Control structure for optimal demand-side management with a multi-technology battery storage system

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Abstract— **Demand-side management (DSM) is proposed as a key solution to increase electric system flexibility, essential for large-scale deployment of renewable energy generation. System flexibility is required to avoid congestions in electric systems and reduce costs for network operators and consumers. IoT deployment, real-time pricing and cost reductions for electric energy storage opens new opportunities for DSM tools, which help matching demand with variable renewable generation. This paper describes the control structure developed, implemented and tested in real demonstrators to deploy demand management programs to reduce energy bills of industrial customers. This structure operates at two stages: remotely, to calculate economically optimal consumption and ESS operation set points and locally to adapt the forecast-based economic program to real-time conditions. The described DSM structure has been developed within a national Spanish research project called EV-OPTIMANAGER.**

Keywords—Control structure, Demand Side Management (DSM), Battery Energy Storage System (BESS), Optimization, Forecasting, IoT (Internet of Things)

I. INTRODUCTION

Demand-side management (DSM) is recognised as a key solution within the changing electricity system with large amounts of variable and distributed generation [1]. The main function is to modulate demand pattern in order to match variable generation and thus, increasing system reliability [2].

In the past, DSM was focussed on moving demand towards night hours with low system demand, as large, conventional power stations required as constant generation as possible. Nowadays, with increasing variable and distributed generation, the main benefit from DSM is to provide system flexibility [3]. An example of recent legislation promoting this new paradigm is the “European winter package” [4], which encourages demand management policies with system support features and opens opportunities for market participation of end users. This European initiative aims at reducing the large disparity of DSM implementation, which is widely influences by national legislation [5].

While large industries have been implementing DSM for many years, domestic customers are reluctant as modifications of demand pattern require adaptation of habits. To overcome this important obstacle, automatic systems, combined with local energy storage systems (ESS) are being proposed which are able to modify demand patterns without any inconvenience for the customer [6, 7]. Existing large ESS projects are obtaining revenues mainly from participation in ancillary service markets [8], which indicates that aggregated domestic systems with distributed storage can also provide additional value to home owners. For this smart-grid approach, IT infrastructure and communications are crucial elements [9, 10].

Considering benefits and future perspectives for increased need of DSM to cope with high penetration levels of renewables energies, a DSM system has been developed over the past 3 years within the EV-OPTIMANAGER Project, combining a software package with hardware tools and a low-cost ESS.

DSM is a topic deeply researched in recent years. For example, [11] proposed a similar management structure using commercial smart meters. The main difference with the solution proposed in this paper consists in the Energy Box, a specific IoT hardware solution which provides local real-time management and monitoring of distributed resources (e.g. grid analysers, solar PV inverters, EV charging points). [6], [7], [12] and [13] propose an optimization system, similar to the proposed in this paper, but remaining at simulation and laboratory stage. In the presented EV-OPTIMANAGER Project, the developed tools have been tested under real-world conditions at customer premises. The proposed system provides real-time control and day-ahead planning in one two-level operation schema, which is a considerable advancement over the systems mentioned above.

This document describes the developed control structure, first test results and possible improvements or new functionalities of the system. Section 2 of this paper describes the global management system structure and in section 3 local devices are described. Main characteristics of the remote system are presented in section 4 and section 5 contains the results of the first tests carried out to the control structure and the main conclusions reached to date.

II. DSM CONTROL STRUCTURE

The proposed DSM control structure includes hardware and software tools, which address different tasks, such as monitoring, optimization and control of appliances (see Fig. 1). These tools can be classified in two groups:

- **Local devices:** Energy Box (EB), battery energy storage system (BESS) and grid analysers (GA)
- **Remote system:** customer and aggregator web servers

Local devices have two main roles: (1) monitoring of customer demand and local BESS to provide field measurements to the remote systems and (2) apply optimised operation set points to the battery power converter. The EB exchanges data with the remote system (Customer Web Server), providing the monitoring data and receiving operation setpoints. In addition, it adapts 15-min set point to real-time operational set points for the BESS.

The main objective of the Customer Web Server is to calculate set points for field devices (minimizing energy bills, using demand and price forecasts) and share results with local devices and the Aggregator Web Server.

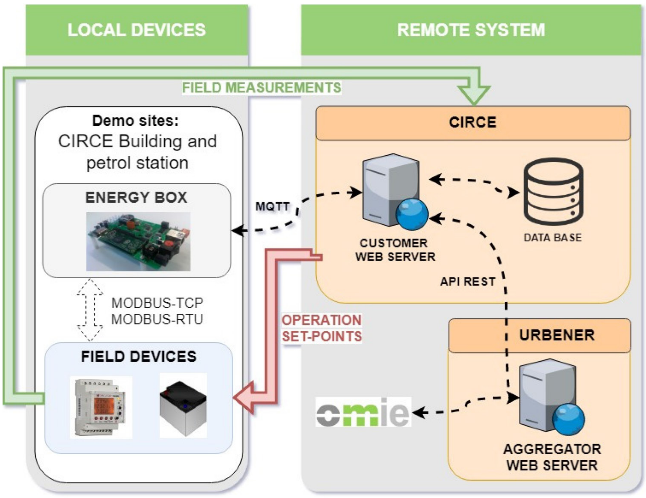

Fig. 1. Overview of proposed DSM control estructure.

The Aggregator Web Server is the main tool of the aggregator, who represents customers in the electric market and in front of other actors of the electric system [4]. The aggregator, with the information provided by the Customer Web Server, communicates with OMIE (Spanish electric market operator) [14] to purchase the energy needed by the consumers, with the aim of obtaining lowest prices for his clients.

III. LOCAL SYSTEM

The proposed control structure is being tested in two demo sites in Zaragoza, Spain:

- **CIRCE Building**. An office building for 100 people with typical office demand and two R&D laboratories.
- **Zoilo Ríos petrol station**, equipped with petrol pumps, washing tunnels, restaurant, lighting, shop and electric vehicle charging points.

The demo sites are equipped local devices (EB, BESS, grid analyser) and share one remote system (Customer Web Server and Aggregator Web Server).

A. CIRCE IoT hardware solution, the Energy Box

The Energy Box 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 processing capacity to implement distributed computing: capture and storage of information, execution of algorithms and control devices among others.

The modular architecture of the Energy Box (Fig. 3) has been completely designed by CIRCE with several 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 (network analysers and BESS) are connected via serial channels with Modbus. The Customer Web Server is connected by remote communication based on MQTT, a protocol widely used for machine-to-machine (M2M) communication in the Internet of Things (IoT) paradigm.

The management block is responsible for gathering all system information for further processing, in addition to performing a 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. Algorithms are implemented in ADA programming language, specific for critical systems with very strict temporal requirements for real-time control.

In the EV-OPTIMANAGER Project, the EB was employed to manage a BESS and system analysers, but it is prepared to monitor and control any device with standard communication capabilities, such as EV charging points and renewable power converters. In this simple case, a decision matrix was implemented (see Table I), in order to establish new set points for battery power P_b' depending on planned battery power P_b and deviation of actual demand $D^{'}$ from expected demand D_0.

Additional variables taken into account in order to establish restrictions, which are: planned and actual grid power (P_{grid} and P'_{grid}) and power limits for battery and grid respectively (P_{bmax} and P_{max}).

TABLE I. DECISION MATRIX OF LOCAL BATTERY CONTROL AT THE EB.

Def. grid power: $\boldsymbol{P'_{grid} = P'_b + D'}$	$\boldsymbol{P_b > 0}$ (charging)	$\boldsymbol{P_b < 0}$ (discharing)	$\boldsymbol{P_b = 0}$ (stand by)
$\boldsymbol{D' > D_0}$	$P'_b = P_b$ $P'_{grid} \leq P_{max}$	$P'_b = P_{grid} - D'$ $P'_b \leq P_{bmax}$	$P'_b = P_{max} - D'$ $P'_b \leq 0$ (only discharge)
$\boldsymbol{D' < D_0}$	$P'_b = P_{grid} - D'$ $P'_b \leq P_{bmax}$	$P'_b = -D'$ $P'_{grid} \geq 0$	No action

In order to avoid oscillations due to fast changes in real-time demand, the control system follows new set point with an integrative delay.

B. Battery energy storage system, BESS

The battery charger is connected to the grid by a bi-directional 50-kW three-level AC/DC converter that is composed by silicon semiconductors (“Grid side” in Fig. 2) and feeds a 700-V DC bus. Batteries are connected to the DC bus through five isolated bi-directional 10-kW DC/DC converters, using silicon carbide (SiC) semiconductors (“Battery side” in Fig. 2). The chosen battery-side topology with SiC technology has important benefits over other topologies [15], mainly due to higher commutation frequency:

- Reduced converter size (smaller and lighter insulation transformers and filters)
- Reduced switching losses

The AC/DC converter, used to exchange power with the electric grid, is designed with a three-level neutral point clamped (NPC) topology. This AC/DC converter can operate in the four quadrants, compensating reactive power if needed, even without batteries.

A Dual Active Bridge (DAB) converter is used to transfer the power between DC bus and battery. At the high-voltage side, SiC MOSFETs have been employed due to the better behaviour at this voltage in comparison with Si MOSFETs, which have been employed at the low-voltage side. The transformer guarantees galvanic isolation between battery and grid side. The elevated switching frequency of 70 kHz reduces considerably the size of the transformer and therefore the size of the entire converter. To reduce battery current ripple , an LC filter is placed between the low-voltage side of the DAB converter and the battery.

The converter design allows the connection of different types of battery packs at 48 V, which is a standard voltage used in the market. Small modifications in hardware and control of DC/DC converters would allow the integration of batteries at higher voltages and even solar PV systems or V2H chargers.

The power electronics topology used in this design 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 at 48 V.

The proposed multi-technology configuration allows the operation of each battery according to its requirements (e.g. power limits, state of charge) which provides cost reductions by facilitating use of second-life batteries. Life extension of batteries, re-using and recovering its SoH through the equalizing process, reduces the environmental life-cycle impact of the system [16].

Fig. 2 shows the three different communication protocols used in the BESS. The EB manages power flows through the batteries and electric grid communicating with AC/DC and DC/DC converters using RS-485 protocol. Ethernet communication capability of the EB provides remote access to the BESS for settings and monitoring by the user.

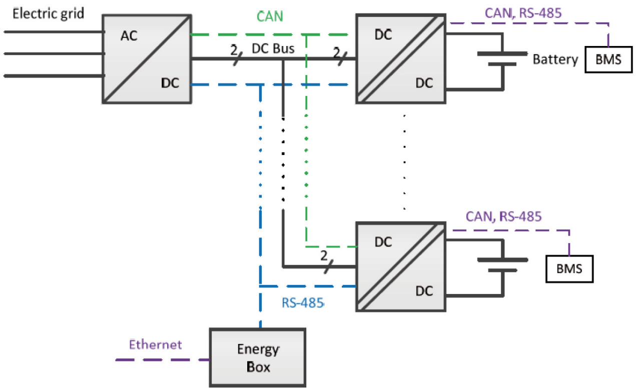

Fig. 2. BESS communication protocols including the EB.

C. Grid analyser

A commercial grid analyser (CVM NET from CIRCUTOR) is installed at every demo site as real-time sensor for consumption data. Data is gathered by the Energy Box for local adaptation of operation set-points, and it is sent to the remote system for further processing.

IV. REMOTE SYSTEM

As mentioned before, the remote system has two main functions: calculate the optimal use of the BESS to reduce energy bills of customers, carried out by the customer server, and communicate with OMIE to purchase energy, task performed by the aggregator server.

A. Customer Web Server

The customer server develops six main tasks:

- Store real-time measurements received from local devices (grid analysers and BESS) provided by the Energy Box
- Calculate and store 15-min average values
- Interact with OMIE to get energy prices
- Forecast customer demand and electric energy prices
- Calculate optimized 24-h operation program (15-min steps) from 72-hour forecasts (see Fig. 3)
- Send 24-h operation program to the EB

Main features of the customer web server:

- OS: Windows 7 Enterprise

- Machine features: Intel (R) Xeon(R) CPU E5-2650 v3 @ 2.30GHz (2 processors), 12 GB RAM
- App Container: Apache Tomcat 8.5
- Forecast and other calculations algorithms: Matlab executables
- Optimization algorithms: GAMS 24.8 running CPLEX solver
- App Remote Centre: Java 1.8

The Customer Web Server executes periodically the following steps:

1. Measurements from grid analysers and BESS are gathered by the EB sent to the customer web server (via MQTT protocol) where they are saved in a Data Base.
2. Every 15 min, averages are calculated from field measurements.
3. Every 15 min, optimized plan using historical 15-min averages is calculated. The sub-steps are:
    - 3.1. Gather information for optimization algorithms.
    - 3.2. Execute Matlab algorithm (forecasts).
    - 3.3. Execute GAMS algorithm (optimal set points).
    - 3.4. Save forecast and optimization results in the data base creating historical logs of all results.
    - 3.5. Create a JSON structure from last optimization result and send it to local Energy Boxes.

There is a specific function on the remote system in which the system sends the last plan calculated on request. This function is used when the EB is rebooted. In this case, the EB sends a request and the remote system responds with the last calculated plan.

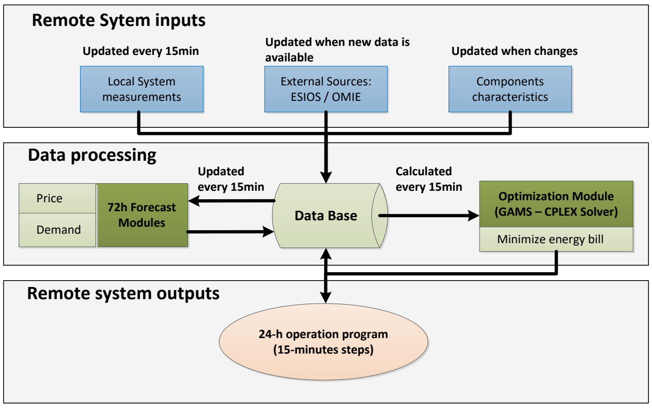

Fig. 3. General structure of the Customer Web Server running forecasting and optimization algorithms [17].

The optimization algorithms provide operation set points for the BESS. Its output is an optimized operation plan for the next 72 h in 15-min steps that minimizes the energy bill of the customer. The objective function is formulated as follows:

$$f = CV_{CS} + CV_{SS} + I + C_{PeajPss} + C_{Pss} \qquad (1)$$

Where CV_{cs} is the cost of energy purchased from the electric grid (at market price), CV_{ss} is the cost of using the battery (related to the ageing derived from charging and discharging), I is the income from selling energy to the grid (zero in the simulations), $C_{PeajPss}$ is the cost of grid access tolls (power price) and C_{Pss} is a penalization for high battery power (to improve battery life reducing charging and discharging power peaks). The introduction of a power price ($C_{PeajPss}$) in the objective function provides a means for reducing demand peaks, obtaining a peak-shaving feature without the need of defining a fixed maximum power limit.

Customer demand and electric energy price forecasts are calculated using statistical methods based on historical data, which outperforms more sophisticated models for short-term predictions (several hours) [18]. Furthermore, some static parameters, such as storage characteristics, grid connection power, nominal device power, are introduced in the database and used in the optimization.

The main constrains are power balance and BESS modelling. The proposed optimization is a Quadratic Constrained Problem and it is calculated using CPLEX solver in GAMS software [19].

The proposed solution could be used to control other resources, besides BESS, with minor changes in the optimization algorithms:

- Adding specific constrains, solar PV generators and EV (V2G and G2V) charging points could be managed.
- The addition of different control loops enable the calculation of flexibility offers to support grid operation (DSO or TSO) [20].
- The inclusion of integer variables allows the control of manageable demands in consumption facilities.

B. Aggregator Web Server

The Aggregator Web Server develops three main tasks:

- Receive and store 72 h consumption forecast data
- Aggregate consumptions into an OMIE's energy purchase programming unit
- Interoperate with OMIE's services to submit purchase orders

The aggregator web server main features are:

- OS: GNU/Linux Ubuntu 16.04.2 LTS Servers.
- Cloud infrastructure [AWS] features:
    - Elastic Load Balancer.
    - EC2 t2.small and t2.medium instances.
- App Container: RedHat JBoss WildFly.

The aggregator web server provides backend and frontend tools to fulfil the workflow of creating, maintaining and operating an OMIE energy purchase programming unit.

Frontend tools facilitate the operation of the energy purchase programming unit making use of Java Web Start to provide multiplatform OS independent support and client local install requirements.

Backend tools are responsible for aggregating and placing purchase orders in OMIE Web Service infrastructure, SIOM2. The architecture of these web services is SOAP based and backend tools include certificate manager for authentication and orders signing.

The Aggregator Web Server must also ensure that an hourly based energy purchase order is placed for every hour of the daily market. This is achieved by a tool which provides a default hourly base consumption, adjusted with forecasts sent by the Costumer Web Server.

V. FIRST TEST RESULTS AND CONCLUSIONS

A simple, robust and secure Control structure to deploy demand-side management (DSM) systems aiming to reduce electricity bills for industrial customers has been described. 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. The local system adapts the 15-min step schedule to the real-time consumption of the customer.

First tests, carried out in late 2018 and early 2019, demonstrated that the solution developed is secure and robust. Although the optimization process is launched every 15 minutes, the EB sends measurements of the grid analysers and the BESS every 10 seconds. In late 2018 and early 2019 long duration communications tests were carried out and more than 95% of the 10-second measures arrived and were stored in the database correctly. Considering that during the test period maintenance and other tasks caused communication failures, the communication success rate is very high. As a conclusion, the Energy Box as communication gateway in the microgrid and the developed remote system are a very robust solution. A four-day evaluation test confirmed that all information gathered by the EB was stored correctly in the data base. Thus, it can be concluded that the communication between EB and remote system works correctly.

The entire operation process (gathering data from the data base, 15-min averaging, data forecasting, optimization calculus and sending results to the EB) takes up to 18 seconds per customer. For a larger deployment, this process needs to be parallelized, which is expected to be achieved with a standard big-data deployment.

As seen in the first tests, the proposed solution is robust and stable, monitoring correctly the local demands and storage systems operation and calculating optimal set points for them.

It also has to be highlighted that with minor adaptations to the optimization algorithms the proposed solution is capable of controlling other resources (e.g. PV generators, EV charging points, manageable loads) or capabilities such as flexibility offers.

ACKNOWLEDGMENT

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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