of networks with significant DER penetration [1–3]. It is now well understood [4–6] that DER cannot anymore operate under the "fit and forget" principle, but some level of DER aggregation and control is required. Under such circumstances, the intermittent RES production as well as the integration of new additional loads, such as plug-in electric vehicles, will require the reinforcement of the existing grid infrastructures according to the foreseeable RES/demand deployment levels, in order to ensure stable and secure grid operation. A cost effective planning strategy is based on the integration of active consumers into distribution grids in a way that they can contribute to the optimization of the value chain between energy suppliers and end-customers. The potential demand elasticity offered by end-users (i.e. household demand) can postpone or defer grid investments and promote the efficient exploitation of the renewable electricity produced at or close to the consumption level. These opportunities impose the development of new operational strategies and tools for enabling the coordination between demand and distributed RES with the objective of supporting the network performance.

According to the "EU Smart Grid Technology Platform 2007 Strategic Agenda Report[1]", distribution networks present significant "structural inertia" as they are dominated by passive elements, principally uncontrolled loads. In the last few years, more and more retailers invest on demand response (DR) actions, i.e. change in end-users electricity demand as one of the ways to increase electricity demand elasticity [7]. DR actions may be either response to changes in the electricity prices over time, or result of peak shaving or even relief of congested networks incentive agreement [8]. There are two demand response mechanisms namely incentive based and price based. Each DR mechanism comprises a number of DR alternatives that can be adopted. More specifically, the alternatives for the incentive based DR mechanism can be classified into two categories: the classical including Direct control and

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[1] ftp://ftp.cordis.europa.eu/pub/fp7/energy/docs/smartgrids_agenda_en.pdf.

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0378-7796/

Interruptible/Curtailment program and the market based including demand bidding, emergency actions, capacity market and ancillary services market. Respectively, the alternatives for the priced based DR mechanism are the Time-of-Use, critical peak pricing, extreme day critical peak pricing, extreme day pricing and real time pricing. The economic benefits of DR actions may be significant for both retailers and end-users. The cost reduction for both retailers and end-users may be significant reaching up to 18% when 40% controllable devices are considered [9]. As the difference between peak and off-peak Time of Use (TOU) rates increases, demand elasticity increases [10] as well.

The main barriers of demand response as identified by different stakeholders (Source: Brattle Group[2]) are the ineffective program design and the low consumer interest. The correlation between these two barriers is high since more effective program design would possibly encourage customer interest. The majority of applied DR mechanisms, which are based on highly centralized control concepts, require the acquisition and processing of a very large amount of local information from a central point. This exhibits considerable complexity on the central coordination point affecting the scalability of such DR mechanisms. Thus, the majority of the manageable demand in all DR implementations concerns large commercial or industrial customers failing to incorporate a large share of small residential customers.

The major part of the literature concerning DR programs for residential customers aims to develop an applicable model of residential loads enabling the identification of an electric use pattern. This is achieved by adopting either a grid oriented approach, which models end-user's consumption as a whole with regards to its general characteristics such as gross domestic product and unemployment rate, or a bottom-up approach where the load profile is derived from the aggregation of electric consumption of various residential appliances or a variety of households [11,12]. Such studies [13] provide a simulation based optimization analysis aiming to quantify the benefits from the provision of DR services from residential customers.

When it comes to the bottom-up approach, the multi-agent systems (MAS) approach has been widely adopted due to their scalability and their ability to model the stochastic nature of residential consumption and the dynamic interactions among homes and the grid. There are several MAS-based applications in the power system literature, such as electricity market [14,15], voltage control [16], load restoration [17], load shedding [18], and the smart grid area [19–30]. The studies analyzed in [26–30] are exclusively dedicated simulating the residential load pattern using multi-agent system approach to optimize the demand response participation of residential consumers.

Besides the simulation analysis for modeling residential consumption, there are also studies focusing on the hardware technologies enabling home energy management for demand response applications [31,32]. In these studies, ZigBee based interfaces are developed for monitoring and controlling the residential loads.

This paper introduces an integrated solution that enables small residential consumer/prosumer to provide DR services for grid (voltage/frequency) support considering both local energy resources as well as end-user's convenience. Both the ICT technologies that enable the monitoring of the local consumption/production as well as the middleware that enables the efficient coordination of distributed energy resources at local level are introduced. Among the various communication technologies that can be deployed in a home energy management system [33], the ZigBee technology has been implemented as it is a low cost and low-power consumption option. The middleware is based on multi-agent systems and it is developed in the Jade platform. The performance of the proposed home energy management for providing demand response services from residential consumers is evaluated in a real household environment where the real dynamic behavior of the consumer as well as the available distributed renewable energy production are considered. The outcome and the experience gained from the demonstration provide a useful feedback to various stakeholders making them aware of potential barriers that may appear in case of a mass DR deployment scenario.

The contribution of this paper lies in the followings:

- *Integrated hardware and software Home Energy Management (HEM) solution*: It proposes an integrated home energy management system enabling the provision of demand response services from residential customers. Both the hardware and software options concerning the interactions among the household loads as well as the interaction between the home and the grid are presented.
- *HEM operation under critical/emergency grid operational conditions*: The proposed HEM solution enables the management of household loads for providing demand response in case of critical (voltage/frequency support) or emergency (islanded operation) grid conditions.
- *Experience from a real environment*: The majority of the proposed HEM solutions are assessed via simulations or tests in a laboratory environment. The proposed home energy management system is implemented in a real residential household environment and the coordination mechanism evaluates in real-time the stochastic behavior of the customer and the intermittency of the distributed RES production. The performance of the hardware and software solution is assessed.

The integrated DR system and the demonstration are developed within the framework of INTEGRAL[3] project financed by the EC in the FP6 framework (November 2007–February 2011). The INTEGRAL project aimed to build and demonstrate an industry-quality reference solution for DER aggregation-level control and coordination, based on commonly available ICT components, standards and platforms. To achieve this Integrated ICT-platform based distributed control solution, the project has taken the following steps:

- Define integrated distributed control as a unified and overarching concept for coordination and control, not just of individual DER devices, but at the level of large scale DER/RES aggregation.
- Show how this can be realized by common industrial, cost-effective and standardized, state-of-the-art ICT platform solutions.
- Demonstrate its practical validity via three field demonstrations covering the full range of different operating including:
  - Normal operating conditions of DER/RES aggregations, showing their potential to reduce grid power imbalances, optimize local power and energy management, minimize cost, etc.
  - Critical operating conditions of DER/RES aggregations, showing stability when grid-integrated.
  - Emergency operating conditions, showing self-healing capabilities of DER/RES aggregations.

The paper focuses on the coordination of local resources for the provision of grid support by small residential customers when grid operates under critical operating conditions. Section 2 presents a

[2] http://www.ferc.gov/legal/staff-reports/06-09-demand-response.pdf.

[3] http://www.integral-eu.com/.

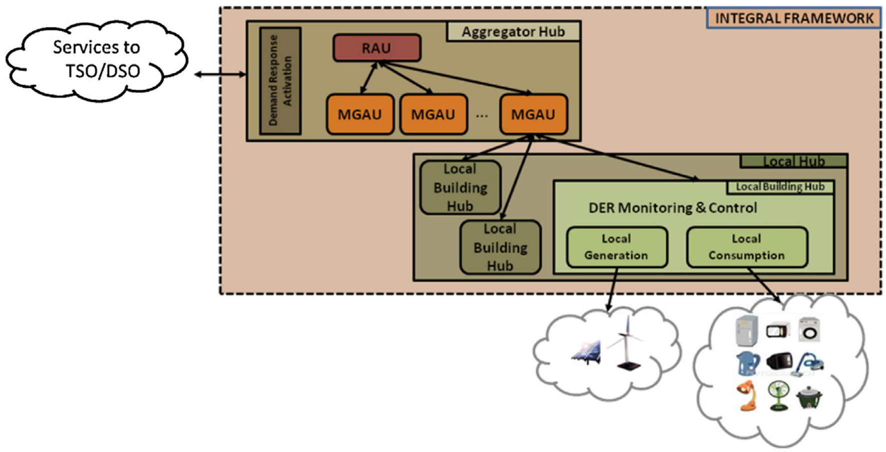

Fig. 1. Conceptual architecture for the provision of DR services from aggregated small residential consumers.

high-level view on the overall system architecture comprising a local (building) and global (aggregator) level. Section 3 presents the ICT technologies that enable the local monitoring of the distributed energy resources and the control of local devices. Section 4 presents the middleware that enables the coordination of the local manageable loads for the provision of DR services considering grid requests and end-user's priorities. Section 5 presents the developed Java based user interface that enables end user to monitor the total energy profile of the house and of each individual resource. Section 6 presents the field demonstration and describes the available local resources. Section 7 presents the use cases that were examined, while the outcomes are analyzed in Section 8. The paper concludes in final section.

2. Conceptual architecture

This section presents the conceptual architecture for the provision of DR services from aggregated small residential consumers when grid operates under critical conditions, i.e. voltage excursions, frequency variations and islanded mode. The vision of this architecture is to provide a self-organised network of connected distributed energy resources forming dynamic clusters of intelligent active nodes. Toward this scope, the DR mechanism consists of two major layers, the local control hub and the aggregator hub, as presented in Fig. 1. The local control hub corresponds to the building area and it is responsible for monitoring and managing the local energy resources, while the aggregator hub is responsible for the provision of grid support services based on the DR requests generated by the system operators.

Fig. 1 presents the information exchange paths between the various stakeholders. The operation and the role of each stakeholder are described below:

Distribution System Operator (*DSO*): Distribution System Operator (DSO) is the owner and operator of the distribution grid/network. It is responsible for monitoring the operation, ensuring the maintenance of and, if necessary, reinforcing the network infrastructures in order to fulfill the short and long term demand requirements. DSOs do not participate in any energy trading and they are unbundled from generation, transmission and particularly from supply and retail. However, they are responsible for the technical validation of the energy scheduling of the retailers.

Transmission System Operator (*TSO*): TSO is responsible for operating, ensuring the maintenance of and, if necessary, developing the transmission system, its interconnections with other systems and for ensuring the long-term network capacity adequacy to fulfill demand requirements. Toward this direction, TSO is also responsible for procuring system services, such as operational reserves and frequency regulation.

Aggregator: The role of the aggregator is to aggregate dispersed energy resources and provide to other stakeholder one single demand profile. Such a hierarchical aggregation structure improves the scalability of the proposed approach as it has been analyzed in [33] for the scenario of large-scale deployment of manageable loads (particularly electric vehicles). The hierarchical aggregation structure consists of the Regional Aggregator Units (RAU) and the MicroGrid Aggregator Units (MGAU). The RAU is located at the primary substation (HV/MV) and manages a number of MGAUs which are located at the secondary substations (MV/LV). The MGAU is responsible for aggregating the demand profile of the households in a specific LV distribution area and providing a single aggregated profile to the RAU. The RAU and the MGAU interacts with the system operators, TSO and DSO, and receives DR requests in case of grid operational issues. In case of global grid operational issues, i.e. frequency fluctuations, the transmissions system operator requests certain DR actions from the RAU. On the contrary, in case of local network issues such as voltage excursions in the distribution network, the DSO requests from the respective MGAU that controls the problematic part of the networks to proceed to specific DR actions.

Local building hub consists of components providing real-time monitoring of the energy profile of household and coordination of the manageable loads. In case of DR activation request, each local building hub is responsible to define the operational status of each manageable load so as to serve the grid support request. In order to minimize the impact of DR actions to the end-user's convenience, a priority list is declared by the end-user defining the importance of each manageable load for a certain period. The priority of the loads can be modified at any time by the user in order to reflect his/her preferences and convenience at the highest possible level.

3. Multi-agent system

Multi-agent systems (MAS) are the evolution of distributed control, where two or more physical or virtual (software) entities, namely agents, interact in order to reduce the complexity of a problem, by dividing it into smaller sub-problems. MAS adopt the object-oriented paradigm by keeping the information needed to solve each sub-problem private. An agent is able to perceive its environment through sensors and act in the environment through actuators [35,36]. The basic properties which define an agent are:

- *Autonomy*: the ability to operate in order to meet its design objectives without constant guidance from the user.

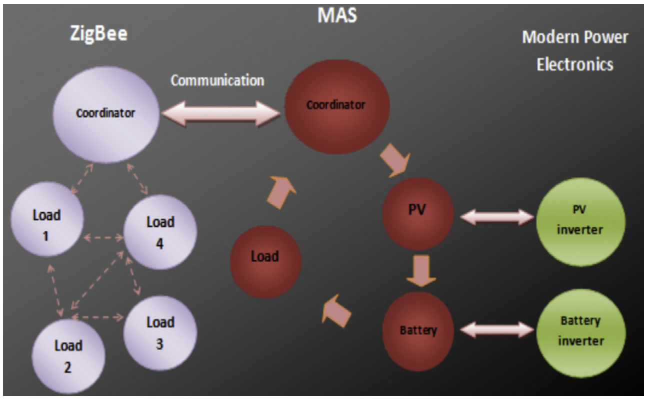

Fig. 2. MAS environment in relevance to the real one.

- *Responsiveness*: the ability to perceive the environment and respond to changes.
- *Social ability*: the ability to interact with other virtual or physical agents.
- *Pro-activeness*: the ability to reason and initiate its own actions in order to meet its design objectives.

An agent is characterized by a certain behavior. This behavior is formed from the tendency to accomplish a set of goals, satisfy objectives and use the resources, skills and services available. The way that each agent uses its resources, skills and services defines its behavior. Additionally, the agents allow for advanced "plug and play" capabilities. Based on their characteristics, the agents can adapt to their environment and act accordingly in order to accomplish the goals set. It should be finally noted, that the agents offer, as well, reduced need for large data manipulation and increased reliability of the control system. If one agent fails, the rest are able to adapt to this new state and continue the system function.

In a MAS environment, each distributed energy resource is represented by an agent, which is characterized by a certain level of autonomy in taking decisions (Fig. 2). Its decision depends on its resources, e.g. the available capacity in case of a storage unit (i.e. battery). Agents have only partial or none at all representation of the environment. Each agent knows the state of the unit it controls, e.g. the current, the voltage, the instant consumption, the total consumption, etc. However, agents can be informed via communication with other agents about the status of the neighboring system, i.e. the grid operation condition. For instance, a load agent is responsible for monitoring the energy consumption of the manageable load and storing the measurements in a database. Moreover, it has the knowledge of modifying the operational mode of the load. A DG agent is responsible for monitoring and storing the energy production of a local generation unit as well as adjusting the production level.

The general description of the MAS system that allows managing the local consumption/production power for grid support services is (Fig. 3):

- *Local Central Controller* (*LCC*): Is the major agent that monitors the local distributed resources and is responsible for the demand side management. The Local Central control receives DR requests from the MGAU for load shedding and manages the local consumption accordingly based on the available distributed resources and the end-users preferences. The end users preferences are expressed by setting the priority to the loads.
- *Load agent*: Represents the loads of the system. Each load Agent controls one or more ZigBee nodes. The importance of each load is defined by its priority. More specifically, high priority load means that this load is crucial for the end-user and cannot be interrupted unless extreme grid conditions occur. Medium priority loads are the loads that are not crucial, but in case of interruption they will impact the end-users convenience. Lower priority loads mean that these loads can be shed in case of grid imbalances with little impact on end-users behavior.
- *DG agent*: Is the agent that controls and monitors the distributed renewable energy resources such as photovoltaic (PV) panels, wind turbines and batteries.
- *Microgrid Aggregator Unit Agents* (*MGAU*): Represents the lowest aggregation layer that aggregates the net load profiles from several distributed LCC and communicates a single net load profile to the upper aggregation layer, i.e. the RAU agent. In case of grid imbalances, the MGAU receives DR requests from the DSO to curtail part of its demand in order to support grid operation. The percentage of load shedding is communicated to the LCC agents that belong to the problematic area in order to offer DR services by reducing their local consumption at equivalent level.
- *Regional Aggregator Unit agent* (*RAU agent*): Represents the highest aggregation layer that aggregates the net load profiles from several distributed MGAU agents and communicates a single net load profile to the DSO/TSO. In case of grid imbalances, the RAU receives DR requests from the TSO to curtail part of its demand in order to support grid operation. The percentage of load shedding is communicated to the MGAU agents that belong to the respective problematic area.
- *DSO/TSO agent*: Represents the system operators that are responsible for monitoring the power system operation and ensuring the reliable power supply of the demand.

Moreover, there are ancillary agents:

- *CA*: communication agent. It provides the communication between the MAS system and the ZigBee net and distributes the information to the different LC.
- *UA*: user interface agent: this agent provides the user interface and usability of the system for the Integral experiments. The number of different situations programming and situations registering will be tracked and managed by this agent. It has associated a data base for registering purposes.
- *DBA*: data base agent. Provides communication between the agents that needs access to data base and the database itself.

All these agents are running under JADE platform in a single PC under Windows and using Java language.

For each agent a graphical interface has been developed so that the user is able to monitor the consumption and the status of the system. The users can be informed about the total consumption of the system, so they are aware of how much energy they consume. Users can also be informed about the maximum production of the distributed generators and adjust their consumption levels in order to utilize efficiently the energy produced locally. More details on the graphical interface are presented in Section 7.

The proposed MAS communication architecture presented in Fig. 3 is a hierarchical aggregation model based on the microgrid and multi-microgrid concepts [37]. The implementation of such a hierarchical communication structure enhances the scalability of the demand response mechanism. When a centralized mechanism is adopted for demand response applications, all the operational specifications and requirements of the distributed manageable resources are stored and processed by a central point increasing the complexity and the computation time of the demand response mechanism. The implementation of a decentralized coordination mechanism distributes the computation intelligence to lower grid levels and reduces the complexity of the management system for

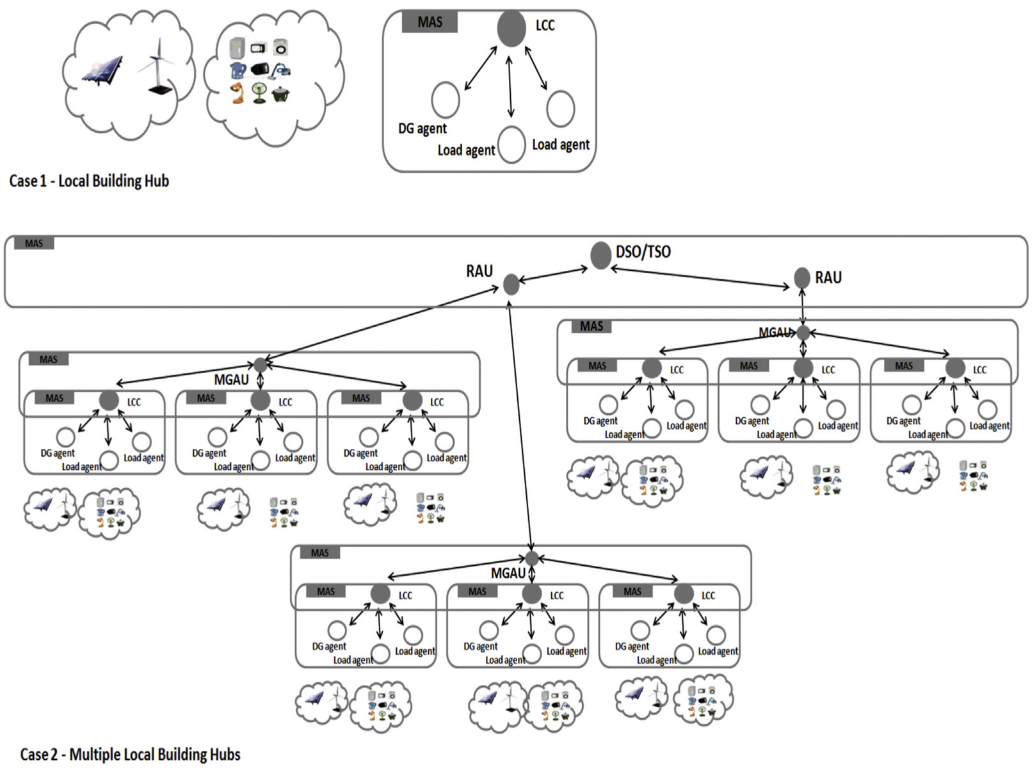

Fig. 3. MAS architecture.

demand response services by dividing the centralized management problem into several equivalent sub-problems which can be solved locally. However, the mere implementation of a distributed management mechanism is not adequate due to the number of communication channels required for the interaction between the coordinator and the manageable resources. The implementation of intermediate aggregation layers significantly reduces the required communication channels to the coordinator by aggregating the demand profile of several distributed resources and communicating a single energy profile to the upper grid levels as it has been analyzed in [34]. Moreover, the implementation of intermediate aggregation layers is implied by the structure of the electrical network for facilitating the provision of demand response services to the grid operators. The RAU agent and the MGAU agent are placed at the primary and secondary substation of the distribution network and they are responsible only for the part of the grid they are controlling. The division of electrical networks into small control areas enables more efficient monitoring and management of the network especially in case of local grid issues such as voltage disturbances.

The response time of the proposed demand response approach is an important factor affecting its operational performance and defines its suitability for providing different network oriented services (voltage or frequency support). The proposed demand response mechanism can be utilized for voltage support application or secondary frequency reserve services where the time requirements are approximately a few minutes. The primary frequency control requires real-time response within a few seconds (i.e. generation droop control), thus, the implementation of the proposed demand response mechanism is not appropriate. The response time highly depends on the implemented communication technology.

There is a variety of communication technologies which are suitable for demand response applications (i.e. GSM, GRPS, 3G, WiMax, etc.) as analyzed in [38], while others are appropriate only for home management applications such as ZigBee. The main consideration when deciding about a communication technology is the ease of implementation, the installation cost and the suitability, in terms of communication range, security, availability and scalability. Considering the aforementioned decision criteria, each communication technology presents advantages and disadvantages depending on the environment it is implemented. The technology that fits well for one environment may not be suitable for the other as it is analyzed in [38]. For instance, the use of DSL connection could be a possible solution due to its widespread availability as well as low cost and high bandwidth data transmission; however, potential reliability and security issues might be raised. The utilization of existing infrastructure such as the mobile phone GSM network would be the most practical and cost effective solution. However, the cost of using GPRS technology is high. The operational cost of GPRS system can be limited when applied in combination with other communication technologies, such as PLC which is widely used in smart metering applications. Powerline networks are mainly characterized by two drawbacks namely low-bandwidth communication channels and short data transmission range.

The proposed communication architecture does not pose any limitation in selecting the most appropriate communication technology. For instance, PLC could be implemented at the lowest aggregation layers of the MAS architecture. Moreover, the local processing of data as well as the exchange of aggregated data among higher aggregation layers reduce the amount of data exchange requirements enabling the utilization of existing infrastructure at the highest level of this architecture, such as GPRS or 3G technology which are already used in advanced metering or mobile applications. Such communication technologies can be implemented in demand response applications for voltage support or secondary reserve services where the time requirements are approximately a few minutes. However, further in depth analysis on the enabling communication technologies is out of the scope of this paper.

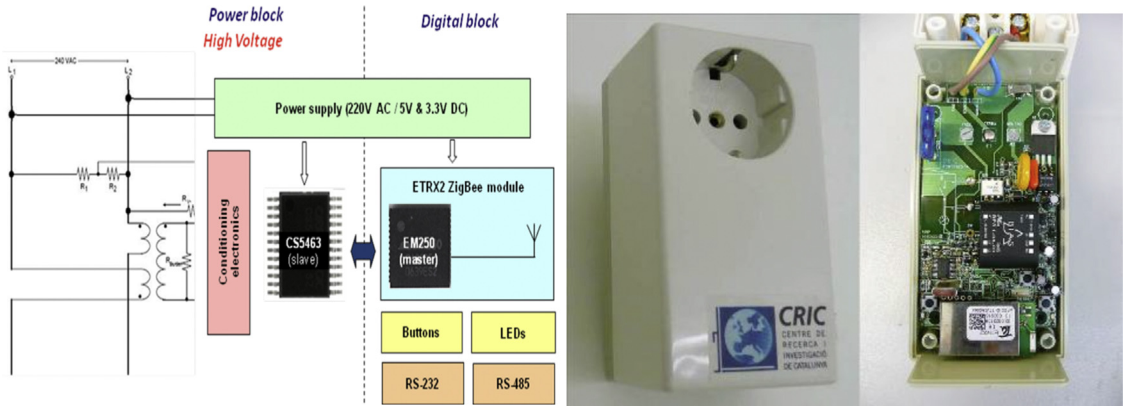

Fig. 4. Meter nodes based on EM250 (developed by Ateknea solutions).

4. Enabling technologies for HEM

The monitoring of the household consumption and production is a functional requirement for the development of the home energy management system that responds to the DR requests. For this purpose, a network of devices of sufficient sensitivity, here referred to as meter nodes, has been developed in order to provide the local building hub with the necessary information concerning different electrical grid parameters through a radio frequency (RF) communication link.

The communications among network devices relies on ZigBee protocol, which is a high level communication protocol using low-power digital radios based on the IEEE 802.15.4-2003 standard. ZigBee is a low-cost, low-power, wireless mesh networking standard. The low cost allows the technology to be widely deployed in wireless control and monitoring applications; the low power-usage allows longer life with smaller batteries, and the mesh networking provides high reliability and larger range.

A solution based on the EM250 from Ember (now part of Silicon Laboratories Inc.) is adopted for the development of the meter nodes (Fig. 4). The EM250 is a system-on-chip that combines a 2.4 GHz IEEE 802.15.4 compliant radio transceiver with a 16-bit microcontroller. The ETRX2 module from Telegesis Ltd., which mounts an Ember's EM250, is the main component of the digital block. This module can feature a chip antenna or an external antenna with power amplifier, allowing for higher receiving sensitivity of the EM250 and improved antenna performance, thus offering more flexibility for adjusting node radios.

Each node contains a sensor block based on the CS5463 from Cirrus Logic, a single-phase, bi-directional power/energy chip with an integrated power measurement device, power calculation engine and serial interface. The use of independent processing units, executed on independent chips, provides accurate measurements and extended set of analysis parameters (line frequency, instantaneous and RMS values of current and voltage, instantaneous and average active and reactive power, fundamental and harmonic power, etc.). The nodes send the measurements from the loads under control to the coordinator periodically. This period is programmable and depends on the maximum number of active nodes in the network. The nodes are addressed by means of their static address (immutable and unique for each node).

Two types of nodes in the ZigBee network have been developed: one coordinator node acting as a central node and the meter nodes acting as router nodes, assigned to the load and generation nodes (Fig. 5). Each node is associated to an energy resource and is adapted to its particular needs. The different types of nodes are based on the different loads and generation characteristics, and can be summarized within the following groups:

- *Central node*: this node has a USB connection and is attached directly to the central computer.
- *Meter node*
  - *Static*: this node provides the measurements of V and I on the load attached to the device. It has the measuring capabilities and it is also able to control the operational mode of a load up

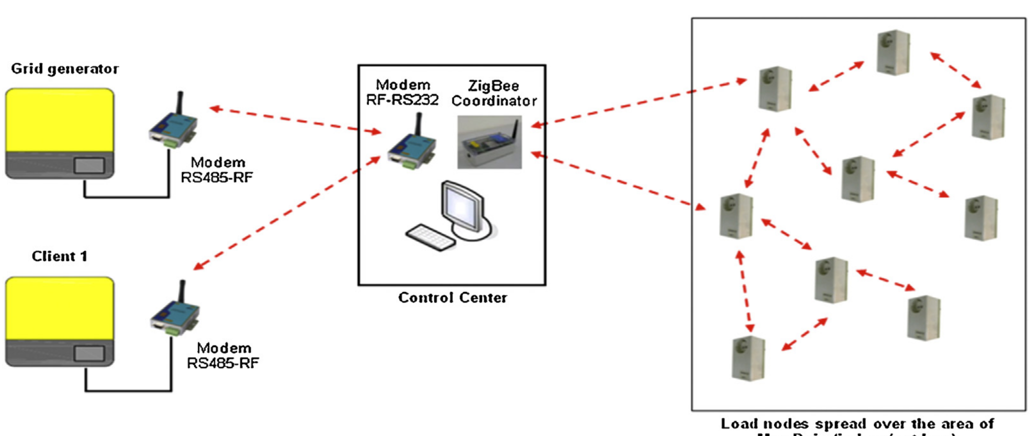

Fig. 5. ZigBee mesh topology.

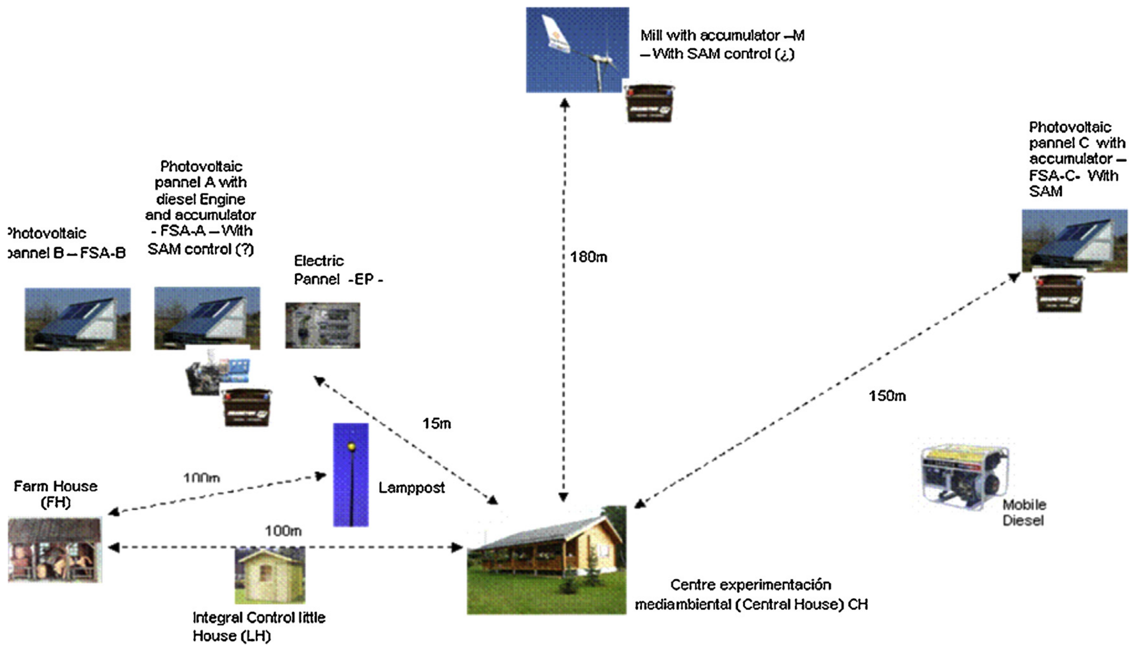

Fig. 6. Demo site – rural household in Mas Roig, Spain.

to 16 A. This node is always present in the ZigBee system and it has to be registered and identified.

- *Mobile*: this node provides the measurements of *V* and *I* on the load attached to the device. It has the measuring capabilities and it is also able to control the operational mode of a load up to 16 A. However, this node has the capability of appearing and disappearing into the system (as an example, an iron, which can be plugged in or out). When plugged in, the device appears into the ZigBee system automatically. In the opposite case, the node disappears. No pre-registration action is required for the mobile nodes.
- *RS485-RF communication*: this is not a ZigBee based node but an RF modem. This modem provides a communication link from the central computer to the device where this node is attached and includes an RS485 port. Through this modem and with the appropriate driver, the central computer can read from that device by means of a ModBus or any other protocol.

Concerning the firmware of the ZigBee nodes, this is based on the EmberZNet PRO ZigBee stack, which permits the creation of mesh networks using highly efficient routing algorithms. This firmware allows for self-managed and self-healing mesh network. This means that failed nodes and new nodes are automatically removed or included in the network.

ZigBee is a wireless communication technology which has been widely implemented in home automation applications and has been realized as the most suitable communication standard for smart grid residential network domain by the US National Institute for Standards and Technology [39,40]. According to the comparison analysis of communication technologies for smart grids in [38], ZigBee is considered a competitive alternative for home automation due to its simplicity, mobility, robustness, low bandwith requirements, low deployment cost, its operation within an unlicensed spectrum, easy network implementation. The use of ZigBee offers great flexibility on the inclusion of new elements into the system, and this is important for the "mobile" elements (or nodes). The main disadvantages of ZigBee technology are the short operational range, the low processing capability and small memory size. The operational range constraint can be overcome by implementing a Mesh ZigBee topology as shown in Fig. 5. The selected topology for the Mas Roig micro-grid is mesh type. With this topology, the consumption and delays are the lowest possible, because every element is only active when transmitting. Unless there is a direct link with the ZigBee coordinator, the neighbor nodes can act as re-transmitters forming a communication path between distant ZigBee nodes and the ZigBee coordinator. As the ZigBee nodes are utilized for measuring only the instant consumption and controlling remotely the operational mode of the loads (ON/OFF) and since the measuring data are stored in a database and processed centrally by the LCC, the processing capability and memory size requirements of ZigBee nodes are low.

Table 1
High priority loads.

Load	Estimated distance (m)	Number of node
Lights in the living room (menjador) 35 W	40	
Light in the toilet (11 W)	40	1
Class A refrigerator 90WH approx. 180 W/24 h	5	

5. Demonstration site

The demonstration site is a rural household environment. The different elements in the field are shown in Fig. 6. These elements are communicated with the system by ZigBee nodes and RF modems, and produce the different control actions for the local hub.

The following tables (Tables 1–3) present the RES production units and their technical characteristics as well as controllable loads and their respective priority. In Fig. 7, some indicative pictures of the ZigBee nodes installed in the demonstration site are presented.

6. Field test use cases

This section presents the different use cases of demand response services from residential consumers which are implemented and evaluated in the demo. The following UML diagrams present the full context of the examined use cases illustrating the communication

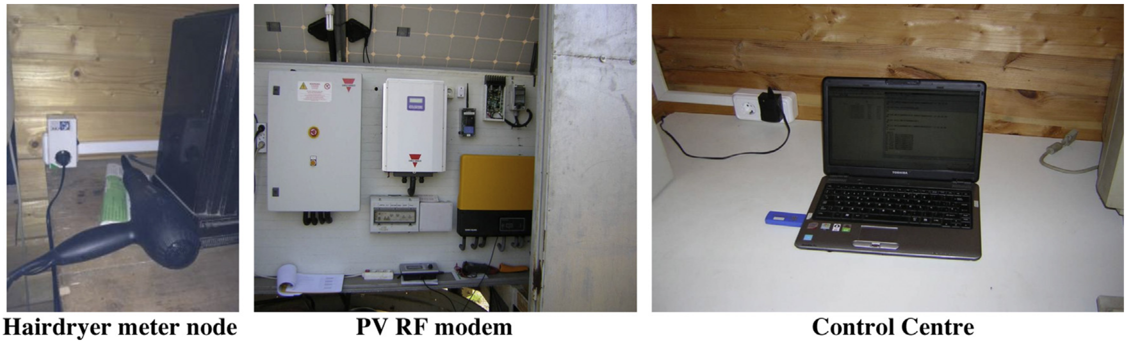

Fig. 7. Indicative ZigBee nodes as well as the control center installed in the demo site.

Table 2
Medium priority loads.

Load type	Estimated distance (m)	Number of node
Light in kitchen (24 W)	10	1
Light in room (24 W)	10	
Washing machine. 1200 heat/450 motor/750 spin dry, approx. 750 W × cleaning × 2 cleaning per week 1500 W/7 days = 214 W/24 h	10	1
Dryer 2.200E/1200 W. Depending on program (used not very often 1–2 days at month 1 h = 40 W/24 h)	10	1
Vacuum cleaner. 1.200 W. 1/2 per day = 600 W/24 h.	10	1
Air conditioning: high efficiency 3 devices × 86 W = 258 W/h × 10 h = 2.580×/24 h. Only used 2–3 months per year	10	1
Water pump 1000 W/h × 1 h per week/7 days = 142 W/24 h	40	1
Water pump 750 W × 1 h per week/7 days = 107 W/24 h	40	1
Computer 125 W × 3 h approximately 379 W/24 h	10	1

paths among the different actors from the upper grid level (i.e. system operators) down to the lowest grid level (i.e. household loads). More specifically, when a network (voltage or frequency) disturbance occurs, the system operators (DSO/TSO) define the appropriate amount of demand response requested from the whole or a specific area of the system. Thus, the network operator initiates the demand response process by communicating demand response request signals to the aggregator hub. Since the paper mainly focuses on the coordination of local household resources and the enabling technologies, the network operators were not simulated in the demonstration but virtual network operator's request signals were assumed in case of grid abnormal conditions instead.

Table 3
Low priority loads.

Load type	Estimated distance (m)	Number of nodes
Static nodes (nodes that are previously set up and constantly running).		
Entrance light (24 W)	15	1
Studio light (35 W)	40	
Exterior lights (22 W)	40	1
Mobile nodes (these nodes can appear or disappear, depending if the device is plugged in. Once the device is plugged in, it appears automatically to the ZigBee system. Each device has to have a unique ZigBee node associated – to be able to record the consumption).		
Microwave: 1.050/750 W	15	1
Bread Toaster: Tefal 1.050 W	15	
Iron: 1.200 W	15	
Scanner 19.2 W/h	15	1
Printer: 44 W/h	15	
Fax: 66 W	15	
TV: 65 W	15	1
Power audio amplifier 10.4 W	15	
DVD: 12 W	15	
New devices nodes: 4	15	4

Different use cases were examined in the real test field:

A. *Normal case*: The user can see the information of the system and actual status. It includes:
   - o General system status and control view (includes information on actions, actual status and data forecast).
   - o Actual ZigBee node status and measurements.
   - o Simulation data and status (in progress or stopped).

   During the monitor operation the LCC agent requests data from all the system agents: loads and production/storage units. The data include consumption and available energy in the batteries. According to the data, the LCC forecasts the system status and sends actions plans to the loads (Fig. 8).

B. *Voltage drop*

   After a voltage drop the system operator requests a specific percentage of load shedding in order to maintain voltage within acceptable limits. The sequence of actions is presented in Fig. 9. Voltage events are mainly local events and refer to a specific area of the network. Thus, the DSO sends DR request signals to the MGAUs belonging to the problematic area.

   As soon as the LCC of the local hub receives a DR request from the respective MGAU, it updates the current energy profile of the household and decides the appropriate DR actions (i.e. load shedding) that satisfy the MGAU's DR requests considering the load priority defined by the end-users so as to reflect its preferences.

C. *Frequency drop*

   After a frequency drop the system operator requests a specific percentage of load shedding in order to maintain frequency within acceptable limits. The sequence of actions is presented in Fig. 10. Frequency events are system wide events reflecting the unbalance between demand and production. A frequency drop can occur after the loss of a generation unit, and as a result, the transmission system operator sends DR request signals to all RAUs requesting a specific percentage of load curtailment.

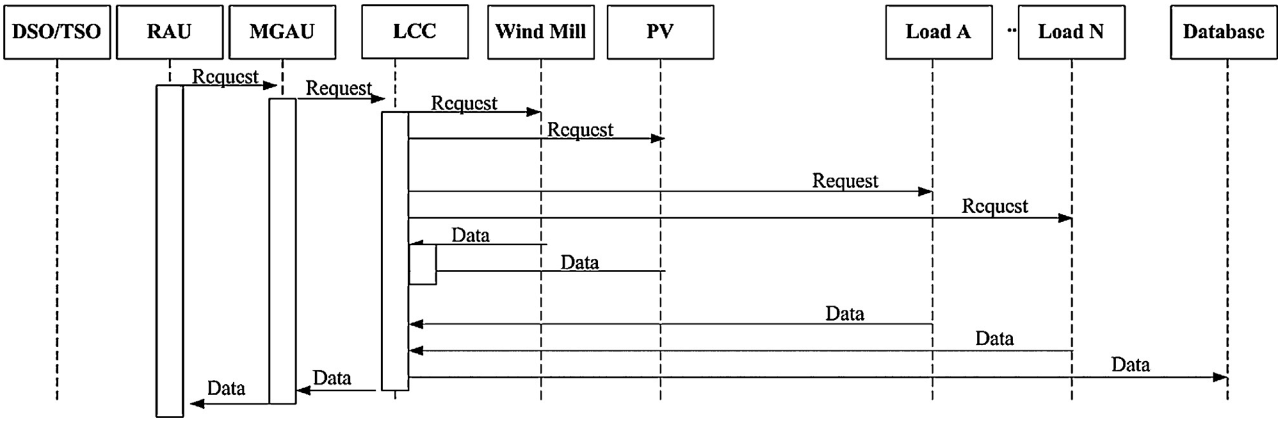

Fig. 8. UML diagram for normal operation.

D. *Island mode operation*

If a critical instability occurs in the main grid, the system proceeds to intentional islanding (Microgrid operation). The process for intentional islanding includes the following steps:

- Calculation of critical loads and their status (type, active or reactive).
- Calculation of internal power generation, including ancillary services.
- Calculation of danger loads that can be covered with internal power generation.
- The power exceeds will be calculated for the activation of non-danger loads if advisable (loads with medium critic level).
- Proceed to start of danger loads and proceed with the rest of loads.
- Proceed to intentional islanding.

During the period the system is in island mode, the overall consumption is served locally by the distributed energy resources of the field test (batteries, PV, wind turbine). The amount of generation from the RES depends on weather conditions (such as sun, wind) and the SOC of the batteries before islanding. The balance between local generation and demand must be carefully controlled and in case of imbalance, load shedding will be initiated according to a load priority list (Fig. 11).

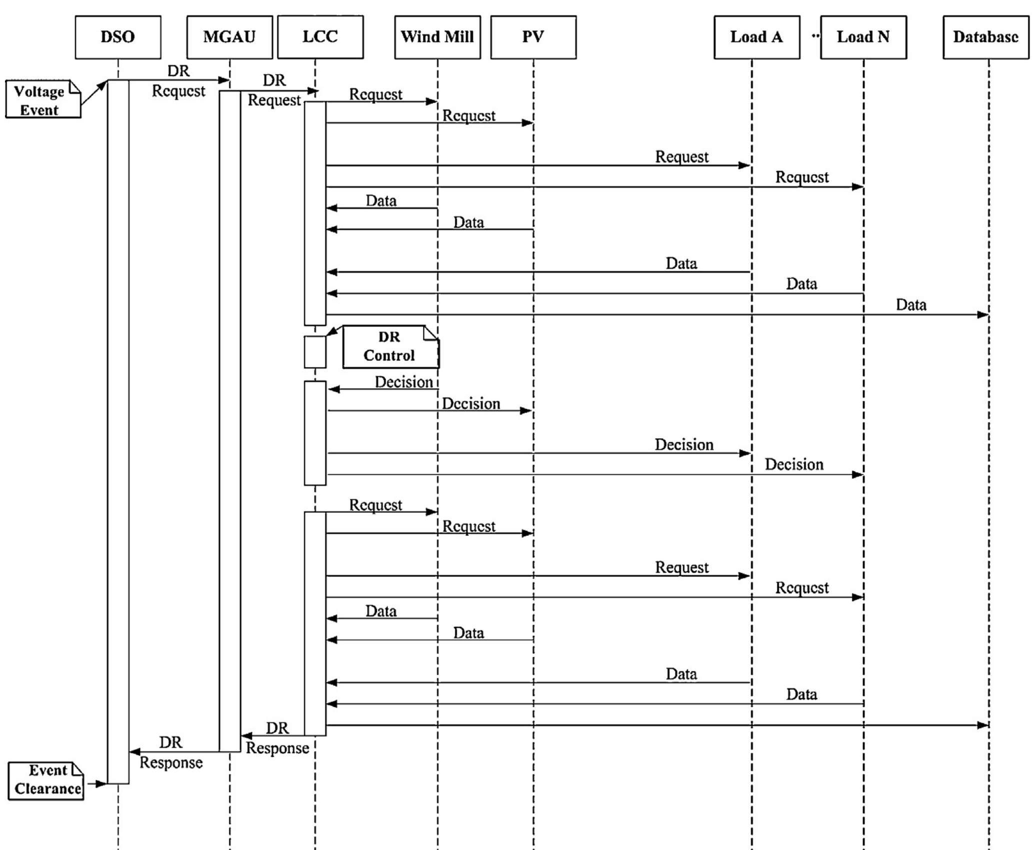

Fig. 9. UML diagram for voltage support services.

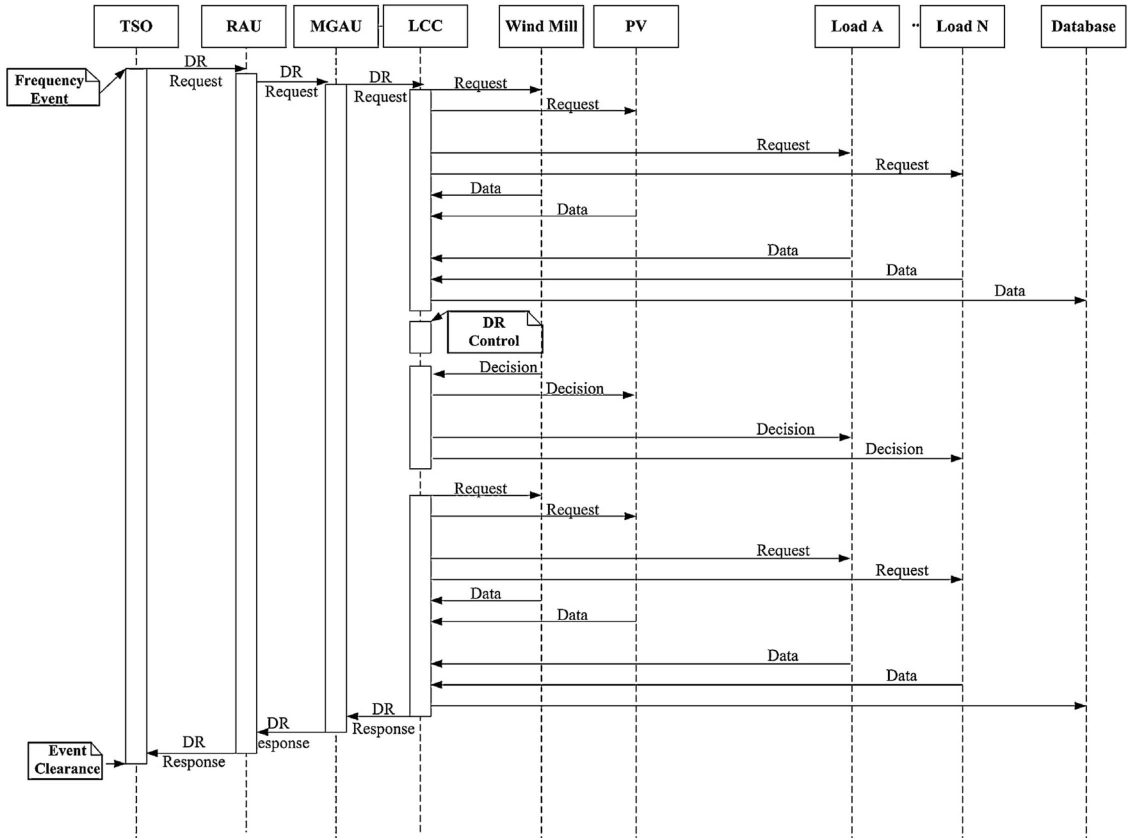

Fig. 10. UML diagram for frequency support services.

In order to avoid power shortages during islanding two approaches can be adopted:

i. *Time maximization*: The main concept is to keep the system live, as much as possible by lowering the consumption of Mas Roig. Loads with lower priority are disconnected first in order to serve more critical loads. The batteries, through their droop-controlled inverter, are responsible for power balancing.
ii. *Maximizing the number of load served*: In contrast with the previous approach, the consumption that can be served during island mode is maximized. Time is not a priority in this case. Load maximization assumes that the production of RES is maintained at the highest possible level during islanding. In order to maximize the number of loads that are served, loads that consume more than other are shed first according to a high-to-low priority order.

The available local production is updated periodically so as to ensure the equilibrium between available production and requested consumption.

The load shedding process is based on two criteria: the priority and the instant consumption of each load. Concerning the load priority, the loads are categorized in three main categories namely high, medium and low priority loads, as it is presented in Section 5. The level of priority reflects the importance of each load and it is defined by the end user according to his/her preferences. However, the end user can redefine the priority correlation of the loads at any time. As far as the load consumption is concerned, the loads of the same priority are ranked in a descent order such that the most consuming load is placed first.

In case of load shedding request, the most consuming and less important loads are firstly shed. The load shedding procedure is initialized with the low priority loads which are listed in a descent

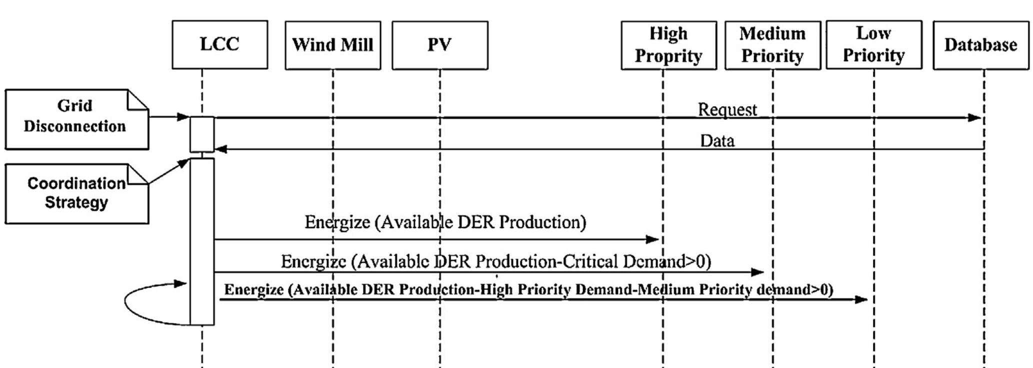

Fig. 11. UML diagram for island mode operation.

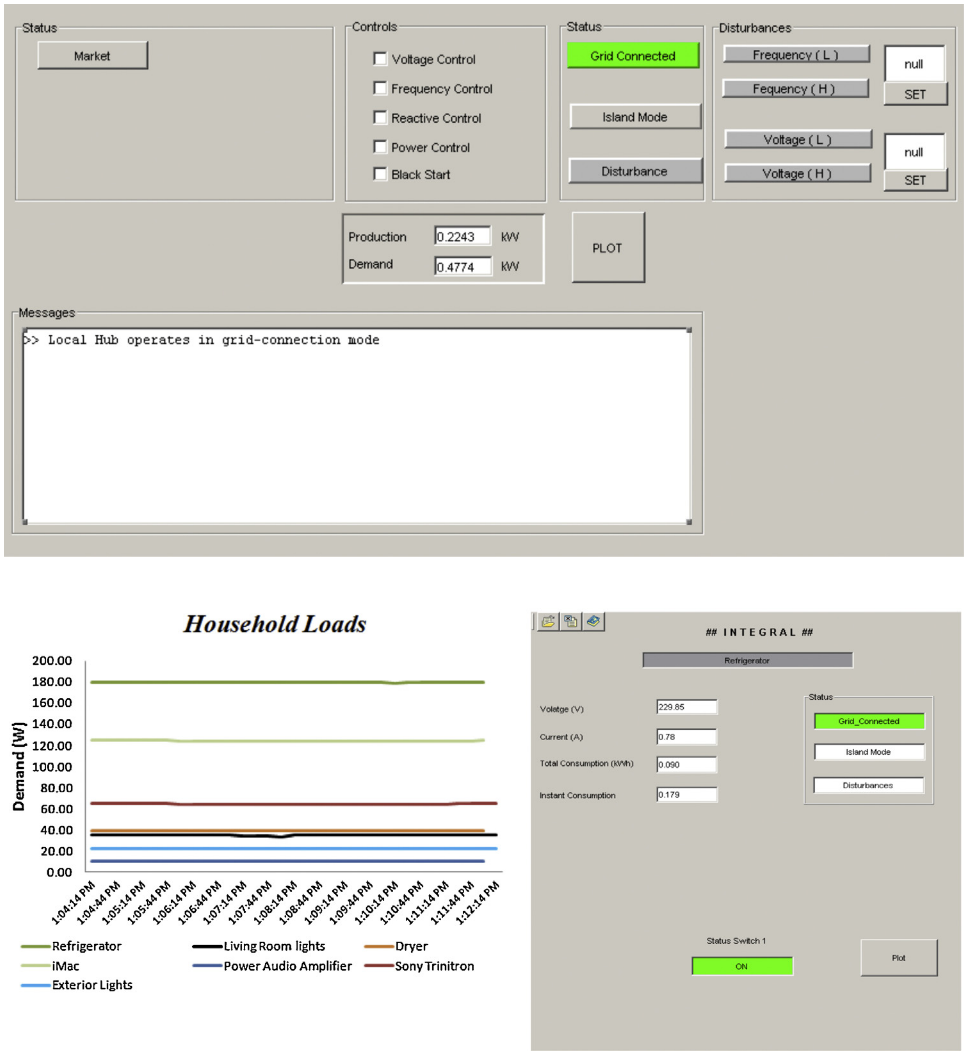

Fig. 12. Real monitoring results of normal operation. (For interpretation of the references to color in text near the reference citation, the reader is referred to the web version of this article.)

consumption order. Starting from the top of the list, the loads are shed until the amount of the demand reduction fulfills the load shedding request. Otherwise, the same procedure is followed for the next priority category. The termination criterion of the load shedding mechanism is defined by the achieved amount of load reduction which must be at least equal to the requested amount of load shedding.

7. Results

This section aims to present the results of the examined use cases and evaluate the performance of the proposed ICT technologies and MAS system examining the use cases presented in Section 6. It focuses on the operation of the local hub and the coordination of the household resources in order to respond to demand response requests. Since it was impossible to set up a real communication channel with the system operators during the development phase of the demo, virtual network operators' request signal were assumed in case of grid abnormal conditions for demonstration purposes.

A. *Normal operation*

Fig. 12 shows the monitoring system though the user interface platform. The system operates under normal grid operation mode as it is indicated by a colored (green shaded) indicator. The available local production is rather low, half of the household demand, due to the unfavorable weather conditions during the experimental day. The detailed household consumption is presented in Fig. 12 along with an indicative example of the load user-interface of the refrigerator.

B. *Voltage drop*

The multi-agent system monitors the voltage in the field test in order to maintain it within specific limits. In case the local voltage exceeds these limits, then immediate action should be taken in order to support the grid. In case of a voltage drop, there is need for reduction of the local consumption. In this case it is assumed that the DR requests equals to 10% demand reduction. The LCC will respond to this DR request by reducing the household demand at least 10% while supplying as many loads as possible. The total demand of the local building hub has been reduced to 0.4091 kW which corresponds approximately to a 13.6% load reduction (Fig. 13). The DR time including the communication delay and relevant computations is less than 2.5 s.

C. *Frequency drop*

We assume that in case of system frequency drop, the system operator requests from all RAUs to request a 20% load curtailment, which corresponds to a 20% reduction in the consumption

Fig. 13. Real monitoring results of voltage drop use case.

of each household. The total demand of the local building hub is reduced from 0.498 kW to 0.398 kW, after the DR process. As shown in Fig. 14, at 2:00 PM the dryer completes its workload providing a margin for a load increase equal to its operational load. Thus, two low priority loads (entrance light and power audio amplifier) that were shed by the demand side management process can be supplied. Such a dynamic behavior proves the adaptability of the MAS system to the changes occurred in

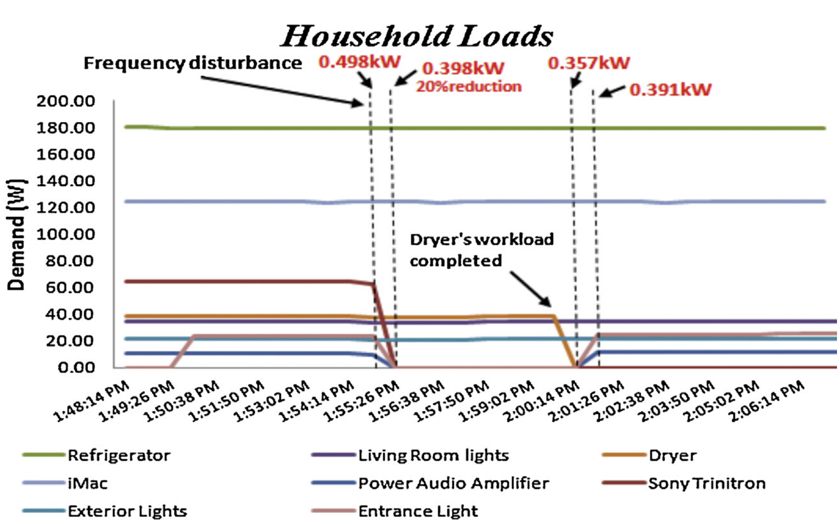

Fig. 14. Real monitoring results of frequency drop use case.

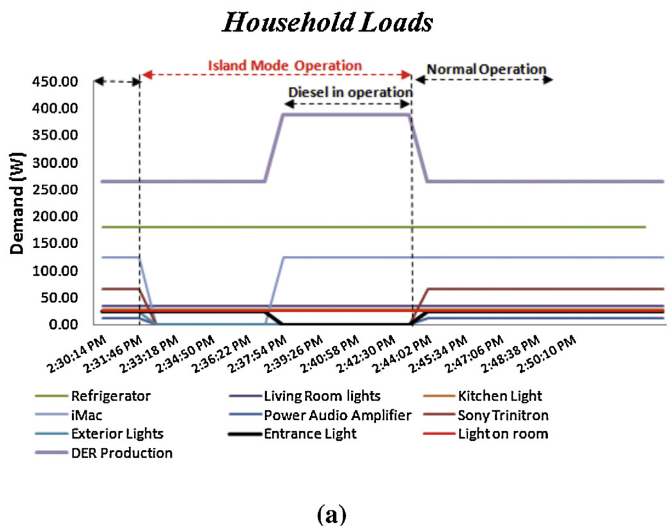

Fig. 15. Real monitoring results of island mode use case: (a) time maximization; (b) load maximization.

its environment and, consequently, the ability of the developed demand side management mechanism to maximize the end-users convenience given the dynamic behavior of the household demand.

D. Island mode

When a severe grid disturbance occurs, the household operates in island mode allowing only part of the demand to be supplied by the available local renewable sources. Initially, it is important to ensure that crucial loads remain alive. If the total demand of high priority loads is greater than the available RES production, then the diesel is set in operation. Otherwise, the rest of available local production is allocated to medium and high priority loads. As it can be seen from Fig. 15 only the lights in the kitchen and room from the medium priority loads and the light in the entrance from low priority loads remain alive. When the owner of the house decides to set the small diesel generator in operation, 1 kW of local power production is added to the available total generation. The two different load shedding strategies namely time and load maximization are presented in Fig. 15(a) and (b), respectively. In the time maximization scenario, unless the RES production is adequate to supply the household demand, the diesel generator is used to supply only the energy difference between the RES production and the aggregated power needs of the high and medium priority loads (Fig. 15(a)). In the load maximization approach, the diesel generator serves the load margin between RES production and total household demand (high, medium and low priority loads – Fig. 15(b)). Unless the available local power generation is not adequate to serve the whole household demand, load is shed based on loads priority.

8. Conclusions

An integrated solution that enables small residential consumer/prosumer to provide DR services for grid support considering both local energy resources and end-user's convenience is developed and successfully implemented in a real household environment. The demonstration results proves that the cooperation between ICT technologies that enable the monitoring of the local consumption/production and the MAS system that enables the efficient coordination of distributed energy resources at local level can adequately support the participation of individual households in DR services.

The efficiency of the ICT based multi-agent DSM for emergency and critical grid condition depends on the response time of the DSM process. Two time responses should be considered: one for the agent communication and another for the ZigBee node measurement period. Concerning the ZigBee node measurements, the interval of the records depends on the number of deployed ZigBee nodes and the distance among them, since the ZigBee nodes that are closer to the coordinator act as transmitter for the distant ones becoming possible bottlenecks. As far as the agent communication is concerned, the agents for controlling the Mas Roig site were executed in the same Jade platform in one PC unit. This minimizes the message transferring delay since there is no need for remote communication between different platforms or PC units, the delay of which depends on various factors (channel bandwidth, amount of transferred information etc.). In Mas Roig experiments, the load curtailment time response was less than 2.5 s. However, in larger scale applications, for example in case of hundreds of agents and ZigBee nodes, the time response will be much higher and thus the control system might become inefficient. For this purpose, a hierarchical multi-microgrid approach has been introduced.

It is important to ensure that any DSM mechanism has little impact on the consumer's convenience and requires the least user intervention. The nondeterministic behavior of end users requires the development of highly adaptive solutions. In the presented ICT based MAS application, this is ensured by the inherent adaptability offered by the multi-agent systems as well as the implementation of a mesh ZigBee network exploiting highly efficient routing algorithms.

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