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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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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/.