

Optimal demand-side management with a multi-technology battery storage system

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Abstract. Demand-side management (DSM) is considered as a key solution for more energy system flexibility, which is needed for the transition to low-carbon electricity generation based on variable renewable resources. Increased flexibility reduces energy bills for customers and congestions in electricity transport and distribution networks, which reduces costs for network operators, as demand is matched with available renewable generation. Recently, smart-meter deployment, real-time pricing and cost reductions for electricity storage opened new opportunities for dynamic DSM optimization tools.

This paper describes software and hardware tools and a low-cost energy storage system (ESS) to elaborate demand management programs, which reduce the energy bill of industrial customers. These tools operate at two levels: remotely, to calculate the economically optimal consumption and ESS operation program and locally to adapt the economic program to the real-time user state. The described tools have been developed within a national Spanish research project called EV-OPTIMANAGER, which was co-funded by the Spanish Government through the “Retos-colaboración 2015” research program.

Key words

Demand Side Management (DSM), Optimization, Energy Storage System (ESS), Forecasting, Power electronics.

1 Introduction

Demand-side management is one of the most promising tools in the next-generation electric energy environment [1] and can be defined as “changes in electric usage by end-use

customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized” [2].

Many legislations have been developed across the world to promote DSM. One recent example is the “European winter package” [3] that enables the application of demand management policies to ease electric system operation and a way for customers to participate in the market. While in the past, DSM was seen as a means for flattening demand profiles and thus, improving usage of electricity assets, nowadays its main benefit lies in the provision of flexibility to the system, which enables high penetration levels of renewable energy [4].

An important obstacle for the implementation of DSM schemes is the reluctance of customers to adapt habits to external signals such as real-time energy prices. This problem is solved if automatic systems are combined with a local energy storage system (ESS) which can modulate demand patterns without any inconvenience for the customer [5]. In fact, ancillary service markets have been one of the primary sources of revenue for many energy storage projects built to date [6].

Despite the enormous potential, the level of DSM implementation varies greatly between different countries [7], which is mainly due to national legislation. For example, in Spain no active demand management is

permitted. Only a simple, rather static tool called “interrumpibilidad” service is in place, which is only provided by large consumers, where the customer gives the grid operator the permission to interrupt supply during pre-defined peak demand periods.

In view of its benefits and perspective of improved DSM policies – also in Spain – the EV-OPTIMANAGER Project has been working for the last 2 years on the development of a DSM system which consists of a software package combined with hardware tools and a low-cost energy storage system. This solution is designed to carry out demand management to reduce the electricity bill of industrial customers. Section 2 of this paper describes the global management system structure and in section 3 forecasting and optimization algorithms are described. Characteristics and benefits of the ESS are presented in section 4 and section 5 contains the main conclusions of this paper.

2 DSM system structure

As can be seen in Fig. 1 the management structure operates at two levels. At the first level, economical optimization and the interaction with the user take place on a remote system. At the second level, a local system, adapts optimization set-points to real-time operation conditions of the consumer.

A. Remote system

The remote system is a platform that provides monitoring and energy management services from the cloud. The heart of its architecture is a database, where information from each local system is stored together with periodic energy price data from the Spanish TSO (REE) and the market operator (OMIE). Price data is obtained automatically via web service from REE’s web platform e-sios. All this information (“Remote System Inputs” in Fig. 2) feeds the

forecasting and optimization algorithms, which also reside in the remote system.

The optimization algorithm calculates a demand program for the next 24 hours in 15-minutes steps, which minimizes the energy bill for the client. This demand program consists of an operating regime for each storage system, which in the end creates the optimized load curve for the next 24 h. In the case of the project demonstrator, 2 storage systems were connected to the system. It is worth noticing that the optimizer considers a time-horizon of 72 h in order to capture opportunities with larger time-scales. However, only a program for the next 24 h is sent to the local system, which is updated every 15 minutes.

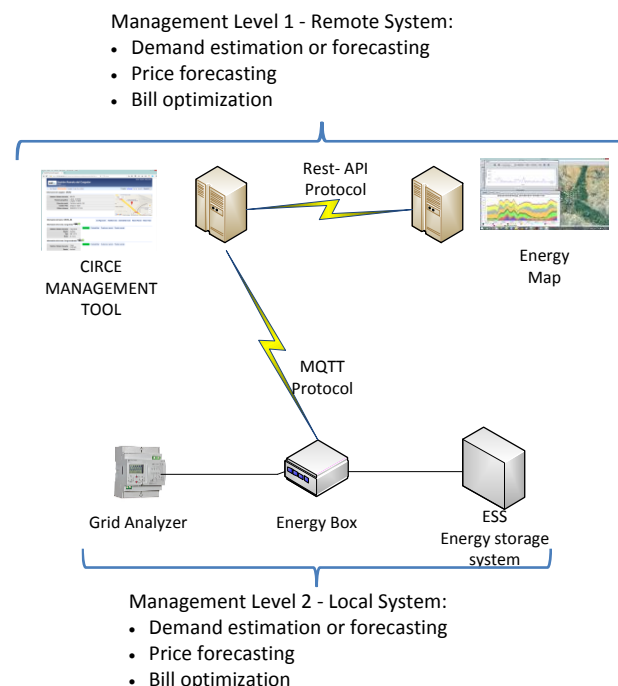


Fig. 1 Global view of the proposed DSM system.

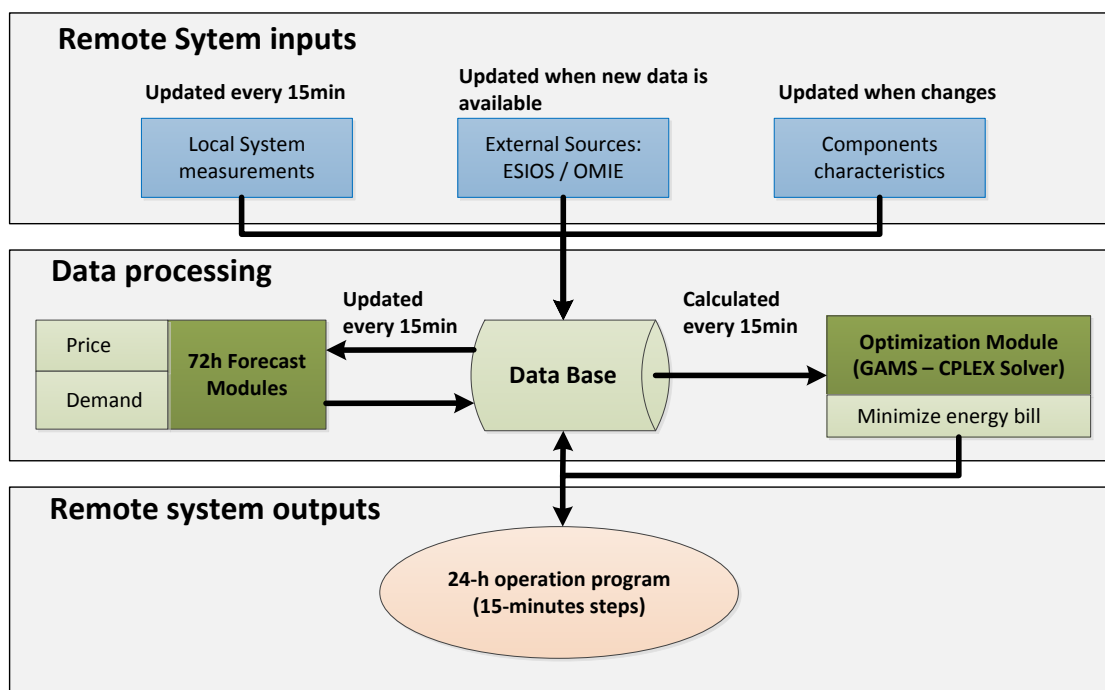


Fig. 2. General structure of the remote system running the forecasting and optimization algorithms.

Required system variables can be grouped into static data, related to configurations and characteristics of the equipment of the system (those typically do not change), and predictive data, coming from forecasting algorithms (those change continuously, based on latest information).

The remote system provides also the interface with the customer or Human-Machine Interface (HMI). It gives the customer information about its electric energy consumption in terms of energy and costs.

The remote system is also the interface for the customer to introduce information about its facilities (configuration of static variables for the optimization process).

Local system

The local system has three hardware components: storage system (described in section 4), CIRCE's Energy Box and sensors.

The Energy Box is a solution for micro-grid management developed by CIRCE. It is a multi-purpose concentrator for the operation in various scenarios of advanced electrical networks and Smart Grids. In addition to its versatile communication capabilities, it contains an embedded computer that provides computing and processing capacity to implement distributed computing: capture and storage information, execution of algorithms and control of the installation among others.

The modular architecture of the Energy Box (Fig. 3) has been completely designed by CIRCE with different physical communication interfaces: Ethernet, serial connectors, ZigBee and Wi-Fi. The central processor (Computer Module) is based on Raspberry Pi technology for industrial environments, which guarantees continued interoperability, support and supply. The software is also an integral creation of CIRCE. Its architecture is divided into two blocks: communication and management. The communication block integrates the different protocols. For the EV-OPTIMANAGER pilot, field devices serial channels with Modbus for network analysers. This is complemented by remote communication capabilities with core systems based on MQTT, a protocol used for machine-to-machine (M2M) connections in the Internet of Things (IoT) paradigm.

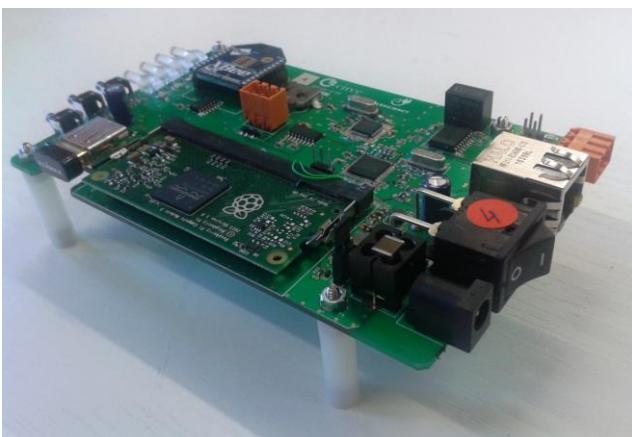


Fig. 3. View of the PCB of the Energy Box, the local control device.

The management block is responsible for gathering all system information for further processing, in addition to performing real-time management of the system. For this management, local algorithms are implemented which convert 15-min setpoints from the optimized program to real-time set-points for each controlled device in a time step of 5 seconds. The programming language used is ADA, specific for critical systems with very strict temporal requirements.

As third component of the local system (sensors) a commercial grid analyser is installed at the consumer facilities to monitor the real-time demand of the customer, allowing the adaptation of the optimal set-points by the Energy Box and feeding the demand forecast algorithm.

3 Forecasting and optimization algorithms

The optimal 24-h operation program in 15-minutes steps is calculated based on 72-h hour demand forecasts, the electricity price forecast and other characteristics of the customer such as state of charge of storage systems or the grid access contract.

A. "Energy map" and forecasting algorithms

Every customer has access to a web platform called "energy map", developed by URBENER, used to interact with the remote system. According to a previous analysis of the customer facilities, the "energy map" estimates the demand for the next hours based on typical demand profiles which are originated by foreseeable production pattern, for example.

If the customer is not able to estimate its consumption profile to create the energy map, the remote system forecasts the demand using stochastic techniques (based on variations of ARIMA). The remote system also forecasts the electricity price for the optimization horizon using stochastic techniques from data gathered from the OMIE and e-sios web pages (data services from the grid operator and the market operator).

Other information, before described as static data, needed for the optimization is introduced by the customer or by the system installer/operator using the "energy map" interface.

B. Optimization algorithm

The objective of the optimization algorithm is to provide consumption and ESS operation plan for the next 72 hours, which minimizes the customer bill. The objective function can thus be formulated as follows:

$$f = C_{Pgrid} + C_{Egrid} - I_{Egrid} + C_{SS} + C_{PSS}$$

Where:

- C_{Pgrid} , cost of grid access tolls (power price)
- C_{Egrid} , cost of the energy purchased from the grid
- I_{Egrid} , income from selling energy to the grid
- C_{SS} , cost of using the battery

- C_{PSS} , penalization for high battery power

The introduction of a power price (C_{Pgrid}) and battery power penalization (C_{PSS}) reduces the maximum power consumed from the grid carrying out a kind of peak shaving without the need of defining a specific maximum power limit. The penalization for high battery power reduces the charging and discharging power of the batteries, prolonging the life of the batteries.

The main constraints are

- Power balance
- Storage system modelling

The resulting QCP optimization problem (Quadratic Constraint Programming) is programmed in GAMS language and solved within the remote system using the CPLEX solver. The high-level modelling system GAMS has been chosen for its user-friendly interface which facilitates the implementation of the kind of optimization problem which was required here. Also scalability to larger problems is given [8]. The well-known solver CPLEX developed by IBM [9] is able to solve the required QCP problem and was selected for reliability reasons. During the project, it has been verified that the pair GAMS – CPLEX is reliable and efficient solving the kind of optimizing problem shown in this paper.

C. Local adaptation algorithm

As the optimized demand program is calculated according to forecasts, there will always be deviations: forecast errors. To deal with these forecast errors, the local system adapts the operation set-points provided by the remote system according to the actual consumption of the customer at any time. Every 5 seconds the local system recalculates and adapts the operation set-points for the storage system. This adaptation is made following a simple decision tree combined with a closed-loop control algorithm, tracking the state of charge of the storage system.

4 Storage system

To implement and test the optimized operation programs in a real environment an electric energy storage system (ESS) has been developed. The innovation of this storage system consists in a novel power electronics topology and its capability to use different types of batteries in the same facility.

A. Power electronics

The battery charger regulator is connected to the grid by a bi-directional 50-kW AC/DC three level converter which is composed by silicon semiconductors (“Grid side” in Fig. 4; Error! No se encuentra el origen de la referencia.) and feeds a 700-V DC bus. Batteries are connected to this DC bus through five isolated bi-directional 10-kW DC/DC

converters, using silicon carbide (SiC) semiconductors (“Battery side”, see Fig. 4 and Fig. 5). The chosen battery-side topology has important benefits over other topologies [10][11]: use of smaller and lighter insulation transformers reducing the size of the converters and improving its efficiency and the SiC technology allows a higher commutation frequency reducing noise and losses.

The converter design has been optimized to connect different types of battery packs at 48 V. However, slight hardware and control modifications of the DC/DC converters would allow the integration of batteries with higher voltages and even solar PV systems.

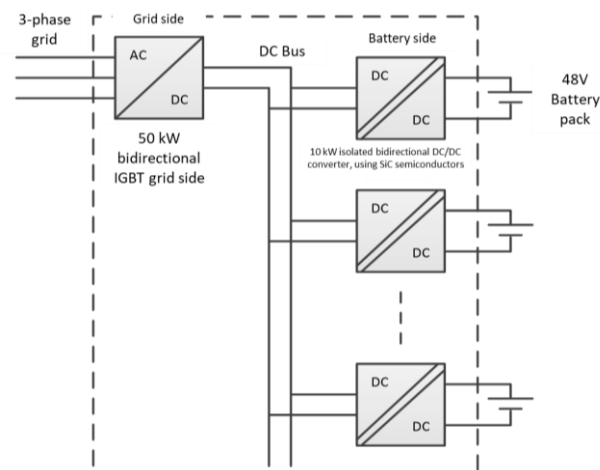


Fig. 4. Block diagram of the battery regulator.

The battery charger is highly modular, being each converter encapsulated in rack cabinets, facilitating maintenance and expansion of the system with more battery packs and generation technologies.

B. Batteries

The power electronics topology used in this design, and described in the previous section, allows the use of batteries grouped in packs of different technologies, State of Health (SoH) or capacity. In laboratory, Li-ion and Lead-acid batteries have been tested successfully. These packs can provide up to 10 kW power and nominal battery voltage is fixed at 48 V.

In the case of using lead-acid batteries, the charger incorporates a standardized equalizing process to enlarge the life of the batteries and recover part of its initial capacity.

The main benefit of using this topology, which permits the combination of different battery packs, is reducing cost and environmental impact of the system. Cost reduction is obtained from the option of using second-life batteries. Life extension of batteries, re-using and recuperating its SoH through the equalizing process, reduces the environmental life-cycle impact of the system.

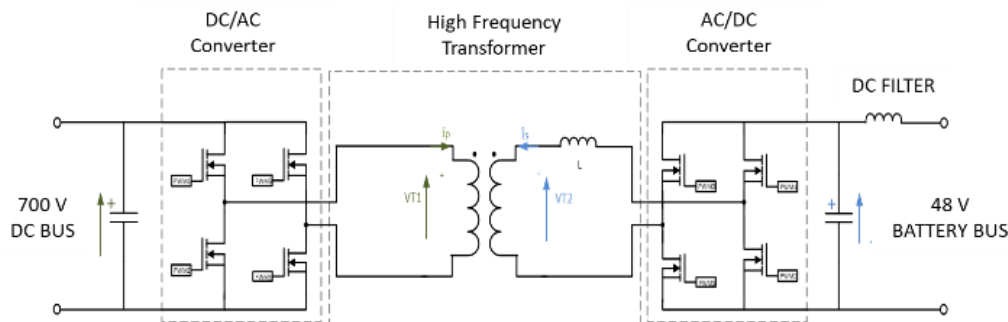


Fig. 5. Battery side converter topology.

5 Conclusion

This paper presents pilot project of an integrated demand-side management (DSM) system, which aims to reduce electricity bills for industrial customers. The DSM system includes control and hardware solutions with specific focus on integration of multiple battery technologies, facilitating second-life use of vehicle batteries in stationary applications. System control includes a management structure and a group of forecasting and optimization algorithms for the operation of the energy storage system (ESS). The management structure has two control levels: remote and local. The remote system is allocated in the cloud and carries out the economical optimization of the energy consumer calculating an optimal operation schedule for the next 24 hours based on forecasts and estimations. The local system adapts the 15-min step schedule to the real-time consumption of the customer. This management system is able to reduce the electricity bill and if combined with a PV system, it also maximises self-consumption.

The back-bone of this management system is the energy storage system. It has been designed to use different types and technologies of batteries and with different SoH, including regenerated batteries, which reduces system costs and the environmental impact of the batteries.

The project is still ongoing. Thus, final quantification of savings at the demonstration site will be available at the end of the test operation phase.

Acknowledgement

This paper shows the results of a thorough research and work carried out in the EV-OPTIMANAGER Project. This project is supported by the "Retos-colaboración 2015" research program.



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