Multi-Agent Electricity Markets and Smart Grids Simulation with connection to real physical resources

Tiago Pinto[1], Zita Vale[1], Isabel Praça[1], Luis Gomes[1], Pedro Faria[1]
[1] GECAD – Knowledge Engineering and Decision-Support Research Center, Institute of Engineering – Polytechnic of Porto (ISEP/IPP), Porto, Portugal
{tmcfp, zav, icp, lufog, pnfar}@isep.ipp.pt

Abstract. The increasing penetration of distributed energy sources, mainly based on renewable generation, calls for the urgent emergence of novel advanced methods to deal with the associated problems while enabling both the system and the involved players to take full advantage of the potential of these resources. The consensus behind Smart Grids (SG) as one of the most promising solutions for the massive integration of renewable energy sources in power systems has led to the practical implementation of several prototypes and pilots that aim at testing and validating SG methodologies. The urgent need to accommodate such resources of distributed and intermittent nature and the impact that a deficient management of energy sources has on the global population require that alternative solutions are experimented. This chapter presents a multi-agent based SG simulation platform that is connected to physical resources, so that realistic scenarios with palpable influence on real resources can be simulated. The SG simulator is also connected to the Multi-Agent Simulator of Competitive Electricity Markets (MASCEM), which provides a solid framework for the simulation of restructured electricity markets. With the cooperation between the two simulation platforms, huge studying opportunities under different perspectives are provided, resulting in an important contribution in the fields of transactive energy, electricity markets, and SG. A case study is presented, showing the potentialities for interaction between players of the two ecosystems, namely by demonstrating a case in which a SG operator, which manages the internal resources of a SG, is able to participate in electricity market negotiations to trade the necessary amounts of power in order to fulfil the needs of SG consumers.

Keywords: Demand Response; Electricity Markets; Energy Resource Management; Multi-Agent Simulation; Smart Grids.

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1 Introduction

The use of Renewable Energy Sources (RES) has increased significantly, stimulated by policies and incentive programs aiming at decreasing the dependency on fossil fuels and avoiding environmental damages. The European Union has defined the well-known “20-20-20” as targets [1]. The agreed national targets will enable the EU as a whole to reach 20% energy consumption from renewable energy sources in 2020, more than doubling the 2010 level of 9.8%. In October 2014, a commitment has been achieved to reduce EU domestic greenhouse gas emissions by at least 40% below the 1990 level by 2030 [2]. Renewable energy sources such as wind and solar variable and intermittent nature poses new challenges to the power sector and also to Electricity Markets (EM). Many different market approaches have been experimented all around the world, and all have been subject to multiple revisions. The primary focus is on adapting electricity markets to deliver their intended economic efficiency and reliability outcomes under the new paradigm of growing share of renewable energy sources [3]. One of the main EU priorities concerns the formation of a Pan-European Energy Market. The majority of European countries have already joined together into common market operators, resulting in joint regional electricity markets composed of several countries. Additionally, in early 2015, several of these regional European electricity markets have been coupled in a common market platform, operating on a day-ahead basis [4]. That achievement has been enabled by the Multi-Regional Coupling (MRC), a pan-European initiative dedicated to the integration of power spot markets in Europe. The common market platform has resulted from an initiative of seven European Power Exchanges, called Price Coupling of Regions (PCR) [4], which have joined efforts to develop a single price coupling solution used to calculate electricity prices across Europe and allocate cross-border capacity on a day-ahead basis. This is a crucial step to achieve the overall EU target of a harmonized European electricity market.

However, the centralized top-down approach of electricity markets has proven to be insufficient to take full advantage from the participation of small players, both consumers and Distributed Generation (DG). Electricity markets still do not allow integrating the required amount and diversity of DG and put serious limitations to the participation of small and medium size resources [5]. Moreover, the tentative reforms of retail markets are not being able to achieve the envisaged goals as they are being built under the same top-bottom principles as wholesale markets. Electricity prices for smaller consumers still do not reflect the market prices and the introduction of flexible, innovative tariffs adapted to consumers’ needs and behaviours, able to promote and fairly remunerate their contribution towards an increasingly efficient energy system are still distant targets. New approaches that are able to bring a closer connection between small consumers and DG and the wholesale electricity market are required promptly. A pioneer solution to overcome the current problems is currently being implemented in the New York electricity market, in the US. The creation of Local electricity markets as part of the Regional electricity market is being put into practice, enabling smaller portions of the power network (microgrids) to participate in the electricity market as aggregators of the resources that are part of the portion of the grid. This way, resources can be managed at a local level, enhancing the potential of smaller sized resources, and their participation in electricity markets is facilitated by the microgrid operators. This provides an important incentive for the development of adequate methods to manage resources at lower levels and make their connection with higher, wholesale electricity markets, levels more effective.

One of the main achievements of the power and energy sector in recent years is the common acceptance by the involved stakeholders that power systems require major changes to accommodate in an efficient and secure way an intensive use of renewable based and DG [6], [7]. The conclusion that the so-called Smart Grids (SG) are required is a crucial foundation for the work to be done in the coming years towards the modernization and restructuring of the power sector according to the new paradigms [8]. Huge investments have already been made in projects concerning smart grids [9], including research and development projects, pilot installations, and rollout of smart metering. A list with 459 projects related to smart grids involving Member States is included in [9]. The large number of smart grid related projects is resulting in important advances in the field, namely concerning demonstration pilots and management and control methodologies. However, the quick emergence process of smart grids is not entirely free of problems. A large number of practical applications, although very expensive, are enabling solutions that present serious limitations and provide little return of investment. It is not clear that the rolled out equipment is sufficiently open and flexible to be useful for the next generation of smart grid solutions that should appear in the coming years. Additionally, although important contributions are being achieved, these still remain as solutions for partial problems. In highly dynamic and co-dependent areas, such as power networks, smart grids and electricity markets, the cooperation between different systems becomes essential in order to look at the global problem as a whole. Most of the smart grid related works consist in practical implementations, highly industry driven, and involving almost exclusively large stakeholders in the field, such as regulators, operators and utilities, resulting in an almost complete focus on achieving fast ways to overcome present problems.

A closer attention should also be given to the demand side and especially to its interaction with the new methods for smart grid operation and management. The demand side role is recognized as very important in many documents as in [10]. However, most projects are not considering this matter or are considering it in a very shallow way. Demand Response (DR) is a high value resource with low cost, when compared with the other available substituting resources [11]. It has already been proved in practice that DR is able to adequately prevent and/or solve emergency situations [12]. DR use in Europe is still very insipient [13] and even in the US, where the integration of DR is much more mature, the way it should be implemented is still a focus of controversy, as exemplified by the FERC Order 745 saga, in which a decision of the US Court of Appeals is preventing the application and derailing DR remuneration [14]. The potential of DR is still highly unexplored, and the delay in implementing adequate measures to take full advantage of its benefits is causing significant drawbacks. Suitable models and solutions to explore the full potential of DR are urgently needed.

Simulation combined with distributed artificial intelligence techniques is growing as an adequate form to study the evolution of electricity markets and the coordination with smart grids, in order to accommodate the integration of the growing DG penetration [8], [9]. Modelling the smart grid environment with multi-agent systems enables model enlargements to include new players and allows studying and analyzing both the individual and internal performance of each distinct player; as well the global and specific interactions between all the involved players [15].

MASGriP - Multi-Agent Smart Grid simulation Platform [7], [15] is a multi-agent system that models the internal operation of SGs. This system considers all the typically involved players, which are modelled by software agents with the capability of representing and simulating their actions. Additionally, some agents, namely the ones representing small players, are directly connected to physical installations, providing the means for an automatic management of the associated resources. MASGriP uses real-time simulation [16] to complement simulations with the analysis of the impact of the methods in the energy flows and transmission lines.

The Multi-Agent Simulator of Competitive Electricity Markets (MASCEM) [17], [18] is a modelling and simulation tool that has been developed to study complex electricity markets' operation. It provides market players with simulation and decision-support resources, being able to provide them competitive advantage in the market. MASCEM includes the market models of several real electricity markets, especially from EU operators. Simulations in MASCEM are based on real data, extracted in real-time from the websites of several market operators.

The presented work considers the integration between MASCEM and MASGriP, providing the means for a joint simulation of electricity markets and smart grids. The participation of smart grid players in electricity markets, in a controlled, simulated environment, brings huge studying opportunities, with the aim of bringing DG participation in the market a step closer to reality. It also provides invaluable studying opportunities for the solidification of the smart grid concept, and smart grid participation in competitive electricity negotiation environment. Additionally, the connection to real physical installations, the real-time simulation capabilities, and the use of real data to generate simulation scenarios, brings huge advantages for the validation of the achieved results, and consequent projection of simulated results into the reality.

This chapter consists of 6 sections. After this introductory section, section II presents the MASCEM electricity market simulator. Section III is dedicated to the MASGriP smart grid simulator, including the description of this simulator's connection to physical infrastructures. Section IV describes energy resource management methodology that is applied by the smart grid operator agent to manage the smart grid resources before and after participating in electricity market negotiations using the MASCEM simulator. Section V presents a case study concerning the joint simulation of electricity markets and smart grids that is provided by the connection between the two simulators; besides describing the simulation process, this section also presents the simulation results, providing a discussion on the influence of the joint simulation in the management perspectives of the smart grid operator; showing the real-time simulation results referring to the network impact of applying the methodologies, including different types of DR. Finally, section VI presents a discussion of the most relevant conclusions and future work.

2 MASCEM electricity market simulator

MASCEM [17, 18] provides a simulation platform for the study of complex electricity markets. MASCEM considers the most important entities and their decision support features, allowing the definition of bids and strategies, granting them a competitive advantage in the market. Players are provided with biding strategic behavior so that they are able to achieve the best possible results depending on the market context. MASCEM players include: market operator agents, independent system operator agents (ISO), market facilitator agents, buyer agents, seller agents, Virtual Power Player (VPP) [19] agents, and VPP facilitators.

MASCEM allows the simulation of the main market models: day-ahead pool (asymmetric or symmetric, with or without complex conditions), bilateral contracts, balancing market, forward markets and ancillary services. Hybrid simulations are also possible by combining the market models mentioned above. Also, the possibility of defining different specifications for the market mechanisms, such as multiple offers per period per agent, block offers, flexible offers, or complex conditions, as part of some countries' market models, is also available. Some of the most relevant market models that are fully supported by MASCEM are those of the Iberian electricity market – MIBEL, central European market – EPEX, and northern European market – Nord Pool.

Simulation scenarios in MASCEM are automatically defined, using the Realistic Scenario Generator (RealScen) [20]. RealScen uses real data that is available online, usually in market operators' websites. The gathered data concerns market proposals, including quantities and prices; accepted proposals and established market prices; proposals details; execution of physical bilateral contracts; statement outages, accumulated by unit type and technology; among others. By combining real extracted data with the data resulting from simulations, RealScen offers the possibility of generating scenarios for different types of electricity markets. Taking advantage on MASCEM's ability to simulate a broad range of different market mechanisms, this framework enables users to consider scenarios that are the representation of real markets of a specific region; or even consider different configurations, to test the operation of the same players under changed, thoroughly defined scenarios [20]. When summarized, yet still realistic scenarios are desired (in order to decrease simulations' execution time or facilitate the interpretation of results), data mining techniques are applied to define the players that act in each market. Real players are grouped according to their characteristics' similarity, resulting in a diversity of agent types that represent real market participants.

In order to allow players to automatically adapt their strategic behavior according to the operation context and with their own goals, a decision support system has been integrated with MASCEM. This platform is ALBidS (Adaptive Learning Strategic Bidding System) [18], and provides agents with the capability of analyzing contexts of negotiation, allowing players to automatically adapt their strategic behavior according to their current situation. In order to choose the most adequate strategy for each context, ALBidS uses reinforcement learning algorithms (RLA), and the Bayesian theorem of probability. The contextualization is provided by means of a context definition methodology, which analyzes similar contexts of negotiation (e.g. similar situations in the past concerning wind speed values, solar intensity, consumption profiles, energy market prices, and types of days and periods, i.e. business days vs. weekends, peak or off-peak hours of consumption, etc.). This contextualization allows RLAs to provide the most adequate strategic support to market players depending on each current context. ALBidS strategies include: artificial neural networks, data mining approaches, statistical approaches, machine learning algorithms, game theory, and competitor players' actions prediction, among others. Figure 1 shows the connection between MASCEM and ALBidS, including the diverse modules that compose both systems.

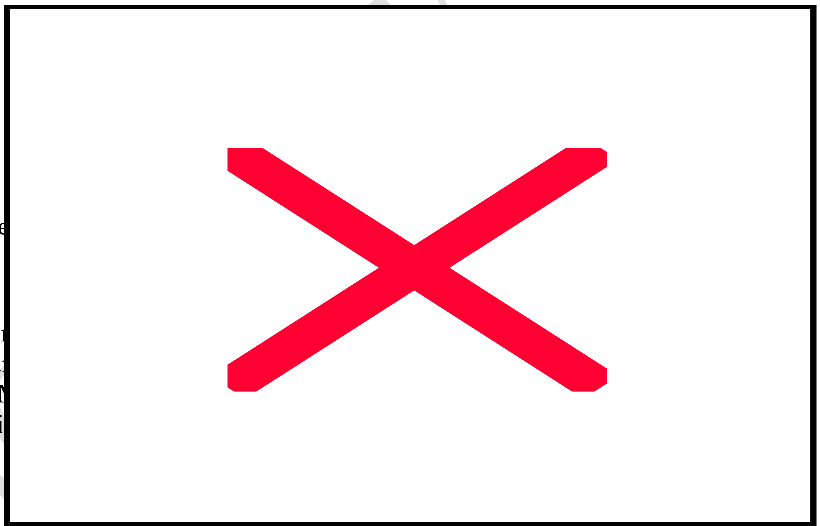


Fig. 1. Inte

ALBidS is implemented as a
responsible for an algorithm,
simultaneously, increasing the pe
build a suitable mechanism to ma
the minimum degradation of
methodology to manage the effi
been developed [18].

All communications between
messages [21]. FIPA suggests Agent Communication Language (ACL) as a standard for communications between agents. Its content includes the content language, specifying the syntax, and the ontology which provides the semantics of the message assuring the correct interpretation [22]. MASCEM agents use ontologies to allow the interoperability with other systems that intend to participate in the available electricity markets, as is the case of MASGriP [23]. These ontologies are also used to facilitate the interoperability with ALBidS, and they open the possibility for interaction with agents from external systems [23].

3 MASGriP smart grid simulation platform

MASGriP simulates, manages and controls the most relevant players acting in a smart grid environment [15]. The proposed system includes fully simulated players, which interact with software agents that control real hardware. This enables the development of a complex system capable of performing simulations with an agent society that contains both real infrastructures and simulated players, providing the means to test alternative approaches (Energy Resource Management (ERM) algorithms, DR models, negotiation procedures, among many other) in a realistic simulation environment [7].

3.1 Multi-agent model

MASGriP provides a simulation platform that allows the experimentation and analysis of different types of models, namely energy resource management methodologies, contract negotiation methods, energy transaction models, and diverse types of DR programs and events. Among the many alternative DR models that are supported by MASGriP, both price-based and incentive-based models are considered [12], regarding three types of actions: loads curtailment, reduce, and shift. Direct Load Control (DLC) [12] is also included.

The simulated players in MASGriP have been implemented to reflect the real world. These players include some operators, such as the Distribution System Operator (DSO) and the Independent System Operator (ISO). However, the majority of players represents energy resources, such as several types of consumers (e.g. industrial, commercial, residential), different types of producers (e.g. wind farms, solar plants, cogeneration units), EVs with vehicle-to-grid capabilities, among others.

Aggregators present an important role in the future power system management and operation. Some examples of the considered aggregators are: VPPs [19], which can aggregate any other resource, including other aggregators; Curtailment Service Providers (CSP) [24], which aggregate consumers that participate in DR programs; SG operators, which manage the players that are contained in a specific SG. These players introduce a higher level of complexity in the system management.

The communications are implemented through the JADE platform, compliant with FIPA specifications [21]. FIPA supports agents' interoperability by standardizing their communications and content languages. To facilitate the exchange of information, our own ontology has been developed, where each event has its own predicates and characteristics [23]. By using FIPA-ACL, external developed players and resources will also be able to participate in simulations within this system by using the implemented communication system. The interface with software agents that allow the interaction with real players (humans) and with real hardware (loads, generators units, storage systems, protections, etc) is achieved using an interface agent that allows the communication with hardware. Communications are performed using Internet Protocol (IP) to communicate with a Programmable Logic Controller (PLC) and RS-485 to communicate with soft-starters, measurement units, etc.

3.2 Connection to physical resources

MASGriP agents that represent physical players detain all the information concerning the physical installation, including its geographic coordinates and the electric characteristics. Concerning the type of player, the business model and the contracts being used, each agent has the necessary information to share with the other agents.

The sharing rules can be modified according to negotiations between the players and the aggregators, making MASGriP a dynamic system.

MASGriP is also used to control real physical installations through its integration with the SCADA (Supervisory Control and Data Acquisition) Office Intelligent Context Awareness Management (SOICAM). SOICAM was developed in GECAD under GID-Microrede project. The physical installations consist of four main spaces. Three of these are campus buildings where GECAD (Knowledge Engineering and Decision Support Research Group) operates. These buildings include several offices, classrooms, kitchens, and bathrooms. The fourth place is a laboratorial controlled house. SCADA-House [25] is located in a GECAD laboratory, and contains a large set of different loads, normally used in a common house. These loads are connected to a SCADA management system, which is controlled by a software agent. Some resources are not available in our lab, making their physical integration in the system impossible. In order to overcome this limitation, OPAL-RT [26] is used to simulate resources that are not physically available. The integration between OPAL-RT and the remainder of the system is done through the Java API of OPAL-RT. Among many other resources, the OPAL-RT platform simulates wind generators making it possible to obtain outputs according to their electrical models, which can also be validated by using the platform capabilities. Additionally, OPAL-RT is also able to perform real time simulations of the components, loads and facilities that cannot be used or simulated in conventional systems. The integration of real loads in OPAL-RT is possible through the connection to software agents that represent different players in the electricity market (e.g. large consumers, large producers, and virtual players) and players connected to the distribution network (such as facilities and microgrids) [25]. This merge allows the use of different methods for management and control of the distribution network while the real time simulator analyses the impact of the methods in the energy flows and transmission lines.

The GECAD buildings where SOICAM is implemented cover more than 30 researchers. SOICAM was implemented in June, 2014. The system monitors all the consumption and generation of GECAD. The generation data (namely solar and wind based) is stored individually every 10 seconds. The consumption data is divided by three main types (Fig. 2): Illumination; Heating, Ventilation and Air Conditioning (HVAC); and electrical sockets. The consumption data is also stored every 10 seconds. All data is stored in a SQL Server database, allowing the study of consumption and generation in GECAD, as well as its management by MASGriP's software agents.

SOICAM is also able to control HVAC systems. This functionality is only available for one building, affecting 19 researchers. The possible control is only on/off for now. New hardware is being developed and implemented to allow individual load management and control. Using refined control over the load and not only on/off control, the SOICAM performance and utility is increased.

SOICAM uses five switchboards to incorporate the energy analysers and the HVAC control system. These switchboards communicate with two main communication switchboards (one for each building) via RS485. The main communication switchboards aggregate the energy analysers' information. The information can be accessed by MODBUS/TCP.

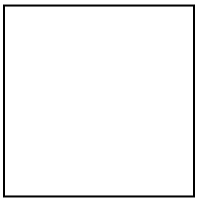


Fig. 2. Monitored loads (blue: illumination; red: HVAC; green: electrical sockets)

The data acquired by SOICAM is used to test and validate the participation of SOICAM as a SG player. Additionally, the use of MASGriP for real-time control enables the simulation of real scenarios with visible outcomes on the loads.

The inclusion of a large set of different players, the combination of technical and economic treatment of future power systems, the inclusion of both real and simulated players, and the facilitation in adding or testing alternative algorithms, such as energy resource management methods, forecasting methodologies, DR models, and negotiation procedures, are characteristics that distinguish the proposed simulation platform from other existing simulators. The integration with MASCEM enables the simulation platform to go yet a step further, by including electricity market simulation capabilities to the joint simulations.

4 Day-ahead and hour-ahead energy resource management

The mathematical formulation of the ERM platform is classified as a mixed-integer non-linear programming problem (MINLP). The SG operator can maximize the profits or minimize the costs to supply the required energy in both phases of proposed methodology. The XA index refers to each phase of the methodology, namely day-ahead scheduling (DA) and hour-ahead scheduling (HA). To maximize the profits (2), the SG operator uses the cheaper resources, *i.e.* minimize the cost (1), and maximize the income (In).

$$Minimize\ f = C \tag{1}$$

$$Maximize\ f = In - C \tag{2}$$

The intention of a SG operator is to obtain profits from ERM, as well as the consumers, who wish to minimize the costs. The ERM platform allows that consumers attempt to use more energy in lower price periods and avoid the energy use in higher price periods. To determining the SG operator's income (3), is considered the revenues from supplying the demand power to the consumers $P_{Load_{XA}(L,t)}$, the selling energy to the electricity market $P_{Sell_{XA}(t)}$, the charging process of storage units $P_{Ch_{XA}(ST,t)}$, the charging process of EVs $P_{Ch_{XA}(V,t)}$. To limit the charge of the EV a weight λ was applied in order to charge the essential energy to make the return trip. The SP_X terms refer to SG prices and the index X refers to the type of energy resources used in the income.

$$In = \sum_{t=1}^{T}\left[\begin{array}{l}\sum_{L=1}^{N_L} SP_{Load(L,t)} \times P_{Load_{XA}(L,t)} + SP_{Sell(t)} \times P_{Sell_{XA}(t)} + \\ \sum_{ST=1}^{N_{ST}} SP_{Ch(ST,t)} \times P_{Ch_{XA}(ST,t)} + \lambda \times \sum_{V=1}^{N_V} SP_{Ch(V,t)} \times P_{Ch(V,t)}\end{array}\right] \tag{3}$$

For the operation cost (4) of the resources managed by the SG operator, is considered the cost of all the available resources, namely the DG cost $P_{DG_{XA}(DG,t)}$, the cost with the energy bought to external suppliers $P_{SP_{XA}(SP,t)}$, the cost of energy discharged by the storage systems $P_{Dch_{XA}(ST,t)}$, the cost of energy discharged by the EVs $P_{Dch_{XA}(V,t)}$, , the DR events from the system operator (load curtailment $P_{Cut_{XA}(L,t)}$ and load reduction $P_{Red_{XA}(L,t)}$), and the non-supplied demand $P_{NSD_{XA}(L,t)}$ and penalization with generation curtailment $P_{GCP_{XA}(DG,t)}$ considering the "take-or-pay" contracts.

$$C = \sum_{t=1}^{T}\left[\begin{array}{l}\sum_{DG=1}^{N_{DG}} c_{DG(DG,t)} \times P_{DG_{XA}(DG,t)} + \sum_{SP=1}^{N_{SP}} c_{SP(SP,t)} \times P_{SP_{XA}(SP,t)} + \\ \sum_{ST=1}^{N_{ST}} c_{Dch(ST,t)} \times P_{Dch_{XA}(ST,t)} + \sum_{V=1}^{N_V} c_{Dch(V,t)} \times P_{Dch_{XA}(V,t)} + \\ \sum_{L=1}^{N_L} c_{Cut(L,t)} \times P_{Cut_{XA}(L,t)} + \sum_{L=1}^{N_L} c_{Red(L,t)} \times P_{Red_{XA}(L,t)} + \\ \sum_{L=1}^{N_L} c_{NSD(L,t)} \times P_{NSD_{XA}(L,t)} + \sum_{DG=1}^{N_{DG}} c_{GCP(DG,t)} \times P_{GCP_{XA}(DG,t)}\end{array}\right] \tag{4}$$

Problem constraints of the ERM platform include both technical and economic aspects, such as the Kirchhoff's Law, voltage limits, line thermal limits, the maximum capacity considering the available resources, the storage resources, and DR power limits. A more detailed description of all the constraints used is presented in [8].

The decision process for the ERM hour-ahead model (5) determines whether there is surplus or shortage of generated energy between the newer forecast (hour-ahead forecast) and the day-ahead scheduling, for each period *t*. To determining the decision process (5), is considered the hour-ahead forecast the demand power to the consumers

$P_{Load_{FHA}}$, hourly forecasts of the renewable energy sources $P_{DG_{FHA}}$, and the results of day-ahead scheduling, particularly the generation $P_{DG_{DA}}$ and the load $P_{Load_{DA}}$.

$$\left(\sum_{DG=1}^{N_{DG}} P_{DG_{FHA}(DG,t)} - \sum_{DG=1}^{N_{DG}} P_{DG_{DA}(DG,t)}\right) \geq \left(\sum_{L=1}^{N_{L}} P_{Load_{FHA}(L,t)} - \sum_{L=1}^{N_{L}} P_{Load_{DA}(L,t)}\right) \quad (5)$$

The set of the additional specific constraints of hour-ahead is divided into two groups: overproduction (6), when there is surplus of generated energy, and overconsumption (7), when there is shortage of generated energy. Fig. 3 show the decision process for the ERM hour-ahead model.

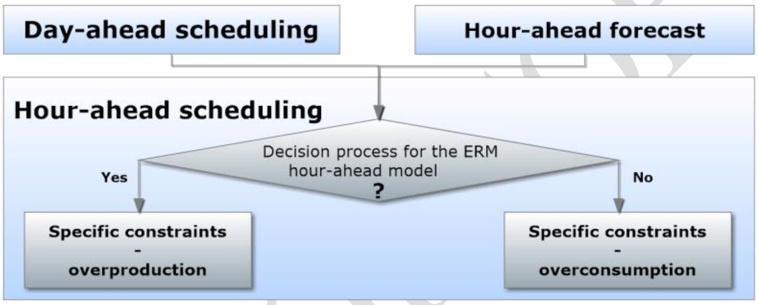


Fig. 3. Decision process for the hour-ahead scheduling methodology

For specific constraints of the overproduction (6) and overconsumption (7), is considered the technical limits of the distributed energy resources for the each period *t*. where $X_{Cut_{XA}}$ represent the binary variable of DR curtailment of load in XA phase of methodology proposed. The $P_{X\,Min}$ terms refer to minimum active power and the index X refers to the type of energy resources used. The $P_{X\,Max}$ terms refer to maximum active power and the index X refers to the used type of energy resources.

$$
\begin{aligned}
&P_{DGMin(DG,t)} \le P_{DG_{HA}(DG,t)} \le P_{DG_{DA}(DG,t)} \\
&P_{SPMin(SP,t)} \le P_{SP_{HA}(SP,t)} \le P_{SP_{DA}(SP,t)} \\
&P_{Ch_{DA}(ST,t)} \le P_{Ch_{HA}(ST,t)} \le P_{ChMax(ST,t)} \\
&P_{Dch_{HA}(ST,t)} \le P_{Dch_{DA}(ST,t)} \\
&P_{Ch_{DA}(V,t)} \le P_{Ch_{HA}(V,t)} \le P_{ChMax(V,t)} \\
&P_{Dch_{HA}(V,t)} \le P_{Dch_{DA}(V,t)} \\
&P_{Red_{HA}(L,t)} \le P_{Red_{DA}(L,t)} \\
&P_{Cut_{HA}(L,t)} = \begin{cases} 0 & \text{, if } X_{Cut_{DA}(L,t)} = 0 \\ P_{MaxCut(L,t)} \times X_{Cut_{HA}(L,t)} & \text{, if } X_{Cut_{DA}(L,t)} = 1 \end{cases} \\
&P_{Sell_{DA}(t)} \le P_{Sell_{HA}(t)} \le P_{SellMax(t)}
\end{aligned}
\tag{6}
$$

$$
\begin{aligned}
&P_{DG_{DA}(DG,t)} \le P_{DG_{HA}(DG,t)} \le P_{DGMax(DG,t)} \\
&P_{Sp_{DA}(SP,t)} \le P_{Sp_{HA}(SP,t)} \le P_{SpMax(SP,t)} \\
&P_{Ch_{HA}(ST,t)} = P_{Ch_{DA}(ST,t)} \\
&P_{Dch_{DA}(ST,t)} \le P_{Dch_{HA}(ST,t)} \le P_{DchLimit(ST,t)} \\
&P_{Ch_{HA}(V,t)} = P_{Ch_{DA}(V,t)} \\
&P_{Dch_{DA}(V,t)} \le P_{Dch_{HA}(V,t)} \le P_{DchLimit(V,t)} \\
&P_{Red_{DA}(L,t)} \le P_{Red_{HA}(L,t)} \le P_{MaxRed(L,t)} \\
&P_{Cut_{HA}(L,t)} = \begin{cases} P_{MaxCut(L,t)} \times X_{Cut_{HA}(L,t)} & \text{, if } X_{Cut_{DA}(L,t)} = 0 \\ P_{Cut_{DA}(L,t)} & \text{, if } X_{Cut_{DA}(L,t)} = 1 \end{cases} \\
&P_{Sell_{HA}(t)} \le P_{Sell_{DA}(t)}
\end{aligned}
\tag{7}
$$

5 Case Study

The potential of the joint simulation of SG and EM using MASGriP and MASCEM is demonstrated by a case study based on real data, which includes several players that control physical installations. The interface between the two environments is done by the SG operator, which is responsible by managing the internal resources of the SG using the ERM methodology that is presented in section 4, and by participating in the EM in order to purchase the required amount of power to fulfill the SG needs when the local generation is low, and sell eventual surplus power when the generation is higher. The ERM is performed in a day-ahead basis, including the DG, consumption and market price forecasts for the following day. The market transacted power and resulting prices are used by the SG operator to adapt its management results, namely by performing a new ERM in an hour-ahead basis for each hour of the objective day.

5.1 Case study characterization

The simulated scenario considers a SG that is simulated using MASGriP, concerning a real distribution network located in Portugal, with 25 bus (Fig. 4). The private distribution network is connected to the main grid trough a MV/LV transformer. The SG accommodates distributed generation (photovoltaic and wind based generation) and storage units, which are integrated in the consumption buildings (8 residential houses, 8 residential buildings, and 1 commercial building). The two loads that are connected to Bus 5 are physical installations, namely Buildings I and N of GECAD. The used data concerning these loads results from the measurements, and the simulation results have a direct impact on the real loads of these two GECAD buildings. The accommodated photovoltaic generation, wind based generation and storage units are related to the building installed consumption power, according to the current legislation in Portugal. Further details on the considered distributed network can be seen in [28].

The presented case study considers a simulation day during the summer time in Portugal, namely 4th September 2014. In this context, the photovoltaic generation reaches high values, especially during the mid-hours of the day. The sequence of events for this case study is presented in Fig. 5, considering the actions of the SG operator agent when managing the energy resources, in the scope of MASGriP, and when participating in the EM, using MASCEM, in order to sell the surplus of generated power of the SG or buying the required power to fulfill the requirements of the SG consumers when necessary.

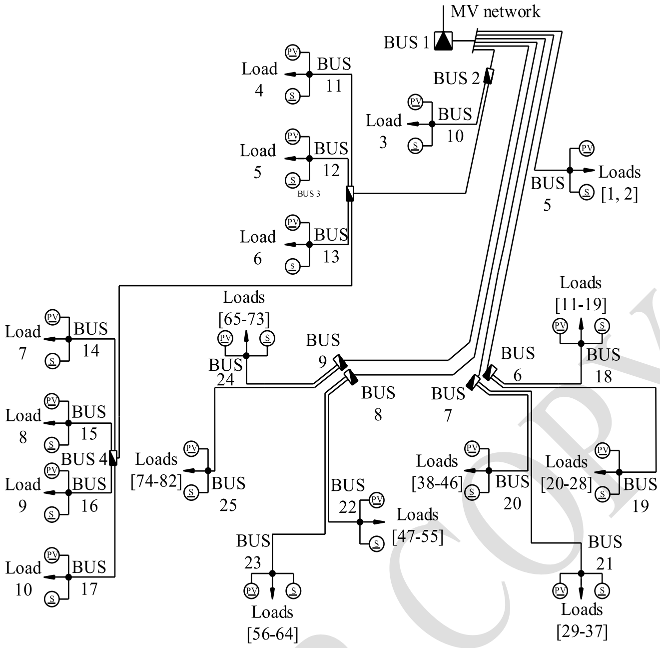


Fig. 4. Distribution network used for the SG simulation

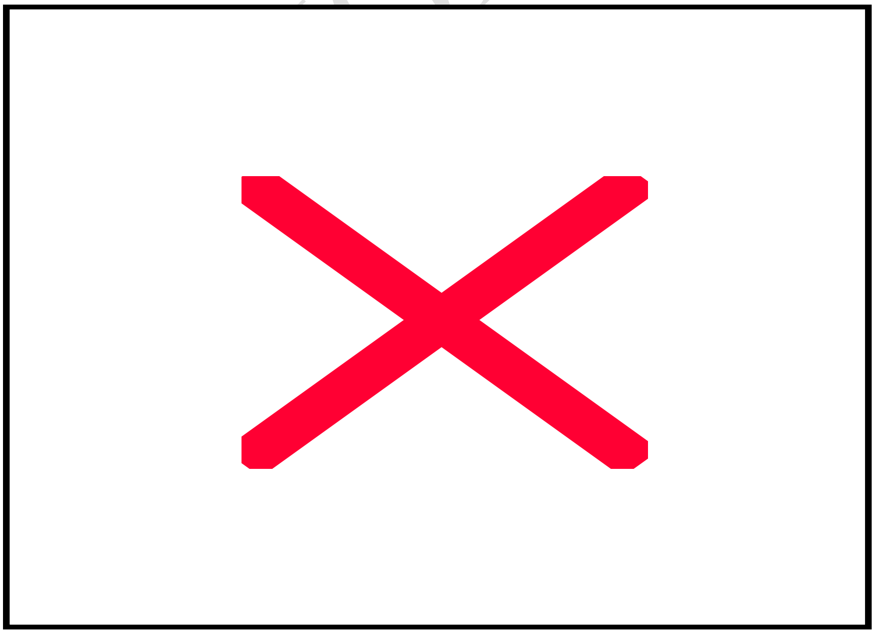


Fig. 5. Simulation sequence process

From Fig. 5 it is visible that the SG operator agent starts by executing some preliminary forecasts, considering the expected market price of the following day, the expected DG (including the forecast of the wind speed, solar intensity, and temperature in order to model the expected generation), and also the expected consumption of all the consumers that are part of the SG. These forecasts are performed using ALBidS, as presented in [28-31], and are used to perform a day-ahead ERM. From this management results the optimal hourly schedule of generation, consumption, application of DR programs, charge and discharge of EVs' batteries, and also the total hourly needs for power that must be bought from outside the SG, and hourly surplus power that can be sold in order to improve the incomes of the SG operator. Using the results of the day-ahead ERM, the SG operator agent participates in the EM simulation, using MASCEM, in order to negotiate the amounts of power that must be sold or purchased.

Finally, the achieved market results are used to execute new, adapted, hour-head ERM, considering the deals that have been established in the market, and new, updated, hour-ahead forecasts of DG and consumption in the SG; and bilateral contract and balancing market prices, which can be used no negotiate extra amount of power, as required by the 24 hour-ahead ERMs. From the hour-ahead ERMs result the final scheduling of the SG resources, and eventually new amounts of power (to sell or buy) that should be negotiated with external entities by means of bilateral contracts or by participating in near real-time markets, such as balancing markets. These negotiations are the last resource to achieve the required power to fulfil the SG consumers' needs, or as a final opportunity to sell extra power to increase the incomes of the SG operator.

Real-time simulation using the connection to OPAL-RT is executed after each ERM, in order to analyse the impact of the scheduled actions in the power network, and validate if such results are suitable to be implemented, from the network standpoint. The present case study allows in all the loads the use of incentive-based demand response programs pay participating customers to reduce their load at maximum until 30% of the initial load. Moreover, it allows the energy shifting in commercial building located at bus 5 (loads 1 and 2), at the maximum of 60% of the initial load [32]. The use of DR resources can be seen both in the simulated environment by analysing the outcomes of the software agents, and also in the real resources, by verifying the implication of loads curtailment, reduce, and shift, in the physical installations.

The ERM methodology has been developed in TOMLAB Optimization with CPLEX solver using MATLAB R2014a 64 bits software. The simulations presented in this case study have been executed in a machine with one Intel® Xeon® E5-2620v2 - 2.10 GHz processor, with 12 cores, 16GB of Random-Access-Memory (RAM) and Windows 8.1 Professional.

5.2 Results

Fig. 6 presents the scheduling results of the day-ahead ERM, including the DG, consumption and day-ahead market price forecasts. The results shown in Fig. 6 concern the generated power; the initial expected load, and the final load resulting from the application of DR; the charge and discharge of batteries; and the amount of power that needs to be transacted outside the considered SG.

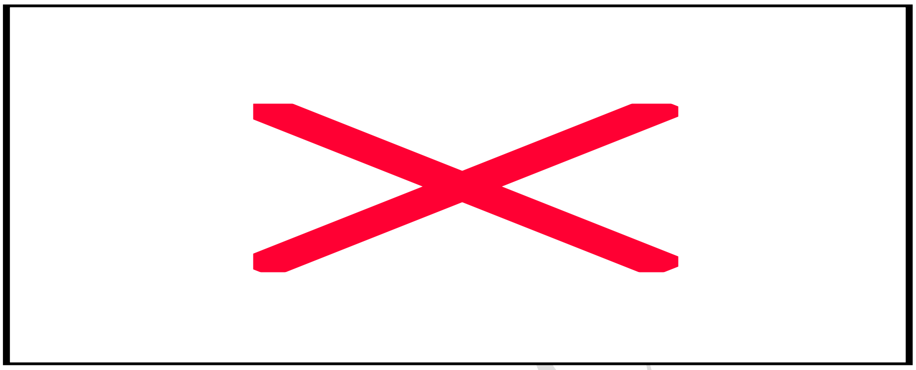


Fig. 6. Scheduling results of the day-ahead ERM

From Fig. 6 it is visible that, due to the high value of photovoltaic generation during the day, the SG achieves large volumes of generated power during most hours of the day (during day-time). This amount is used to charge the batteries, so that the consumption can be guaranteed in the last periods of the day (when the generation decreases), namely from periods 20 to 24. During the first hours of the day, since the batteries have not yet been charged (all batteries started the simulation completely empty), and there is still no photovoltaic generation, the consumption has to be assured by external sources; in this case, from power bought in the electricity market. Additionally, DR programs are used to lower the consumption during these first hours of the day, so that the cost of purchasing power externally is minimized. The reduction of loads has been applied during hours 1 to 7, and the shifting of other loads has also been used, namely in periods 2, 4 and 6. Fig. 7 details the loads shifting process in the GECAD buildings (Bus 5).

From Fig. 7, as can be confirmed by the comparison between the dashed line and the solid line of Fig. 6, some loads (referring to GECAD’s buildings) have been moved from hours 2, 4 and 6 to hours 13, 15 and 23. This DR process allows taking load away from periods where the demand is higher, when compared to the generated production, and incentivising consumers rather to make this consumption in hours that are more convenient to the network (due to lower consumption, higher generation, or lower energy prices from external sources).

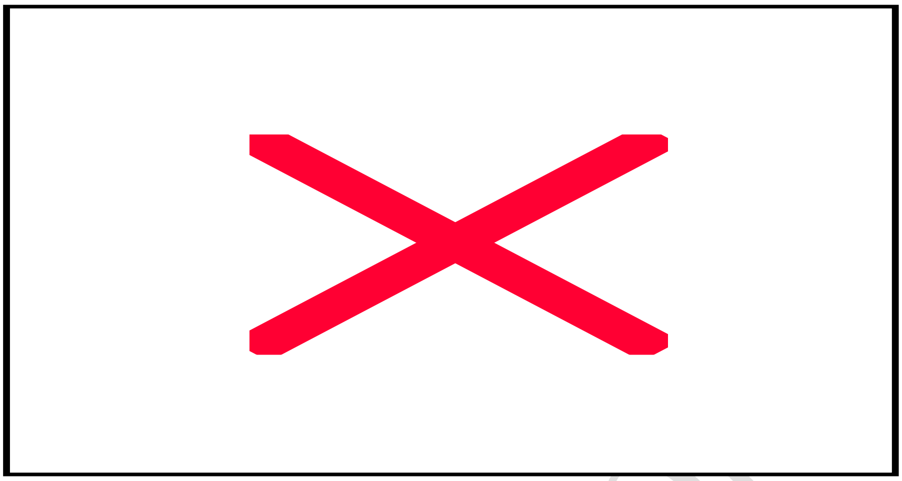
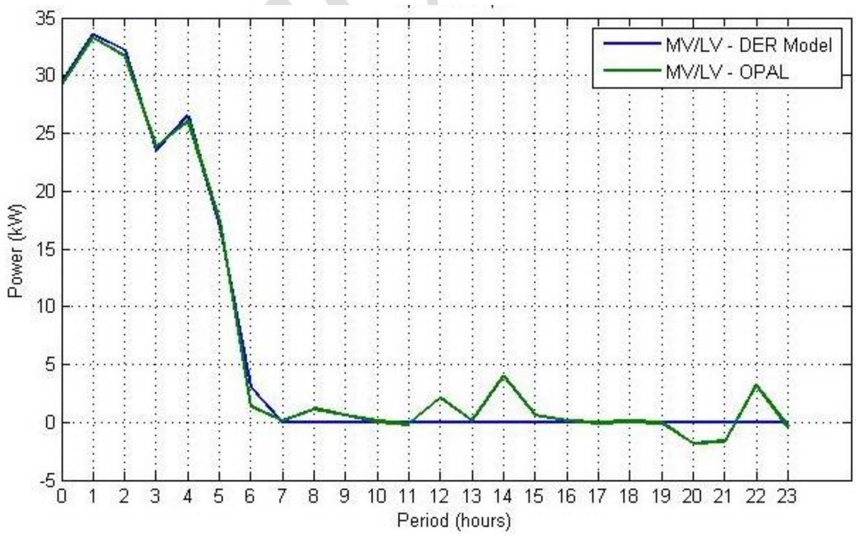


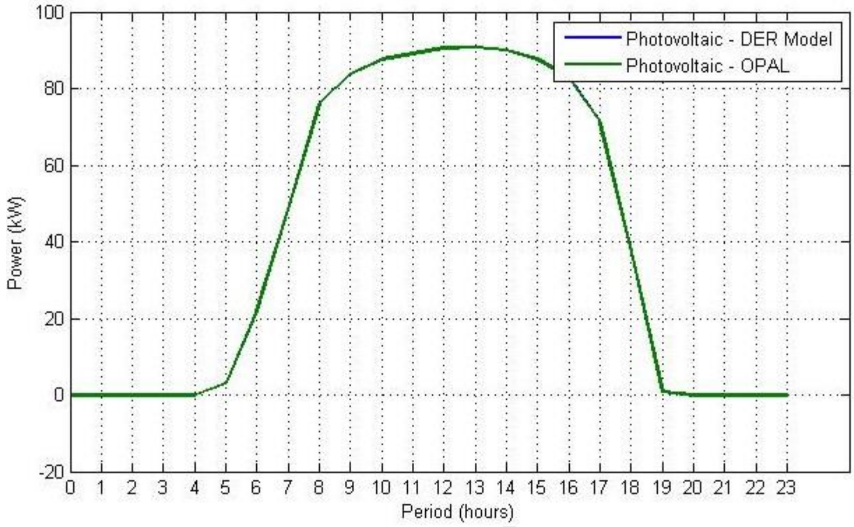
Fig. 7. Loads shifting in GECAD's buildings

After the execution of the day-ahead ERM, real-time simulation using OPAL-RT is executed, so that the impact of the optimal scheduling results on the power network can be evaluated. Fig. 8 presents the comparison between the data resulting from the ERM, and the values resulting from the OPAL-RT simulation.

(a)



(b)



(c)

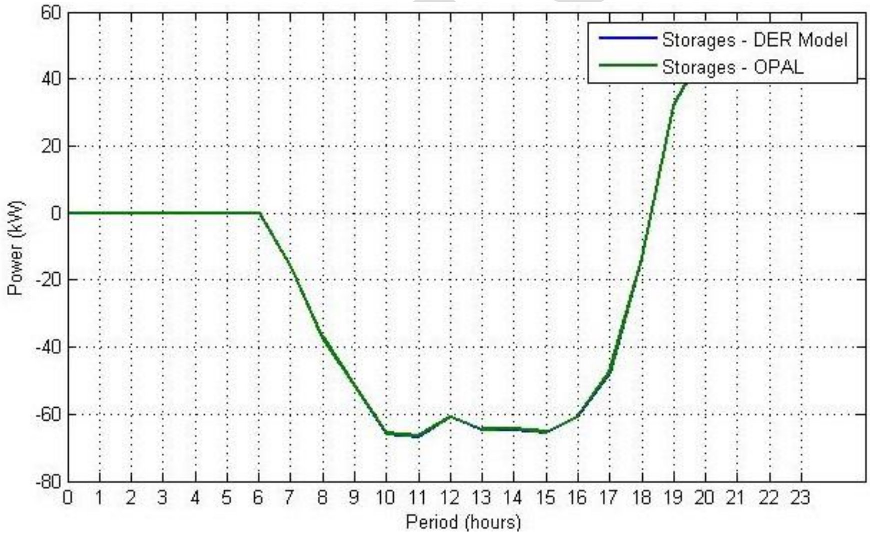


Fig. 8. ERM and OPAL-RT results comparison, regarding: (a) energy traded by the SG with the external network in MV; (b) total photovoltaic generation of the SG; and (c) total SG storage charge and discharge.

From Fig. 8 it is visible that the output from the OPAL-RT simulation is almost identical to the results of the day-ahead ERM, especially for the cases of photovoltaic generation (Fig. 8 b) and batteries (Fig. 8 c). This occurs because the model has been built with flow sources based on Three-Phase Programmable Source (PLL). The most notorious difference is verified in the interaction with the external network, in bus 1

(Fig. 8 c), due to the response time of the physical components. The synchronization is not instantaneous, and for this reason some discrepancies occur. This can be better visualized by Fig. 9, which shows the behaviour of the loads, comparing the expected behaviour as resulting from the ERM, and the actual behaviour that results from the real time OPAL-RT simulation.

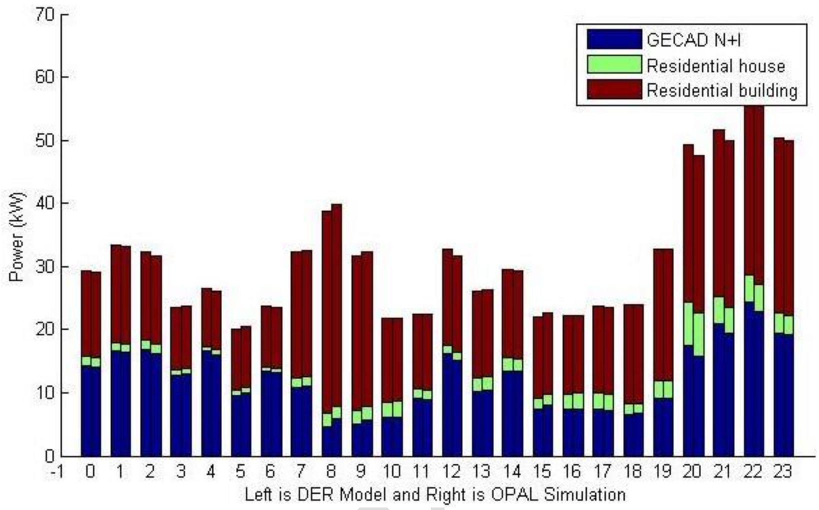
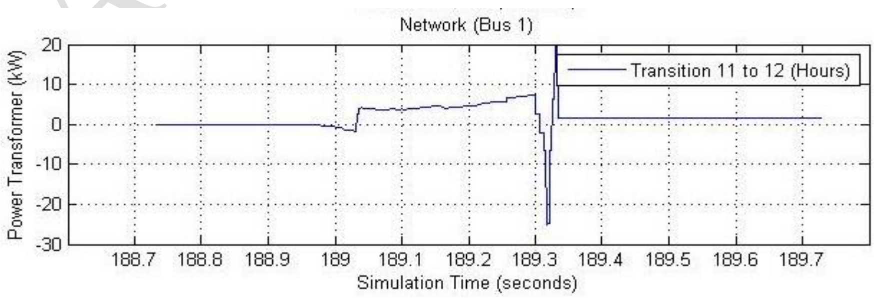


Fig. 9. Comparison of the loads as result from the day-ahead ERM scheduling, and as result from the OPAL-RT real time simulation.

From Fig. 9 it is visible that the real-time simulation results are very similar to those expected, as result from the day-ahead ERM. The larger discrepancies are verified in the results of the real buildings (GECAD building N and I). Since these loads have different response times, which require a larger synchronization process, the results are more unstable when compared to the simulated loads. The synchronization process can be visualized by Fig. 10, which presents the active power synchronization during the transition from one hour to the following, in two different Buses: (a) Bus 1 – power transformer; and (b) Bus 5 – GECAD buildings.

(a)



(b)

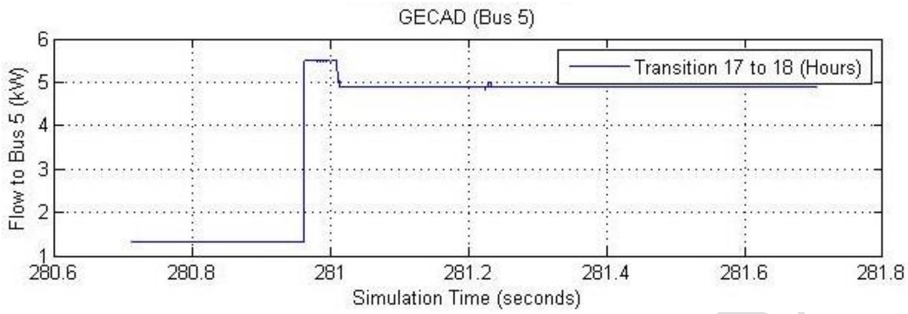


Fig. 10. Active power synchronization during hour transition in: (a) Bus 1 – connection with the external MV network; and (b) Bus 5 – GECAD buildings.

From Fig. 10 a) one can see that the synchronization in Bus 1 takes approximately 306 ms, This time corresponds to the time that the MASGriP software agent takes to send to the variable values from the ERM to the OPAL-RT simulation. The total number of variables that are sent in each hour transition is of 116. In Fig. 10 b) it is visible that the synchronization regarding Bus 5 is much smoother, since the number of variables referring to a single Bus is much smaller.

Considering the results of the day-ahead planning, the SG needs to purchase some amount of power in the day-ahead EM in order to fulfil the consumption needs of the SG, namely from hour 1 to hour 7. Fig. 11 presents the market results achieved from MASCEM, concerning the participation of the SG operator in the EM to buy the required power during the first hours of the considered simulation day.

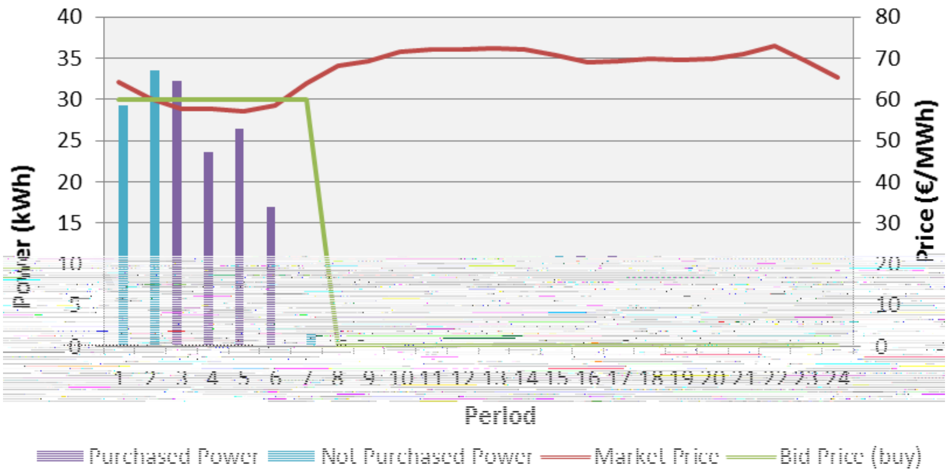


Fig. 11. EM results of the SG operator agent when participating in the day-ahead market in MASCEM, with the objective of buying the demanded power.

Fig. 11 shows that the participation of the SG operator was able to purchase the required amount of power from the market in hours 3 to 6. This occurred due to the bid prices that the SG operator has presented in the EM, which are superior to the EM price during these hourly periods. These higher values reflect the maximum value that the SG operator agent is willing to pay for the purchased power, taking into account the values of the optimization performed in the day-ahead ERM, using the day-ahead EM price forecasts as basis. However, in hours 1, 2 and 7, the SG operator was not able to purchase the required amount of power. This occurs due to bid price from the SG operator, which is inferior to the established market price during these hours. This means that this amount will have to be ensured by another means, either by participating in other types of negotiations (bilateral contracts with nearby SG or neighbour players, or in balancing markets), or by applying further DR programs. How this amount of power will be achieved is determined by the hour-ahead ERM process, which already considers the real values of day-ahead market results, and more up-to-date forecasts of both demand and generation. The hour-ahead ERM runs independently for each hour, one hour before it occurs; thus it is able to include up-to-date, hour-ahead forecasts of demand, consumption and generation. Fig. 12 presents the results of the final, adapted hour-ahead energy resource scheduling plan.

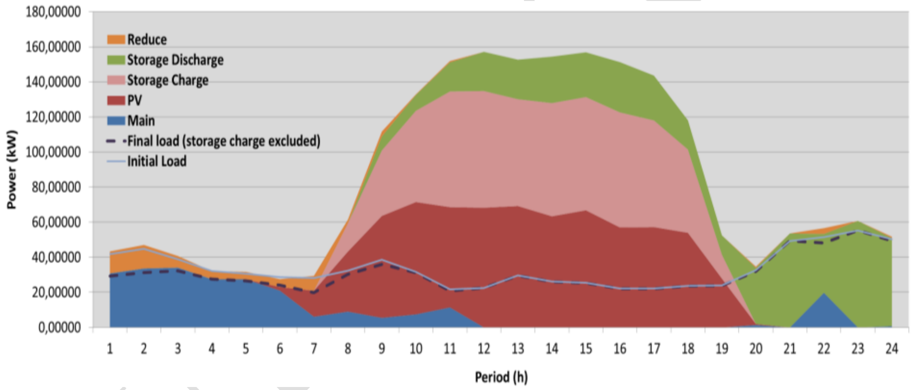


Fig. 12. Scheduling results of the hour-ahead ERM

Fig. 12 shows that, considering the already transacted power from the day-ahead EM, and the updated forecasts, the hour-ahead ERM results include the need for further energy transactions with external entities, in order to deal with the changes of expected consumption and generation throughout the day. For this reason, additionally to the amount of power that were already required to be bought (the amount from hours 1, 2 and 7 that could not be transacted in the day-ahead EM), there is now the identification of a further need in some other hours. These amounts need to be bought from alternative market opportunities, e.g. bilateral contracts with nearby SG, or near real-time balancing markets. Additionally, further DR is also required, in order to face the changes that are expected from the day-ahead planning to a more up-to-date hour-ahead plan. Further loads reduction is verified from hours 1 to 7, and in hour 22. The need for load reduction in hour 22 is verified due because the energy stored in the batteries during the day is not enough to supply all the load in the final hours of the day, as expected in the day-ahead planning.

6 Conclusions and Future Work

The practical implementation of SG is, nowadays, a reality. Several pilot implementations have been experimented and full scale tests and validations are being conducted in order to draw conclusions and refine the used methods, so that the replication and consequent spread of SG implementation can be performed safely. With the worldwide implementation of SG, management and negotiation mechanisms need to be robust in order to take full advantage of the potential of DG and local control of demand.

This chapter has presented the integration between two complementary multi-agent simulators, MASCEM and MASGriP, which together provide the means to create realistic simulation environments, involving the SG and EM. Taking advantage on this integration it is possible to simulate the participation of SG players in electricity markets, in order to reach conclusions on the steps that are necessary to enable the full participation of DG in the markets; and also to validate potential alternatives for a competitive SG market environment.

A case study based on real data has been presented, which includes a SG that is composed by a simulated distribution network that includes several real loads, including two buildings. The presented simulation included the participation of a software agent (the SG operator) in both simulators simultaneously, by managing the internal resources of the SG using day-ahead and hour-ahead ERM methodologies; and by participating in the EM in order to transact the required amounts of power to fulfil the needs of the internal SG resources. Additionally, real-time simulation capabilities provided by the integration of MASGriP with OPAL-RT have provided the means to test and validate the impact of the planned actions in the power network.

The cooperative multi-agent simulation platform presented in this chapter opens important studying opportunities under different perspectives, which result in important advances in the fields of transactive energy, EM, and SG. Among the many contributions that this work provides some can be referred, such as: multi-agent simulation of SG environment; multi-agent simulation of EM; joint simulation of EM and SG by interconnecting MASGriP and MASCEM; participation of SG operator in multi-agent EM simulation; adaptation of SG operator's ERM based on the results achieved in the EM.

As future work, the participation of SG players in alternative EM, e.g. bilateral contracts and balancing markets, can bring major added value. Additionally, the simultaneous management of several SG and the participation of different SG operators in the same EM environment are also relevant. Regarding the used methodologies, the integration of further near real-time ERM methods are important, in order to provide a closer adaptation to the reality. As seen from the simulation results, changes from the day-ahead to the hour-planning were significant; thus, a step further that approximated the scheduling plans towards real time should also bring additional benefits by adapting the plans so that they can be better prepared to deal with unexpected changes.

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