Energy Management Systems for Microgrids Equipped with Renewable Energy Sources and Battery Units

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ENERGY MANAGEMENT SYSTEMS FOR MICROGRIDS EQUIPPED WITH RENEWABLE ENERGY SOURCES AND BATTERY UNITS

BY

ADRIANA CAROLINA LUNA HERNÁNDEZ

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ENERGY MANAGEMENT SYSTEMS FOR MICROGRIDS EQUIPPED WITH RENEWABLE ENERGY SOURCES AND BATTERY UNITS

Ph.D. Dissertation

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Curriculum Vitae

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Received the B.S degree in Electronic Engineering from the Universidad Nacional de Colombia 2006 and the M.S. degree in Industrial Automation from the Universidad Nacional de Colombia in 2011, Bogotá, Colombia. She is currently pursuing toward the Ph.D. degree in the Department of Energy Technology at Aalborg University, as part of the Microgrids Research Programme (www.microgrids.et.aau.dk).

Her current research interests include energy management systems of microgrids, and specifically in architectures and algorithms for scheduling and optimization for operation level in microgrids.

Abstract

The electric power system has been transformed and evolved towards decentralized systems, which interact with each other and within the whole electrical system. In this way, microgrids are essential components to increase the reliability and efficiency of the power system. They are low-scaled electrical distribution networks that integrate distributed energy resources, loads, power converters and grid components in a stable way, working either in grid-connected or islanded modes.

In order to operate microgrids, hierarchical schemes have been developed. The lower levels regulate voltage/current and coordinate power sharing, while the higher levels deal with power managements in order to ensure feasibility and optimality. On top of that, an energy management level is required to define commands and conditions so that the microgrid operates in an economically optimal way. Some of the issues that involve the implementation of energy management systems in microgrids are the need of incorporating flexibility related to the architecture and algorithms, also, it is important to consider the active participation of consumers and the inherently variable nature of the renewable generation. The inclusion of energy storage systems in microgrids provides the energy management with additional degrees of freedom, and therefore, makes the microgrid more flexible to the changeable situations.

This project is focused on implementing adaptable energy management systems for microgrids in order to coordinate generation, demand, and storage, as well as compensate the effects of the variability of renewable energy generators and load fluctuations, in view of the user necessities. The considered hybrid energy systems comprise of renewable sources (solar photovoltaic and wind turbine), conventional systems (utility grid connection), battery-based energy storage systems and loads. In this work, a modular structure of energy management system is introduced in order to conduct the function of optimizing the energy dispatch of distributed resources. One of the modules includes the optimization problem formulation, which has been modeled as mixed-integer linear programming in order to ensure optimality when the problem is feasible.

Moreover, the design and implementation of energy management systems are conducted, evaluating firstly deterministic cases by using 24 h-ahead data in order to optimize the use of the distributed energy resources. This thesis considers grid-connected microgrids working under demand response programs in two cases, when injecting energy to the grid is profitable and promoting self-consumption. This type of approach can be applied to low-scale microgrid such as household application by optimizing the energy resources of each household, enabling cooperative trading of power between household prosumers, or defining schemes for sharing the use of a common resource.

Finally, an online structure is defined to deal with the variability that cannot be considered one day ahead. Additionally, an evaluation framework is proposed to compare the performance of an energy management system not just against a previous approach, but also against absolute boundaries.

keywords:
Energy Management System, Distributed Storage and Generation, Decision-Making, Microgrids.

Resumé

Den elektriske strøm er blevet transformeret og udviklet sig i retning decentraliserede systemer, som interagerer med hinanden og inden for hele elektriske system. På denne måde, Microgrids er væsentlige elementer for at øge pålideligheden og effektiviteten af elsystemet. De er lavt skaleret elektrisk distributionsnet, der integrerer distribuerede energiressourcer, belastninger, power omformere og netkomponenter på en stabil måde, der arbejder i nettilsluttede eller islanded tilstande.

For at kunne fungere Microgrids har hierarkiske ordninger blevet udviklet. De lavere niveauer regulerer spænding / strøm og koordinere magtdeling, mens de højere niveauer håndtere magt ledelserne for at sikre gennemførlighed og optimalitet. Oven i det, er en energi management niveau, der kræves for at definere kommandoer og betingelser, så elsystemet fungerer på en økonomisk optimal måde. Nogle af de spørgsmål, der involverer implementeringen af energi management systemer i Microgrids er behovet for at indarbejde fleksibilitet i forbindelse med arkitektur og algoritmer, også, er det vigtigt at overveje den aktive deltagelse af forbrugerne og iboende variabel karakter af vedvarende generation. Inkluderingen af energilagringssystemer i Microgrids giver energiledelse med yderligere frihedsgrader, og derfor gør elsystemet mere fleksibelt til de omskiftelige situationer.

Dette projekt er fokuseret på at gennemføre fleksible energistyringssystemer til Microgrids for at koordinere generation, efterspørgsel, og opbevaring, samt kompensere virkningerne af variabiliteten af vedvarende energi generatorer og udsving belastning på grund af brugerens fornødenheder. De betragtes hybride energisystemer består af vedvarende (solcelleanlæg og vindmølle), konventionelle systemer (forsyningsnettet forbindelse), batteribaserede energilagring systemer og belastninger. I dette arbejde, er en modulær opbygning af energistyringssystem indført for at gennemføre den funktion at optimere energi afsendelse af distribuerede ressourcer. Et af modulerne indbefatter optimeringsproblemet formulering, som er blevet modelleret som blandet heltal lineær programmering for at sikre optimalitet når problemet er mulig.

Desuden er udformningen og gennemførelsen af energiledelsessystemer gennemført, evaluere først deterministiske tilfælde ved at bruge 24 timerkommende data for at optimere anvendelsen af de distribuerede energiressourcer. Denne afhandling anser nettilsluttede Microgrids arbejder under efterspørgslen indsatsprogrammer i to tilfælde, når indsprøjtning energi til nettet er rentabel og fremme selvstændig forbrug. Denne type tilgang kan anvendes til lav-skala elsystemet såsom husstand ansøgning ved at optimere energiressourcer i hver husstand, så samarbejdsvillig handel af magten mellem husholdningernes prosumers, eller definere ordninger til at dele brugen af en fælles ressource.

Endelig er en online struktur som behandler den variabilitet, der ikke kan betragtes som en dag forude. Derudover foreslås en evalueringsramme for at sammenligne effektiviteten af et energistyringssystem ikke bare mod en tidligere tilgang, men også mod absolutte grænser.

Nøgleord:
Energy Management System, Distribueret Opbevaring og Generation, beslutningsprocesser, Microgrids.

Thesis Details and Publications

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1^{st} **Authored Journal Papers:**

- Luna, A. C., Díaz, N. L., Graells, M., Vasquez, J. C., & Guerrero, J. M. (2016). Mixed-Integer-Linear-Programming Based Energy Management System for Hybrid PV-wind-battery Microgrids: Modelling, Design and Experimental Verification. IEEE Transactions on Power Electronics. DOI: 10.1109/TPEL.2016.2581021.
- Luna, A. C., Díaz, N. L., Graells, M., Vasquez, J. C., & Guerrero, J. M. Cooperative Energy Management for a Cluster of Households Prosumers. IEEE Transactions on Consumer Electronics, Vol. 62, Nr. 3, 10.2016, s. 235 - 242.
- Luna, A. C.; Meng, L.; Díaz, N. L.; Graells, M., Vasquez, J. C., & Guerrero, J. M. (2017). Online Energy Management Systems for Microgrids: Experimental Validation and Assessment Framework. IEEE Transactions on Power Electronics. Under second revision

Co-authored Journal Publications:

- Meng, L.; Riva, E. R.; Luna, A. C.; Dragicevic, T.; Vasquez, J. C.; & Guerrero, J. M. Microgrid supervisory controllers and energy management systems : A literature review. Renewable & Sustainable Energy Reviews, Vol. 60, 01.07.2016, s. 1263-1273.

- Meng, L.; Luna, A.C.; Rodríguez, E.; Bo, S.; Dragicevic, T.; Savaghebi, M.; Vasquez, J. C.; Guerrero, J. M.; Graells, M.;& Andrade, F. Flexible System Integration and Advanced Hierarchical Control Architectures in the Microgrid Research Laboratory of Aalborg University. IEEE Transactions on Industry Applications, Vol. 52, Nr. 2, 03.2016.

- Riva, E.; M. L. D. Silvestre, G. Zizzo, N. N. Quang, A. C. L. Hernandez, & J. M. Guerrero. Book Chapter in: Communication, Control and Security Challenges for the Smart Grid. IET, 2017, ch. Chapter 7- Optimal Energy Management in Smart Grid.

- Díaz, N. L., Luna, A. C., Vasquez, J. C., & Guerrero, J. M. Centralized Control Architecture for Coordination of Distributed Renewable Generation and Energy Storage in Islanded AC Microgrids. IEEE Transactions on Power Electronics, 2017.

- AlSkaif, T.; Luna, A. C.; Guerrero, M.; Guerrero, Josep M.; & Bellalta, B. Reputation-based Joint Scheduling of Households Appliances and Storage in a Microgrid with a Shared Battery. Energy and Buildings, Vol. 138, 03.2017, s. 228–239.

Selected Publications in Proceedings with Peer Review:

- Luna, A. C.; Díaz, N. L.; Andrade, F.; Graells, M.; Vasquez, J. C.; & Guerrero, J. M. Economic Power Dispatch of Distributed Generators in a Grid-Connected Microgrid. Proceedings of the 2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia). IEEE Press, 2015. s. 1161 - 1168.

- Luna, A. C.; Díaz, N. L.; Meng, L.; Graells, M.; Vasquez, J. C.; & Guerrero, J. M. Generation-Side Power Scheduling in a Grid-Connected DC Microgrid. Proceedings of the 2015 IEEE First International Conference on DC Microgrids (ICDCM). IEEE Press, 2015. s. 327 - 332.

- Luna, A. C.; Díaz, N. L.; Graells, M.; Vasquez, J. C.; & Guerrero, J. M. Online Energy Management System for Distributed Generators in a Grid-Connected Microgrid. Proceedings of the 2015 IEEE Energy Conversion Congress and Exposition (ECCE). IEEE Press, 2015. s. 4616 - 4623

- Díaz, N. L., Luna, A. C., Vasquez, J. C., & Guerrero, J. M. (2015). Energy Management System with Equalization Algorithm for Distributed

Energy Storage Systems in PV-Active Generator Based Low Voltage DC Microgrids. In Proceedings of the 2015 IEEE First International Conference on DC Microgrids (ICDCM). (pp. 293-298). IEEE Press.

- Luna, A. C.; Díaz, N. L.; Graells, M.; Vasquez, J. C.; & Guerrero, J. M. Modular Energy Management System Applicable to Residential Microgrids. 2016 IEEE International Conference on Consumer Electronics (ICCE). IEEE, 2016. s. 542 - 543.
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- de Bosio, F; Luna, A. C.; de Sousa, L. A.; Graells, M.; Saavedra, O.; & Guerrero, J. M. Analysis and Improvement of the Energy Management of an Isolated Microgrid in Lencois Island based on a Linear Optimization Approach. Proceedings of 8th IEEE Energy Conversion Congress and Exposition (ECCE), 2016. IEEE Press, 2016.

This present report combined with the above listed scientific papers has been submitted for assessment in partial fulfilment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. The scientific papers are not included in this version due to copyright issues. Detailed publication information is provided above and the interested reader is referred to the original published papers. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty of Engineering and Science, Aalborg University.

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Adriana Carolina Luna Hernández
Aalborg University, March 23, 2017

Contents

List of Figures

List of Figures

Part I

Introduction

Introduction

1 Microgrids - Background

Traditionally, Electric Power Systems (EPS) have been structured as one-way power flow systems with centralized generation sources, long distance transmission systems, distribution systems and power demand [1]. Fossil fuels based generation sources have been deployed widely. However, their negative environmental impacts and the need for improving the reliability of the EPS have propelled the development and inclusion of redundancy generation provided mainly by environmentally friendly energy sources. In this context, the number of Renewable Energy Sources (RESs) based generation sides are largely increased, which are more affordable every day. In some regions, wind and solar are cost-competitive with traditional generation technologies at utility scale [2,3].

Nowadays, EPSs are evolving to more complex and interacting sets of systems at multiple levels by means of the development of new technologies, along with innovations in business models and policies. In this way, the whole system tends to be a conglomerate of smarter grids that interconnect hardware, software and communication technologies [4,5].

Accordingly, distributed solutions are becoming an integral part of the electricity system, providing improvements in energy efficiency, generation, and demand-side flexibility, as well as integrating diverse distributed energy resources such as Renewable Energy Systems (RES), Energy Storage Systems (ESS), electric vehicles, smart devices and appliances, among others [6–9].

In this context, distributed autonomous systems known as Microgrids (MG) have appeared as a natural component of the smart grid in order to provide with controllability and management to local power areas and enhance the power system with resiliency properties [10].

Microgrids have been defined in [11] as "low-voltage and/or medium-voltage grids equipped with additional installations aggregating and managing largely autonomously their own supply- and demand-side resources, optionally also in the case of islanding". Based on the standard IEEE 1547.4, a distributed islanded resources system (considered as MG) fulfills four conditions: (i) integrate Distributed Energy Resources (DER) and loads, (ii) have the capability of being disconnected (in parallel) from the area EPS, (iii) containt the local EPS and (iv) be intentionally planned [12]. Therefore, an MG can operate in an interconnected mode linked to the main grid at the Point of Common Coupling (PCC) or in islanded (autonomous) mode when it is disconnected from the main grid [13, 14]. This system integrates a variety of components including power consumers (loads), power converters (PC), DERs such as distributed generators (DG) –RESs or conventional generators– or ESSs, and grid components [15–17], as shown in Fig. 1.

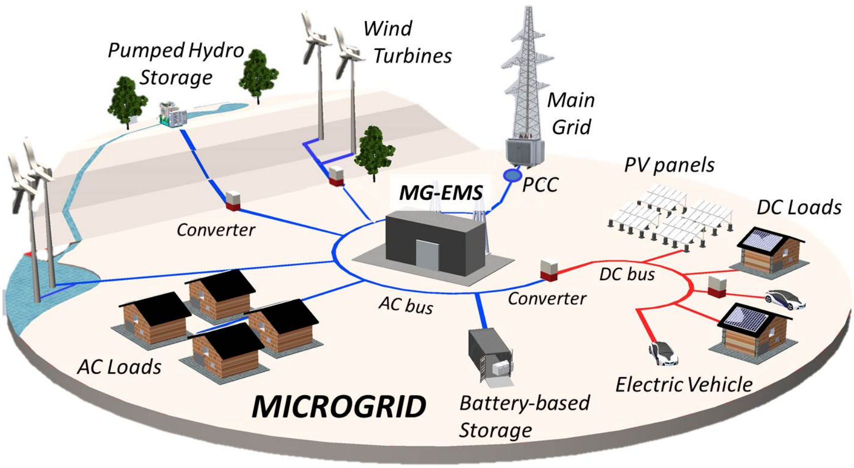

Fig. 1: General Scheme of a Microgrid

The development of microgrids integrating elements of the existing AC network with DC distributed energy resources and DC loads result in hybrid microgrids [18]. These hybrid AC/DC systems are considered the most probable future electric distribution and transmission systems [19].

1.1 Hierarchical Framework for the Development and Operation of a Microgrid

A single control and management system would not be able to make all the necessary decisions to implement a complex EPS. Therefore, the functions required for the development and operation of a microgrid have been established under hierarchical dependence [20–22]. In this way, the decision layers at a higher level of the hierarchy define the tasks and coordinate the lower-level layers, but do not override their decisions.

This architecture also increases the overall reliability of the system so that it can survive when one of the control units is disconnected or decomposed.

This is because the system as a whole is less sensitive to disturbance inputs if local units can respond more quickly than a more remote central decision unit [23].

The hierarchical structure for the operation of a microgrid and its analogy with classical management concepts can be adapted from [24] as presented in Fig. 2. Longer term planning levels, related to strategic level, have been considered in the power system operation, addressing issues related to maintenance, expansion planning and so on, as reviewed in [25, 26]. These long-term decision making levels are not included in the hierarchy framework considered in this thesis, since they are out of the main scope.

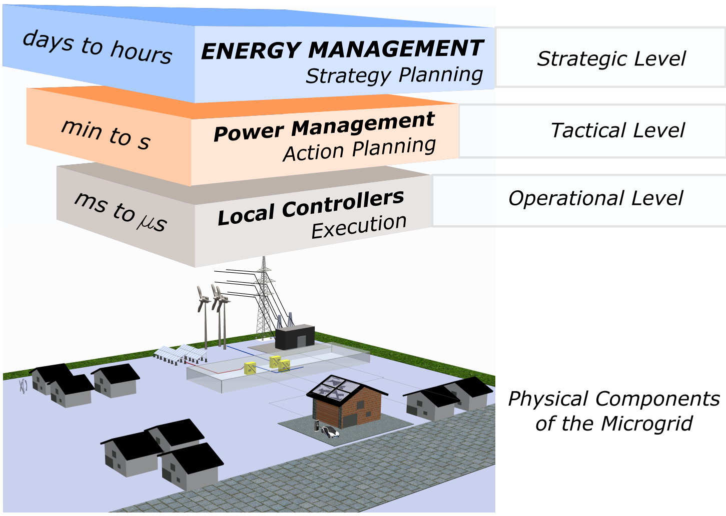

Fig. 2: Layer of management and control of a Microgrid

As can be seen, time-scales become shorter moving towards lower layers in the hierarchy, e.g. local controllers typically response between micro to milliseconds. The local controllers are related to the operational level of management that is an execution level that operates automatically according to the decisions made in upper level. In turn, power management level works for horizons between seconds to minutes. This hierarchical level makes tactical decisions coordinating the operation of the controllers, mainly focuses on the feasibility of the system. Energy management executes decision-making with action times of hours to days. This management layer corresponds to the strategy level which plans the operation of the microgrid in an optimal way considering the available resources, the operational cost of the units and the best time to perform actions.

Power Management Level and Local Controllers

A power management strategy is required for proper operation of a microgrid with multiple DG units [27]. The power management level acts on the instantaneous operational conditions toward certain desired parameters such as voltage, current, power, and frequency. The power management strategies include voltage and frequency regulations, and real-time power dispatching among different power sources in microgrids [19].

The power management in a microgrid has been developed in centralized or distributed architectures. However, according to the summary of projects of North America, Asia and Europe presented in [28], the hierarchical power management with central controller is more suitable for small-scale microgrid and without essential periodically reconfiguration of the systems.

Moreover, the power management involves the upper levels of the hierarchical control scheme that has been proposed and widely accepted as a standardized solution for efficient MGs operation [20, 21]. This hierarchical control includes four control layers. The inner control loops are responsible of the voltage and current regulation of each module [29]. The primary control adjusts the frequency and voltage references provided to the inner control loops. The secondary control deals with power quality control, such as voltage/frequency restoration, as well as voltage unbalance and harmonic compensation. The tertiary control regulates the power flow between the grid and the MG at the point of common coupling (PCC) or between zones regions inside the microgrids [21, 25]. This last level is implemented in a Microgrid Central Controller (MGCC) and is typically associated to supervisory control and acquisition systems.

In this way, the microgrid can assure a stable and reliable operation considering instantaneous conditions of different variables.

Energy Management Level

Energy management layer has the objective of ensuring power for longer time intervals (i.e., sufficient energy is available) than power management (with the objective of regulating instantaneous power), by taking into account prediction of costs, power generation and consumption [19,25]. Energy managements are mainly focused on economics, considering factors like fuel costs, capital costs, maintenance costs, mission profiles, lifetimes, etc [19,30].

In a general perspective, this level can be divided into sub-layers of operation and planning, which work in different time-scales [25]. In this way, the operation scheduling defines the commands for the DG units and loads within the MG some days or hours ahead. The sub-layer of planning is related to maintenance or replacement scheduling of the units and defines constraints related to how the units should be operated. This work is focused on the research of development of energy management systems (EMS) in the operation scheduling layer.

Furthermore, the EMS of an MG (MG-EMS) should be able to gather online measurement data, as well as historic and forecasting data and thus determine and transfer to the MG optimized references and define control actions to the components. Some of the DERs and loads admit to be dispatchable and can follow the tasks set by the EMS

The architecture of the management systems should consider the variable nature of RES, in addition with unpredictability of consumer behavior, limited generation capacity, and power exchange with the grid that may cause energy unbalances [31, 32].

1.2 Energy Management Systems for Microgrids - General Concepts

The International Electrotechnical Commission in the standard IEC 61970, related to EMS application program interface in power systems management, defines an EMS as "a computer system comprising a software platform providing basic support services and a set of applications providing the functionality needed for the effective operation of electrical generation and transmission facilities so as to assure adequate security of energy supply at minimum cost" [33]. An EMS for MG (MG-EMS) also have these features usually consists roughly of modules to perform decision making strategies. Modules of DER/load forecasting, Human Machine Interfaces (HMI) among others are connected to support decision making strategies that schedule and solve optimization problem to take optimal decisions to every generation, storage, and load units [34, 35].

In this way, the MG-EMS operates and coordinates energy components as DERs, loads, power converters and grid components in order to provide reliable, sustainable, and environmentally friendly energy in an optimal way [36–38]. It assigns the set points for DG units and commands control for the controllable loads in order to balance the system based on the operating conditions of microgrid components, some prediction data and the status of the system [39]. When the microgrid is in grid-connected mode, the MG-EMS can be oriented to operate bundled in a Demand Response (DR) program, promote self-consumption or participate in the electricity market. Meanwhile, in the island mode an MG-EMS may be called on to perform unit commitment, economic dispatch and load control [11].

Conventionally, the management of smart grids has been mainly focused on DERs but recently, demand flexibility has been incorporated by defining Demand Response (DR) programs, which provide several economic and technical benefits for utilities and consumers [40]. DR programs are mechanisms aimed to reshape consumer energy profiles, deployed in order to improve the reliability and efficiency of the grid and defer generation capacity expansion [41, 42]. Microgrids can take actions in response to a DR scheme by mean of load management schemes such as demand limiting, demand shedding, demand shifting and on-site Generation [40]. Particularly, the residential sector is more sensitive to the electricity price because it includes more controllable appliances [43].

DRs can be classified in two types, incentive-based scheme and price-based scheme [40, 43]. Incentive-based programs compensate participating users for demand reduction by offering discount rates separated to electricity prices. This is usually called direct scheme since the customer provides the program administrator some permission to directly schedule, reduce, or disconnect loads to save costs. Besides, these programs can also be classified as voluntary, mandatory and market clearing [44]. Programs that are included in this type are Direct-Load Controls (DLCs), interruptible/curtailable load, demand bidding and buyback, and emergency demand reduction [43].

Price-based schemes provide energy customers with time varying rates that define different electricity prices at different times. The price of electricity may differ at predefined times or may vary dynamically according to the time (day, week, or year). The customer reacts to the fluctuations in the electricity prices. Some of the implemented schemes are Time of Use (ToU), Critical-Peak Price (CPP), and Real-Time Price (RTP) [43,45]. In [41], the authors argue that this kind of programs is unfair to customers who already have normal or low level of consumption. Also, following price changes at different time periods may also be confusing to customers. In this case, scheduling techniques, manual or automated, is needed to help customers manage the load.

In light of the above, some of the challenges related to the development of MG-EMS are [36]:

- The definition of a mathematical representation of the system is required in order to realize an optimal operation of the MG. The modeling of the system in the MG-EMS should include the endogenous and exogenous relevant aspects for microgrid management in order to perform both generation and demand side management. The defined model should keep a fair compromise between the definition of a good modeling of the system and its complexity so that it can be implementable.

- The design of an adaptable structure. The architecture of the MG-EMS should be define in order to enable some flexibility in order to easily include additional functions and reconfigure the algoritms to consider the inclusion of new components with similar characteristics.

- The MG-EMS integration in the MG system. Another challenge is to integrate experimentally the EMS into the microgrid since it should consider important components such as communication, information structures, and define the proper relationship with the lower operational levels of the microgrid.

2 Management of Microgrids Equipped with Renewable Energy Sources and Batteries - Motivation

Advanced microgrids include an energy management system that coordinates power exchanges between generation, load, and storage, while considers demand response schemes and regulatory frameworks. Indeed, ESSs are imperative to provide the system with more control and management [46]. Some of the benefits enabled by these technologies within a microgrid are the enhancement of management functions, such as [47]:

- Peak shaving: The variability of solar energy sources and the increasing use of EVs with variable and random consumption profiles can create energy imbalances within the power grid, causing notable differences in the peaks and valleys of the load profile. A grid-connected energy storage system can help to eliminate these peaks and valleys through load leveling, peak shaving, and power demand management.

- Load leveling: Battery energy storage systems (BESS) can provide load balancing services for local grids, by acting as a reserve load that stores energy during periods of low demand in order to increase the total demands or deliver energy during periods of high consumption for helping to balance the load demand.

- Energy Arbitrage: The ability of storing energy at one time of the day and then discharging it at another time, effectively shifting the energy consumption, is what is called energy arbitrage. The purpose is to earn money by doing this, storing low cost energy during time of off-peak demand and selling it at high cost during time of peak demand. The difference in price between peak and off peak demand must be big enough to compensate the losses encountered in the storage process.

- Spinning reserve. The amount of generation capacity that can be used to produce active power over a given period of time which has not yet been committed to the production of energy during this period.

These applications are used in power system applications and their benefits can be brought to microgrids. Furthermore, even when the battery-based storage systems are still not cost-efficient for small-scale applications, in [3] is stated that "at least two basic business models are emerging for end-user storage. First, batteries coupled with solar PV provide end-users the ability to "self-consume" more of their solar generation, rather than send it (sell it) into the power grid, providing economic benefits depending on policy and tariff conditions. Second, batteries can reduce (shave) the end-user's peak power demand and thus reduce "demand charges" (capacity charges) that are based on the customers' peak capacity over the day or month" [4].

Moreover, the possibilities of having aggregated (communitary) or distributed energy storage between clusters of microgrids (such as a neighborhood of household prosumers) [48] brings additional challenges for the optimal operation of integrated power systems in terms of the definition of cooperative schemes which in general can provide more flexibility to a cluster of MG. These scenarios have been addressed in this project and can be considered as preliminary approaches to the concept of transactive energy [49, 50].

2.1 Components. Management Flexibility

A microgrid integrates diverse sorts of components, as presented in [17, 36, 51]. Table 1 summarizes the components that are decisive in the development of control and management strategies.

Distributed Energy Resources. Operation and Challenges

DER units include both Distributed Generation (DG) and distributed Energy Storage Systems (ESS) units with different capacities and characteristics [52].

Related to control, the strategies for operating DER units within the microgrid are established based on the required functions and operational scenarios. In this way, when the microgrid is in grid-connected mode, the main grid is in charge of the voltage and frequency regulation and the DERs can operate as grid-following units. The grid-following control strategy is used to control the output power export of the DER when is not required a direct control of voltage and/or frequency at the PC. In the case of islanded operation of the microgrid, at least one DER unit should work as grid-forming unit, regulating the voltage at the PCC and the system frequency [36].

The control objectives of a DER unit are also determined by the nature of its interactions with the system and other DER units. In this case, noninteractive and grid-interactive strategies can be defined. A grid-noninteractive strategy is constituted when the unit output power is controlled independent of the other units or loads. On the other hand, a grid-interactive control strategy is based the specification of power setpoints as input commands [36].

In light of the above, even when the EMS must take all the devices into account, DERs only can follow the scheduled commands if they are working

Table 1: Classification of some of the components integrated in a microgrid

	Component	Types	Description	Examples
Distributed Energy Resources	Distributed Generators (DG)	Non-renewable	Based on non-renewable resources such as diesel, gas or H_2	Reciprocating engines, gas turbine, fuel cell
		Renewables	Based on renewable resources such as wind, sun, ocean wave	Wind turbines, PV systems, ocean energy
	Distributed Energy Storage System	Short-Tem Applications	Provide high power in short periods	Supercapacitors, Flyweels, SMES
		Long-Term Applications	Ensure energy during long periods	Batteries, [Pump Hydro, CAES]
Loads	Non-controllable Loads	Critical Loads	Required reliable power supply	Hospitals, Military installations, Data Centers
	Controllable Loads	Non-shiftable Loads	Operate at specific times.	Residential and Some industrial loads, lighting
		Shiftable Loads	Can be scheduled at different time periods in the day	Dryer, Washing Machines, Dishwasher

as grid-following units in a grid-interactive mode.

Distributed Generators. Distributed Generators provide energy to the microgrid by using diverse primary energy sources and can be classified as renewable or non-renewable sources. The power flow control of these categories have been typically associated to the ability to be dispatchable or nondispatchable, respectively [25, 36, 53]. The difference between them is that the output power of a dispatchable DG unit can be controlled externally, through set points while a nondispatchable DG unit is normally controlled based on the optimal operating condition of its primary energy source [36]. Therefore, RESs are usually modeled as negative non-controllable loads [14, 36]. Other authors consider these kind of sources as predictive disturbances, in the sense that they put additional burden on both power and energy management objectives [25].

However, depending on the power electronics technology and implemented controllers, the energy provided by some of these renewable sources can be downwards dispatched [15]. Recently, some researchers have proposed curtailing available renewable energy as an additional control action that enables greater flexibility to the system [54]. This functionality has not been widely discussed in the modelling and management of energy in microgrids. Additionally, their management implies some challenges due to the variability of the sources and, consequently to the inherent errors in the forecast energy profiles that will be used in the management.

Energy Storage Systems. Energy storage related to electricity usage is based on different types of technologies with different characteristics of their power and energy capacities, discharging time, etc [18]. ESSs can be classified by considering whether they will be used in short or long term applications.

Short-term applications require storage technologies that can supply a large power, but only for a time up to a few seconds or minutes. These applications are related typically to maintain the voltage level during the start of the emergency generators (bridging power), as well as power quality, reliability and security of power systems.

On the other hand, long-term storage requirements are related to the support of distributed energy generation during several minutes or even hours. These storage technologies are used for uninterruptible power supply or energy management needs, which are associated to high-energy applications. On the basis of the power ratings of storage, pumped hydro and Compressed Air Energy Storage (CAES) present large with capacities from tens of MW up to hundreds MW compared to capacitors, different types of batteries and fly wheels, which range from 10 MW down to several kWs. [7]

For the energy management of microgrids, which require high-energy storage technologies for low/medium scale electrical networks, the most used storage systems are based on batteries [9]. Indeed, the most used type of battery for stationary applications of microgrids is the lead acid battery because this is a very mature technology that offer low cost with good performance. An important development in lead-acid battery technology is the Valve-Regulated Lead-Acid battery (VRLA), which reduces gas emission and are free of maintenance compared to vented Lead-Acid batteries [55].

For lead acid batteries, it is recommended to use at least a two-stage charging procedure in order avoid damages due to overvoltage, a limited current charge mode and a constant voltage charge mode. When the voltage is lower than a threshold voltage (V_γ) defined by the manufacturers, it can be operate under a limited current charge mode and it is able to follow external requirements but, once the battery reaches V_γ, its operation mode should change to a constant voltage charge stage, where its current will tend to zero while the voltage of the battery is kept in a constant value [55,56].

Battery units can be charged/discharged with limited current charge mode under constant current, constant load or constant power. In the development of the energy management systems proposed in this project, the selected process for charging and discharging the battery is constant power method so that the battery can follow the scheduled power reference profile when the battery voltage is lower than V_γ (grid-interactive control).

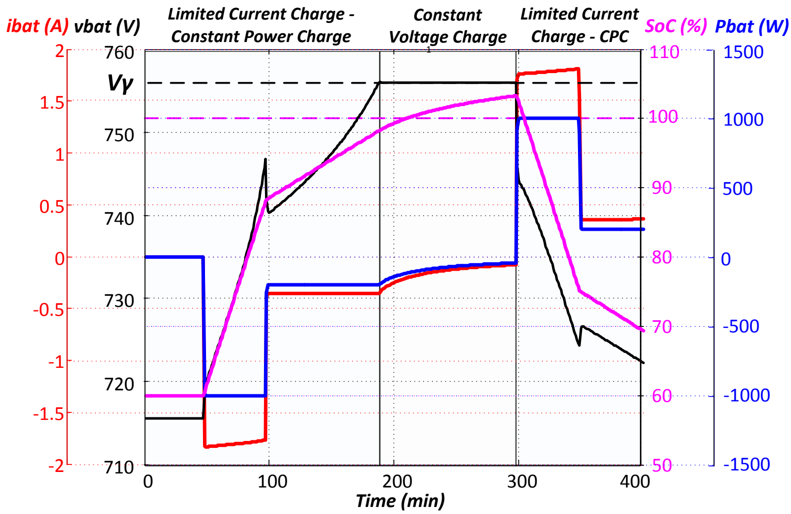

Fig. 3: Charging Procedure for Lead-acid batteries.

Additionally, for the operation and management of a battery unit within a MG, it is convenient to estimate its available energy capacity [57]. The State of Charge (SoC) of a battery expressed this remain energy as a percentage of its rated capacity [58, 59]. This variable is not directly measurable, so its estimation is based on voltage, current or impedance and usually depends on the previous condition of the SoC. There are several methods to estimate the SoC of a battery, such as open circuit voltage method, Coulomb counting method or adaptive system categories [60]. In this thesis, Coulomb counting (or Ah-counting) method have been implemented in the microgrid systems. This method uses battery discharging current as input, some parameters of the battery related to its performance and previous conditions of SoC [60,61].

In light of the above, the behavior of the battery with the proper controllers, under the two operating modes, constant power charge and constant voltage charge, is shown in Fig. 3. The simulation results show the power, voltage, current and SoC of the battery when it is being charged, it is fully charged and when it is being discharged. During the limited current charge stages, the power is constant and the battery is been charged or discharged, which can be seen from the voltage and the SoC. When the battery is operating in the constant voltage charge mode, the voltage is constant, the current goes slowly to zero and the SoC increases accordingly while the battery is being saturated for achieving a full charge. At this stage, it is recommended to return more than a 100% of the SoC to the battery in order to compensate losses during the charging process [55, 62].

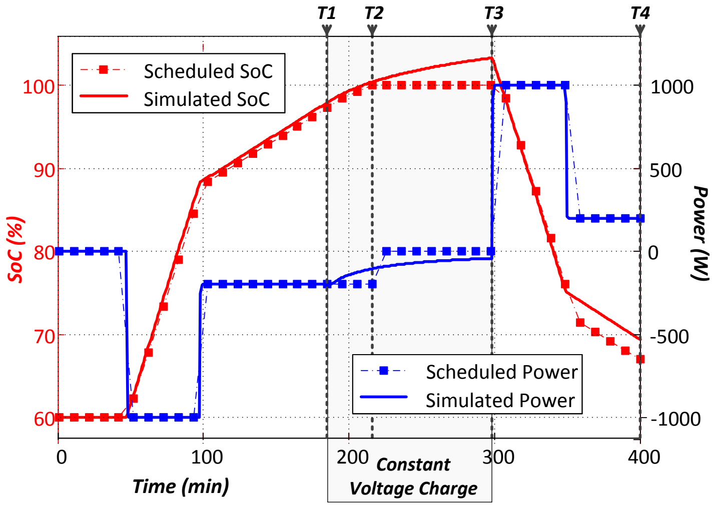

Fig. 4: Dynamic behavior of the Battery versus Scheduled Profiles

Furthermore, the variables used for the management of the battery units in a MG are the average values of the power and the SoC. In the mathematical formulation, it is needed to define some bound to these variables, which are associated to the physical restrictions of the units. In the case of the SoC, it is reasonable to assume that it can be from 0% to 100%. For lead acid batteries, the manufacturers recommends to operate the battery over 50% to avoid their fast degradation [62]. Fig. 4 shows the power and the SoC obtained from the previous simulation (solid lines) and from the simulation of a scheduling algorithm (dashed), which incorporates the predefined SoC boundaries and estimates the SoC as in [63]. Before $T1$, the battery is working in limited current charge mode and consequently, the scheduled power is followed by the battery. Once the battery operation mode changes to constant voltage charge (from $T1$ to $T2$), the schedules and the simulated power differ from each other, which can represent errors in the prediction of operating costs. The difference is also related to the SoC since, from the point of view of management, the battery is charged with 100% but, from simulation, it is charged at a value close to it and, in fact, during this period can exceed that limit. This is because the SoC estimation depends on the value of the current that is changing due to the saturation process [55]. After that (from $T3$ to $T4$), the battery changes its operation mode and follows the scheduled power but, there is a cumulative error in the SoC.

These issues have not been addressed deeply in previous work and represent a source of error that is present whenever batteries are used and their SoCs are estimated from their current. This thesis faces them either by defin-

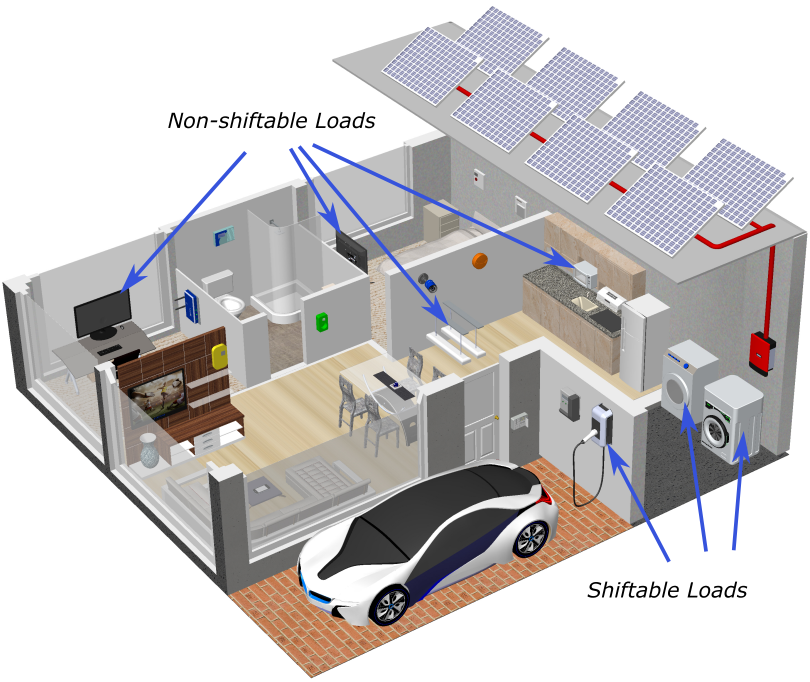

Fig. 5: Some appliances in a household

ing an improved way of modeling the optimization problem [64], by including a proper supervisory control to deal with the errors between the scheduled and the measured profiles [64], or by implementing an online MG-EMS that implements a rolling horizon strategy [65].

Loads

In an MG, electrical loads can be critical (also called sensitive) or non-critical [9,39,66,67]. Critical loads require a high degree of power quality and reliability to continuously supply the requested energy. In this thesis, non-critical loads are considered, which have the possibility to be shed during emergency mode to balance the system [67,68]. Additionally, there are some of these non-critical loads that also can be shifted to different time during the day according to some constraints such as power rating, working duration, and user preferences (Fig. 5).

These features of the different kinds of loads should be considered in the formulation of the load management and have been widely addressed separately from the generation side management. The simultaneous generation, storage and demand management is a challenge that enables more flexibility to the operation and, therefore provides better results [50,69].

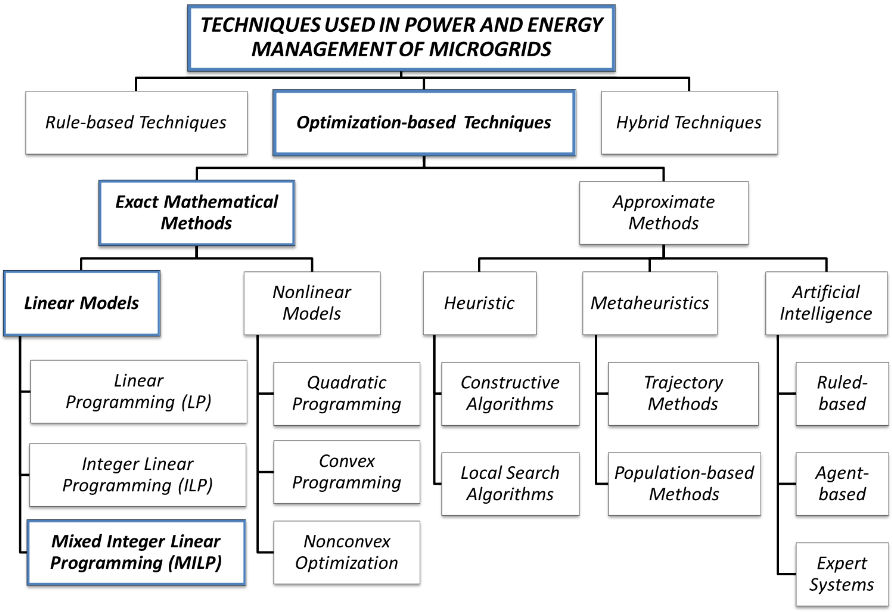

Fig. 6: Some Techniques used for Scheduling of Resources in a Microgrid

2.2 Scheduling Methods used in Microgrid Energy Management Systems - Motivation

In order to provide proper commands to the controllable components of the MG, three kinds of strategies have been implemented in the literature, rule-based or reactive method, optimization-based methods and hybrid methods, as shown in Fig. 6 [70].

With the first technique, the reference points are assigned according to the current situation and defining some scenarios, usually by means of decision trees [71–74]. This method is adapted to the system conditions by providing feasible solutions but can not guarantee the best possible result.

On the other hand, optimization-based scheduling aims to provide the best possible solutions, globally or locally. In general, the mathematical formulation of an optimization problem includes the minimization (or maximization) of an objective function, satisfying a certain set of constraints [75]. This approach can be addressed using exact or approximate methods, depending on the complexity of the system and, therefore, the possibility of defining a completed representation of the model.

The advantage of the approximate methods is that they can handle nonlinear and non-convex objective functions and constraints easily [32]. However, the quality of the obtained solution cannot be guaranteed since they usually implement random or knowledge-based search methods [76]. Additionally, when the problem size increases, the probability of finding the global solution decreases [77].

The exact mathematical methods produce an optimal solution when they are defined in a feasible region. They can be classified into different categories considering if they are linear of non-linear, convex or non-convex, continuous or discrete, and so on [78]. Based on the linearity, an optimization mathematical problem is linear if the objective function and the constraints are linear and, therefore, the boundary of feasible range is hyperplane. If any term in the formulation is non-linear, the problem becomes a non-linear optimization. Linear optimization modeling, is one of the best developed and most used branches of management science [79]. Linear optimization problems can be classified into linear programming (LP), integer programming (IP) and mixed-integer linear programming (MILP), depending if their variables are restricted to be real, integer, or the formulation includes both variable types, respectively.

Hybrid methods combine methods of the previous approaches in order to take advantage of their features.

MILP has been selected for the formulation of the mathematical model of this thesis because it allows to implement the characteristics of the generation and supply side management in a general way, as well as using integer variables. Moreover, binary variables are necessary for the establishment of battery charging status and the direction of the power flow in grid-connected mode of the microgrid.

The defined optimization problems in this collection of papers have been solved using the Algebraic Modeling Language (AML) called GAMS (General Algebraic Modeling System), which is the most used optimization software in process system enginnering field [70, 80]. Within this software, the optimization solver package CPLEX has been selected, which uses a branch-and-cut algorithm to solve MILP.

2.3 Uncertainties in Energy Management System for Microgrids

Power generation units employed in microgrids are usually renewable or non-conventional distributed energy resources. It imposes new challenges in the generation scheduling in microgrids due to the fluctuancy and climate-dependency of these sources. This fact, together with the variable profiles of the demand, implies that the MG-EMS has to cope with non-trivial uncertainties [81].

Given the above, proactive and reactive approaches have been used in previous work. Proactive approaches are developed offline, modifying the deterministic mathematical problem in order to include some additional features and then establish possible scenarios that are used depending on the situation. This approach has the advantage that a feasible solution is found for all considered scenarios. Some of the proactive approaches are stocastic programming, robust optimization or fuzzy programming [63, 82].

Reactive approaches are implemented online and are focused on modifying a nominal plan obtained by a deterministic formulation in order to adjust it to different alterations, modifications or updated system data. Some of these approaches are model predictive control and rolling horizon strategies [38]. In the first case, the control is based on a prediction of the system output, a number of time steps into the future, and its difference with the scheduled set-points. The second approach solves iteratively the deterministic problem by moving forward the optimization horizon in every iteration.

This thesis addresses the uncertainties based on reactive approaches by defining rolling horizon strategy [65, 83] and including proper supervisory controls [64, 83]. The design of the MG-EMS architecture is really important in this case since the processing time of each implemented function takes a crucial role in the performance of the MG-EMS. It is also essential to include contingency actions to set proper references even if the optimization problem is infeasible, there are unexpected big mismatches between the forecasting and the real situation or any other issue in the system occurs.

To illustrate, Fig. 7 has been taken from [65] and shows the proposed online MG-EMS and its integration into a microgrid eqquiped with RESs and a battery unit. The architecture of the MG-EMS is coordinated by a processor and the additional processes, implemented in independent modules, exchange information through the data storage. In this way, the MG-EMS can integrate processes that operates simultaneously. Additionally, the supervisory control level has been designed in order to provide the proper commands to the microgrids based on the commands given by the MG-EMS. This control level includes contingency action in order to provide feasible commands even under big mismatches between the predicted power profiles and the current situation of the microgrid.

3 Thesis Contribution

This thesis addresses the modeling, design and implementation of energy management systems in order to economically optimize the operation of small scale microgrids based on renewable energy sources and battery-based energy storage systems. Research in energy management of microgrid have been typically focused on theoretical analysis. The main motivation is to reduce the gap between optimization theory and experimental operation of microgrids under different scenarios. This thesis is mainly focused on achieving and implementing energy management systems for microgrids with adapt-

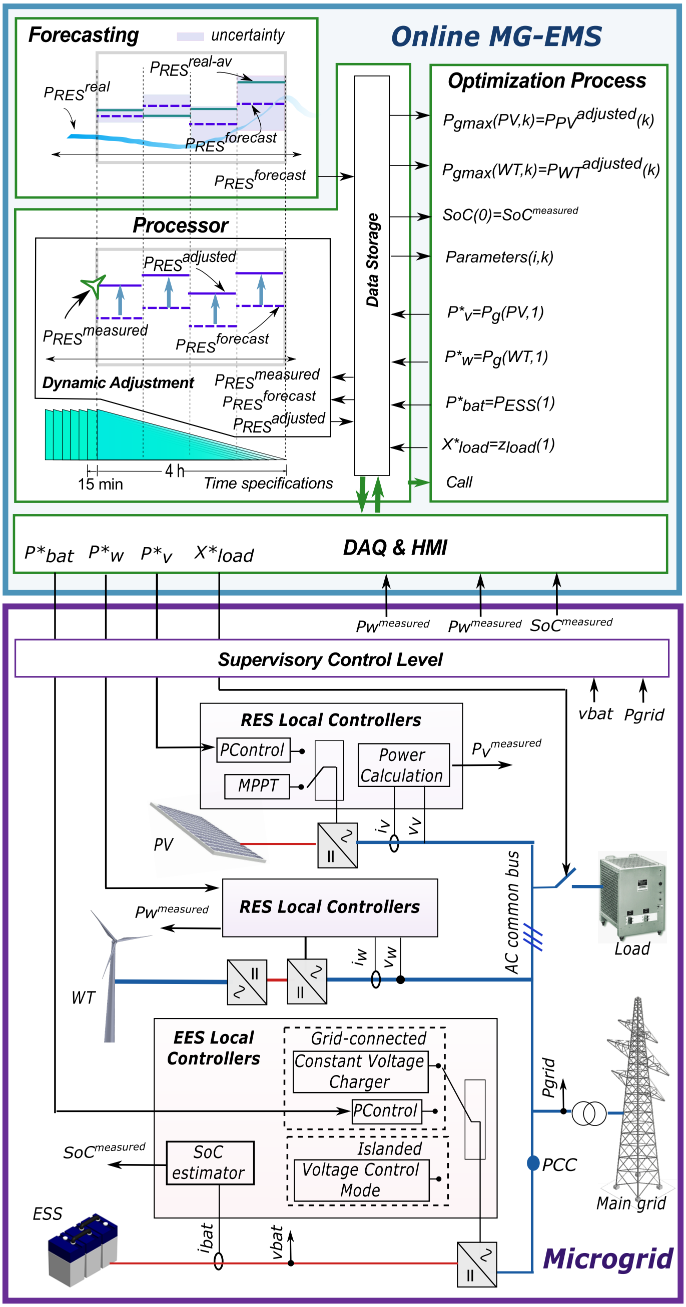

Fig. 7: Scheme of a proposed online MG-EMS integrated into a microgrid with RESs and a battery unit (Source: [69])

able functional algorithms and structures that take into account the relevant physical and regulatory constraints and can be expanded in the case of having more resources of similar characteristics.

For the definition of algorithms, linear models have been used in order to guarantee that the solutions are optimal due to the linearity of the formulation and also take advantage of the algorithms widely tested in the field of engineering processes. Besides, the architecture of the management systems has been developed by integrating modular functional blocks connected to a data storage system.

Moreover, the components that have been considered are distributed generators, energy storage systems, loads and the connection to the network. Defined optimization models simultaneously optimize the use of all the controllable resources at the operation level. Related to renewable energy sources, many previous works have modeled them as non-dispatchable sources. However, recent advances in power electronics enable to perform downwards scheduling of these resources. In this regards, it is established and modeled that the energy available by the RESs can be curtailed or set to zero.

On the other hand, batteries have been chosen as energy storage systems. Accordingly, a two-stage charging procedure has been implemented for their proper operation, i) if the battery has a partial SoC, it is charged under a constant power method to follow the reference or microgrid requirements, and ii) it changes to a constant voltage stage, once it is charged. Some deviations between the scheduling and the implementation have been observed since the charging procedures imply a non-linear behavior that is not modeled in the optimization problem. In order to deal with this non-linearity, an adaptation of the optimization model has been proposed in [64], which modifies the boundaries of power and SoC of the batteries in case of reaching the charged stage mode. In addition, a low-level supervisory system based on a fuzzy inference system is presented to adjust the battery and RESs references to meet the scheduled utility power.

In microgrids connected to the main grid, two scenarios were established, when some profits are obtained for the energy injection into the main grid or when self-consumption is promoted. In the first case [84], a hybrid microgrid installed in Shanghai is used as a case study, where some subsidies are given for the PV generation. In this way, the proposed optimization model aims to maximize the benefit for producing PV energy and minimize the costs of absorbing energy from the main grid. The bi-directionality of the network power is modeled to differentiate the costs in each direction. On the other hand, since the incentives to install renewable energy sources have been reduced, self-consumption is a trend nowadays and has been considered as a possible regulatory framework, including some power injection constraints.

The previous work has been extended to microgrid applications in two particular cases, a cluster of islanded household prosumers that can cooperate to improve the performance of the global system [49], and households with PV generation that share a communitary energy storage system [50].

In the first case, the cooperative operation between prosumers is established by means of a centralized energy management system. In this case, the load management is carried out by shedding them, giving a higher priority to the load of the prosumer that generates more and consumes less energy during the day. The performance of the proposed strategy is verified experimentally by comparing the operation of household prosumers with and without the optimized cooperative operation. The proposed strategy provides performance improvements versus an independent operation of each household prosumer.

In the second case, households with PV generation and controllable and non-controllable loads are connected in a radial configuration. A communitary battery is included in the microgrid in order to reduce the cost of the energy consumption. The energy allocation from the battery is defined through a reputation factor, established by the relation between the power that each household provides for charging the battery over the power that all of them provide during the previous days. The energy tariff for using energy from the main grid are established as a variable price demand response program. The controllable loads are shifted depending on power constraints and user preference times. The proposal manages to reduce the cost of using energy from the main grid while fulfilling all the constraints and defined requirements.

Furthermore, the previous approaches have been addressed as deterministic problems, performing the scheduling 24-h ahead. However, the prediction of renewable energy may differ greatly from the current generation, so scheduling may be difficult to follow or may even be no longer valid. In order to deal with this issue, an adaptive online MG-EMS was proposed with a rolling horizon mechanism. The MG-EMS is implemented in LabView and it calls an Algebraic Modeling Language (GAMS) to solve the optimization problem. The proposal has been implemented experimentally in laboratory radial microgrids in grid-connected and islanded mode. The microgrid includes a supervisory level where some contingency actions are defined, and detailed experimental validation of the whole system is presented. The proposed system operates according to the optimal references established by the MG-EMS even under big mismatches between the prediction and the current energy generation.

Finally, the validation of a particular proposal is typically performed by comparing with a previous approach conveniently selected. This method can give a misconception of the improvements that are achieved with the proposal. Therefore, an assessment framework has been introduced in order to compare the benefits of the proposed MG-EMS with other strategies but also with the best and the worst case, known so far.

Therefore, the generic architecture, laboratory-scale experimental setup and validation demonstrated in this paper can promote further exploration of smart management of microgrid and its engineering application.

4 Thesis Objectives

The research objectives of this project are listed below:

- To investigate the characteristics of the components in small-scale microgrids with renewable energy resources and battery units. To analyze their relevance in the modeling and design of the energy management system at the operation level of a microgrid.
- To study optimization techniques and architectures used in energy management systems for microgrids with renewable energy resources and battery units.
- To determine a suitable optimization technique and to propose scalable optimization formulations for microgrids, according to the physical parameters, policies and other constraints.
- To design and implement an adaptable architecture for the energy management system of a microgrid equipped with renewable energy sources and batteries.
- To integrate the proposed energy management system into the microgrid and verify experimentally the proper operation of the whole system.
- To implement the proposed energy management system in specific low-scale microgrid applications .
- To adapt the proposal to an online scheme in order to deal with the uncertainties due to errors in the forecast of the renewable energy generation and demand.
- To establish an assessment framework to evaluate the performance of the proposal compared with relative and absolute references.

5 Thesis Outline

This thesis is organized as follows:

Chapter II presents the first paper, published in IEEE Transactions on Power Electronics. This paper presents the modeling and design of a flexible structure of energy management system for microgrids with batteries. The associated optimization problem aims to minimize operating costs, taking into account a two-stage charge procedure for ESSs based on batteries. The mathematical formulation is scalable to include more distributed energy resources with similar characteristics. A fuzzy-based supervisory control level is included in the microgrid in order to adjust the references defined for the distributed energy resources, in accordance with the deviation of the scheduled utility power. This supervisory control level can provide balanced references to the controllers, even without the communication with the EMS. The experimental verification is performed by integrating the proposed energy management system based on 24-hour ahead prediction to a grid connected microgrid that promotes self-consumption.

Chapter III contains the second paper, presented in the 31st Annual IEEE Applied Power Electronics Conference and Exposition (APEC) 2016. This paper presents the modeling of an optimization problem, proposed to optimally schedule the distributed energy resources of a real hybrid PV-wind-battery microgrid located in Shanghai, China. Physical constraints, established tariff schemes and subsidies have been considered in order to achieve optimal solutions for a feasible deployment in the real system. Particularly in Shanghai, a time of use scheme is used in the tariff of the energy absorbed from the main grid, where the cost is higher during the day than during the night. Additionally, the national and local governments have established some subsidies for generating energy given by PV systems. The optimization is formulated as a mixed-integer linear programming mathematical model and it has been tested by using a real-time simulation of the model. The results show the economic benefits of the proposed optimal scheduling approach in two different scenarios.

Chapter IV presents the third paper, published in IEEE Transactions on Consumer Electronics. This paper proposes a cooperative operation based on a centralized energy management system for a cluster of islanded household prosumers. This strategy allows an optimal power sharing and storage energy balance by maximizing the use of available renewable energy generation and reducing the probability of load disconnections. The proposed optimization model formulation includes the formulation of a mechanism to define a fair use of the energy, considering the ratio between energy consumption and generation of each prosumer during the day. The performance of the proposed strategy is verified experimentally in a laboratory prototype microgrid by comparing the operation of every household prosumers independently with the cooperate operation. Results show the benefits of using the proposed strategy in clusters of prosumers that integrates renewable energy resources, batteries and loads.

Chapter V presents the fourth paper, published in Energy and Buildings Journal. This paper proposes a reputation-based energy sharing framework for a grid-connected microgrid composed of a community battery and households equipped with PV arrays. Household reputation factors have been defined in accordance with the previous relative energy contribution, and are used to reallocate the available energy in the storage unit. This framework has been applied to a centralized optimization problem that aims to minimize the cost of energy absorbed from the grid in a demand response scheme, prioritizing the households with higher reputations. The optimization model jointly schedules controllable appliances of the households and the energy that each household can receive from the shared storage unit. Numerical analysis is conducted using real data of renewable energy and appliances demand profiles for different classes of households in Spain. The study provides insights on how the shared energy using the reputation-based policy can be fairly and reliably allocated among households within the microgrid and how this framework can reduce power demands from the main grid and energy injection to the main grid without urging households to have a local storage unit.

Chapter VI presents the fifth paper, which has been submitted to IEEE Transactions on Power Electronics. This paper present the design of an adaptable online energy management system for microgrids, its experimental integration into a microgrid under grid-connected and islanded modes, and the proposal of an evaluation framework to quantitatively assess different energy management strategies. The proposed online energy management system is designed in a modular scheme so that it can be easily expandable and reproducible. It has not sequential functions in order to avoid time delays, but the modules are connected to a common data storage. It also includes a function to dynamically adjust the forecast data by taking into account the current measurements. The proposed EMS has been implemented in an experimental test bench, showing its effectiveness under the renewable energy uncertainties and also under big mismatches between the forecasting and the current climatic conditions. Finally, an assessment framework is proposed to evaluate the enhancement attained by different online energy management strategies together with the gaps over ideal boundaries of the best and worst possible solutions.

Chapter VII contains the conclusion and summarizes the main contributions. Additionally, this part presents perspectives for future research.

Part II

Paper 1

Mixed-Integer-Linear-Programming based Energy Management System for Hybrid PV-wind-battery Microgrids: Modeling, Design and Experimental Verification

Adriana C. Luna, Nelson L. Díaz, Moises Graells, Juan C. Vásquez, and Josep M. Guerrero

Abstract

Microgrids are energy systems that aggregate distributed energy resources, loads and power electronics devices in a stable and balanced way. They rely on energy management systems to schedule optimally the distributed energy resources. Conventionally, many scheduling problems have been solved by using complex algorithms that, even so, do not consider the operation of the distributed energy resources. This paper presents the modeling and design of a modular energy management system and its integration to a grid-connected battery-based microgrid. The scheduling model is a power generation-side strategy, defined as a general mixed-integer linear programming by taking into account two stages for proper charging of the storage units. This model is considered as a deterministic problem that aims to minimize operating costs and promote self-consumption based on 24-hour ahead forecast data. The operation of the microgrid is complemented with a supervisory control stage that compensates any mismatch between the offline scheduling process and the real time microgrid operation. The proposal has been tested experimentally in a hybrid microgrid at the Microgrid Research Laboratory in Aalborg University.

The paper has been published in the
IEEE Transactions on Power Electronics, Vol. 32, No. 4, pp. 2769-2783, 2017

Part III

Paper 2

Optimal power scheduling for a grid-connected hybrid PV-wind-battery microgrid system

Adriana C. Luna, Nelson L. Díaz, Mehdi Savaghebi, Juan C. Vásquez,
Josep M. Guerrero, Kai Sun, Guoliang Chen and Libing Sun

Abstract

In this paper, a lineal mathematical model is proposed to schedule optimally the power references of the distributed energy resources in a grid-connected hybrid PV-wind-battery microgrid. The optimization of the short term scheduling problem is addressed through a mixed-integer linear programming mathematical model, wherein the cost of energy purchased from the main grid is minimized and profits for selling energy generated by photovoltaic arrays are maximized by considering both physical constraints and requirements for a feasible deployment in the real system. The optimization model is tested by using a real-time simulation of the model and uploaded it in a digital control platform. The results show the economic benefit of the proposed optimal scheduling approach in two different scenarios.

The paper has been published in
Proceedings of the 31st Annual IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 1227 - 1234, 2016

Part IV

Paper 3

Cooperative energy management for a cluster of households prosumers

Adriana C. Luna, Nelson L. Díaz, Moises Graells, Juan C. Vásquez, and Josep M. Guerrero

Abstract

The increment of electrical and electronic appliances for improving the lifestyle of residential consumers had led to a larger demand of energy. In order to supply their energy requirements, the consumers have changed the paradigm by integrating renewable energy sources to their power grid. Therefore, consumers become prosumers in which they internally generate and consume energy looking for an autonomous operation. This paper proposes an energy management system for coordinating the operation of distributed household prosumers. It was found that better performance is achieved when cooperative operation with other prosumers in a neighborhood environment is achieved. Simulation and experimental results validate the proposed strategy by comparing the performance of islanded prosumers with the operation in cooperative mode.

The paper has been published in the
IEEE Transactions on Consumer Electronics, Vol. 62, No. 3, pp. 235 - 242, 2016

Part V

Paper 4

Reputation-based joint scheduling of households appliances and storage in a microgrid with a shared battery

Tarek AlSkaif, Adriana C. Luna, Manel Guerrero Zapata, Josep M. Guerrero and Boris Bellalta

Abstract

Due to the decreasing revenues from the surplus renewable energy injected into the grid, mechanisms promoting self-consumption of this energy are becoming increasingly important. Demand response (DR) and local storage are among the widely used mechanisms for reaching higher self-consumption levels. Deploying a shared storage unit in a residential microgrid is an alternative scenario that allows households to store their surplus renewable energy for a later use. However, this creates some challenges in managing the battery and the available energy resource in a fair way. In this paper, a reputation-based centralized energy management system (EMS) is proposed to deal with these issues by considering households' reputations in the reallocation of available energy in the shared storage unit. This framework is used in an optimization problem, in which the EMS jointly schedules households' appliances power consumption and the energy that each household can receive from the storage unit. The scheduling problem is formulated as a Mixed Integer Linear Programming (MILP) with the objective of minimizing the amount and price of energy absorbed from the main grid. The MILP problem is coded in GAMS and solved using CPLEX. Numerical analysis is conducted using real data of renewable energy production and appliances' demand profiles for different classes of households and different annual periods in Spain. Simulation results of the different scenarios show that by using the proposed framework higher cost savings can be achieved, in comparison with the classical scheduling scenario. The saving can reach up to 68

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Part VI

Paper 5

Online Energy Management Systems for Microgrids: Experimental Validation and Assessment Framework

Adriana C. Luna, Lexuan Meng, Nelson L. Díaz, Moises Graells, Juan C. Vásquez, and Josep M. Guerrero

Abstract

Microgrids are energy systems that can work independently from the main grid in a stable and self-sustainable way. They rely on energy management systems to schedule optimally the distributed energy resources. Conventionally, the main research in this field is focused on scheduling problems applicable for specific case studies rather than in generic architectures that can deal with the uncertainties of the renewable energy sources. This paper contributes a design and experimental validation of an adaptable energy management system implemented in an online scheme, as well as an evaluation framework for quantitatively assess the enhancement attained by different online energy management strategies. The proposed architecture allows the interaction of measurement, forecasting and optimization modules, in which a generic generation-side mathematical problem is modelled, aiming to minimize operating costs and load disconnections. The whole energy management system has been tested experimentally in a test bench under both grid-connected and islanded mode. Also, its performance has been proved considering severe mismatches in forecast generation and load. Several experimental results have demonstrated the effectiveness of the proposed EMS, assessed by the corresponding average gap with respect to a selected benchmark strategy and ideal boundaries of the best and worst known solutions.

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Part VII

Concluding remarks

Conclusion

1 Summary

This thesis proposes adaptable energy management systems for the operation of microgrids equipped with battery units and renewable energy sources, applied in different scenarios. The incorporation of energy storage systems provides the microgrid with some flexibility for its management since they allow energy reallocation during a predefined time horizon according to predefined objectives. In microgrids, battery-based storage systems are the most suitable storage technology to perform this task since they have sufficient energy capacity, are designed for the voltage ranges in which microgrids operate, and are affordable. However, their operation requires some stages of charging and discharging with dynamics that cannot be completely modeled in the energy management system. This fact imposes some challenges that should be addressed to add more uncertainty due to the mismatch between the model in the energy management system and the real performance of the microgrid. Furthermore, the microgrids under study include also renewable energy sources, which can be manageable downwards. This provides another degree of freedom to the management of the microgrid. However, the variability of these sources, together with additional issues imposed by the particular application, implies some challenges in the modeling of optimization problems and design of energy management systems.

The proposed algorithms are focused on economic objectives and are modeled in a lineal and generic way, in order to enable the expandable functionality related to include more devices of similar characteristics. Simultaneous generation and demand scheduling are performed, providing commands or curtailment references to the distributed energy resources, while shed or shift the controllable loads. The optimization problems are formulated as deterministic models that can be solved by commercial tools. In this way, it is exploited the current development of the solvers and the proposal can be reproduced in real applications. Particularly, the algebraic modeling language GAMS (General Algebraic Modeling System) is used in this project to model and solve optimization problems because it is one of the most used optimization software in process system engineering field. On the other hand, the proposed architectures are easily deployed and adaptable due to their modularity.

In order to deal with the uncertainties, the proposed architecture is used in a rolling horizon scheme. The results are available to be accessed by the supervisory control of the MG, which is in charge of performing contingency actions in case of situations that cannot be perceived by the EMS due to its time scale operation and the linearity of the modeling.

Moreover, an assessment framework was established to evaluate the performance of the EMS comparing with absolute references that give an insight on how much the proposal advanced previous strategies and how much is still possible to improve.

2 Contributions

This sections summarizes the main contributions from the point of view of the Author:

- The design of adaptable energy management systems for microgrids integrated by modules, which share a common data storage system.
- The modeling of scalable optimization algorithms to schedule the use of distributed energy resources and controllable load under different scenarios.
- The adaptation of the proposed energy management system in a rolling horizon strategy in order to deal with uncertainties.
- The integration of the energy management system to a microgrid. Supervisory level controls are defined to read and validate data as well as perform contingency actions.
- The definition of an assessment framework to evaluate the energy management system over previous approaches and absolute boundaries.
- The use of the energy management system in cooperative applications in a centralized structure. Introduction of the energy trading and cooperative operation considering the availability and requirements of different interconnected microgrids.
- A first approximation to neighborhood microgrid in a particular case with communitary battery. This can be considered as a primary approach to the transactive energy application.

3 Future Work

The methods and contributions that developed in this thesis show the following promising aspects that can be investigated in the future:

- Development of management strategies at planning level and their integration within a proposal at operation level by including proper constraints. In this way, important factors that cannot be observed at short term can be considered in the energy management system operation such as the effects of the battery degradation due to its operation or the need of replacement and maintenance of some components of the microgrid.
- Evaluation of the effects of the proposed energy management system over the grid. Considering the problem from the point of view of the DSO and proposed feasible solutions.
- Considering multi-carrier energy microgrids that actively participate in markets.
- Adaptation of the online system to include additional functionalities, such as analysis of power quality issues. Additionally, power management can be included in order to provide feasible reactive power commands.
- Consideration of multi-microgrid systems by combining local and centralized energy management systems. Implementation of the whole system with smart devices, evaluation of the limitations and analysis of the interaction between hierarchies and their functions.
- Modelling the multi-microgrid systems by using artificial intelligent.
- Transactive energy taking into consideration the privacy of the local users and their economic benefits.

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