
Innovative controls for renewable source integration into smart energy systems



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WP6 – Dissemination and exploitation of results

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Key words	Dissemination, Proceedings, Workshop, IRP					

¹ Report

² Administrative (website completion, recruitment completion...)


³ Dissemination and/or exploitation of project results

⁴ Other including coordination

⁵ Public: fully open, e.g. web


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DEFINITIONS

- Beneficiary partners of the INCITE Consortium are referred to herein according to the following codes:
 - **IREC.** Fundacio Institut de Recerca de l'Energia de Catalunya (Spain)
 - **UPC.** Universitat Politècnica de Catalunya (Spain)
 - **TU Delft.** Technische Universiteit Delft (Netherlands)
 - **VITO.** Vlaamse Instelling Voor Technologisch Onderzoek (Belgium)
 - **UniBo.** Università di Bologna (Italy)
 - **UGA.** Université Grenoble Alpes (France)
 - **Efacec Energia.** Efacec Energia - Maquinas e Equipamentos Electricos SA (Portugal)
- **Beneficiary.** The legal entities that are signatories of the EC Grant Agreement No. 675318, in particular: IREC, UPC, TU Delft, VITO, UniBo, UGA and Efacec Energia.
- **Consortium.** The INCITE Consortium, comprising the above-mentioned legal entities.
- **Consortium Agreement.** Agreement concluded amongst INCITE Parties for the implementation of the Grant Agreement.
- **Grant Agreement.** The agreement signed between the beneficiaries and the EC for the undertaking of the INCITE project (Grant Agreement n° 675318).
- **Partner Organisation.** Legal Entity that is not signatory to the Grant Agreement and does not employ any Researcher within the Project and namely, 3E NV (Belgium), Tokyo Institute of Technology (Japan), Politecnico di Torino (Italy), ETH Zurich (Switzerland), Aalborg University (Denmark), NREL (USA), Arizona State University (USA), ABB AB (Sweden).

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ABBREVIATIONS

- **CA.** Consortium Agreement
- **CMO.** Central Management Office
- **EC.** European Commission
- **ESR.** Early Stage Researcher
- **GA.** Grant Agreement
- **INCITE.** Innovative controls for renewable source integration into smart energy systems
- **IRP.** Individual Research Project
- **RES.** Renewable Energy Sources
- **WPs.** Work Packages

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EXECUTIVE SUMMARY

This report brings together the abstracts of the scientific presentations that took place during the 5th INCITE Workshop, which was organised by UGA and was held in Grenoble, France, on 21-23 November 2018.

Scientific abstracts include the contributions from the invited speakers, whose lectures provided scientific and complementary skills training for the Early Stage Researchers (ESRs), as well as presentations of the progress on the Individual Research Projects (IRPs) by the ESRs.

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1. INTRODUCTION


The 5th INCITE Workshop took place in Grenoble (France), 21-23 November 2018. The host of the event was UGA and it was held at G2Elab premises in Grenoble.

This workshop aimed to enhance ESR networking, as the ESRs presented their latest research and the status of their IRPs and had dedicated time to foster their collaborations.

Scientific training included seminars on smart grids and smart districts from technical and socio-economic perspectives, and a visit to the French National High Magnetic Field laboratory and its 20MW power plant. Complementary skills training, on the other hand, focused on the role and management of innovation, which is of great relevance for the ESR career development.


2. PROGRAM

Nº	Topic	Speakers	Time
Wednesday 21/11/2018			<i>Salle des Conseils ENSE3</i>
	Coffee welcome & Introduction	Nicolas Retière – Bertrand Raison	9:45-10:30
	Seminar I: Smart grids, challenges and perspectives	Prof. Nouredine Hadj-Said	10:30 – 12:00
<i>Lunch</i>			12:00 – 13:00
	Seminar II : Considering socio-energy assemblage and collective self-consumption in order to design/manage multi-actors energy systems	Gilles Debizet	13:00-14:30
	IRP 2.1 - Co-simulation of Model Predictive Control (MPC) algorithms for the flexibility of heat pump heating and cooling loads	Thibault Péan	14:30-15:00

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	IRP 2.2 - Control and management of energy storage elements in micro-grids	Unnikrishnan Raveendran Nair	15:00-15:30
	IRP 2.3 - Analysis and Control of the Room Temperature in an Office Building	Tomas M. Pippia	15:30-16:00
<i>Coffee break</i>			16:00-16:30
	IRP 3.1 – An Integrated Approach to Understanding Interoperability Issues in VSC-HVDC Networks	Adedotun Agbemuko	16:30-17:00
	IRP 3.2 – A new modelling approach for stabilisation of smart grids	Felix Koeth	17:00-17:30
	IRP 3.3 – A distributed wind farm control strategy for enhancing primary frequency support	Sara Siniscalchi Minna	17:30-18:00
<i>End of Day 1</i>			18:00

Nº	Topic	Speakers	Time
Thursday 22/11/2018			<i>Salle des Conseils ENSE3</i>
	IRP 4.4 – A multi-period Optimal Power Flow scheme for Low Voltage Distribution Networks & Operation algorithms for Smart- Charging within different business models	Konstantinos Kotsalos	9:00 – 9:30
	IRP 4.3 - Efficient Convex Optimization for Optimal PMU Placement in Large Distribution Grids	Miguel Picallo	9:30 – 10:00
	IRP 4.2 – A fault detection and localization method for LV distribution	Nikolaos Sapountzoglou	10:00 – 10:30

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	grids & A review of fault diagnosis techniques in fuel cells		
	IRP 4.1 – Day-ahead Scheduling of a Local Energy Community: An ADMM Approach	Camilo Orozco	10:30 – 11:00
<i>Coffee break</i>			11:00 – 11:30
	IRP 1.1 - Self-Sufficient Microgrids for Decentralized Economic Dispatch of Distribution Power Networks	Wicak Ananduta	11:30-12:00
	IRP 1.3 - Coordinating Energy Flexibility in the Electricity Distribution Grid	Shantanu Chakraborty	12:00-12:30
<i>Lunch</i>			12:30-13:30
	Supervisory Board Meeting	Salle Paul Janet G2Elab	13:30-15:30
	ESR Interaction	Salle des Conseils ENSE3	13:30-15:30
	Seminar III : Visit of the French National High Magnetic Field laboratory	Benjamin Vincent	15:30-18:00
<i>End of Day 2</i>			18:00

<i>Nº</i>	<i>Topic</i>	<i>Speakers</i>	<i>Time</i>
Friday 23/11/2018			<i>Salle des Conseils ENSE3</i>
	Seminar IV : From Idea to Business: 5 Stages of the Innovation Process	Prof. Karine Samuel	8:30-10:30
<i>Coffee break</i>			10:30 – 11:00
	IRP 1.2 – Real-time Market-based Control of Distributed Energy Resources with Uncertainty	Hazem Abdelghany	11:00-11:30
	IRP 1.4 – A 1-dimensional continuous and smooth model for thermally	Jesus Lago Garcia	11:30-12:00

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	stratified storage tanks including mixing and buoyancy effects		
	Virtual labs	ESRs, José Luis Domínguez and Marta Fonrodona (IREC)	12:00 – 12:30
	Q&A and closing	Marta Fonrodona and José Luis Domínguez (IREC)	12:30 – 13:00
<i>Lunch</i>			13:00-14:00
<i>End of the workshop</i>			14:00

3. ABSTRACTS

In the following pages, the abstracts of the seminars and presentations can be found:

i. Complementary skills training:

- From Idea to Business: 5 Stages of the Innovation Process (K. Samuel, Grenoble INP)


ii. Scientific training:

- Smart grids, challenges and perspectives (N. Hadj-Said, Grenoble INP)
- Considering socio-energy assemblage and collective self-consumption in order to design/manage multi-actor energy systems (G. Debizet, UGA)

iii. INCITE ESR presentations:

WP1. Control strategies for distributed power generation

- IRP1.1 – Self-Sufficient Microgrids for Decentralized Economic Dispatch of Distribution Power Networks (W. Ananduta)
- IRP1.2 – Real-time Market-based Control of Distributed Energy Resources with Uncertainty (H. Abdelghany)
- IRP1.3 – Coordinating Energy Flexibility in the Electricity Distribution Grid (S. Chakraborty)
- IRP1.4 – A 1-dimensional continuous and smooth model for thermally stratified storage tanks including mixing and buoyancy effects (J. Lago Garcia)

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WP2. Control strategies for energy storage systems


- IRP2.1 – Co-simulation of Model Predictive Control (MPC) algorithms for the flexibility of heat pump heating and cooling loads (T. Péan)
- IRP2.2 – Control and management of energy storage elements in micro-grids (U.R. Nair)
- IRP2.3 – Analysis and Control of the Room Temperature in an Office Building (T. Pippia)

WP3. Control strategies for RES integration

- IRP3.1 – An Integrated Approach to Understanding Interoperability Issues in VSC-HVDC Networks (A. Agbemuko)
- IRP3.2 – A new modelling approach for stabilisation of smart grids (F. Koeth)
- IRP3.3 – A distributed wind farm control strategy for enhancing primary frequency support (S. Siniscalchi Minna)

WP4. Monitoring tools and secure operation of smart grids

- IRP4.1 – Day-ahead Scheduling of a Local Energy Community: An ADMM Approach (C. Orozco)
- IRP4.2 – A fault detection and localization method for LV distribution grids & A review of fault diagnosis techniques in fuel cells (N. Sapountzoglou)
- IRP 4.3 - Efficient Convex Optimization for Optimal PMU Placement in Large Distribution Grids (M. Picallo)
- IRP4.4 – A multi-period Optimal Power Flow scheme for Low Voltage Distribution Networks & Operation algorithms for Smart- Charging within different business models (K. Kotsalos)


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3.1 Complementary skills training

From Idea to Business: 5 Stages of the Innovation Process

By Prof. Karine Samuel (INP Grenoble)

This lecture was aimed as an introduction for the ESRs to innovation management by having a look into the role of the innovation in the modern economy. Innovation is a crucial process as it embeds technology in societal changes. In the same time, 70% of the inbuilt expenses in R&D lead to commercial failures. Innovation is, therefore, a key to produce value by delivering new products. Different typologies of innovation were presented and discussed: incremental innovation vs. radical innovation, Techno push approach vs. Market pull approach, invention vs. innovation. A methodology was finally presented to create an efficient business model and make the link between the users' needs and the delivery of new products.

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3.2 Scientific training

- **Seminar I: Smart grids, challenges and perspectives**

By Prof. Nouredine Hadj-Said

The first lecture done by Prof. Nouredine Hadj-Said aimed at presenting some challenges and technical concerns linked to the insertion of dispersed generation into the electrical grid (and mainly the distribution grids). After a reminder concerning the main aspects of the control of electrical grids, the lecture was dedicated to the technological, organizational and economic impacts of the insertion of dispersed energy sources and electrical vehicles into the distribution grid.


- **Seminar II: Considering socio-energy assemblage and collective self-consumption in order to design/manage multi-actor energy systems**

By Gilles Debizet

This second lecture aimed at presenting some cross disciplinary works on energy, buildings and districts. After a presentation of the local project EcoSesa, the lecture focused on heat storage to increase efficiency, building management and the impact of occupants' behaviours, the possible types of governance of cities' energy system.

- **Visit to the French National High Magnetic Field laboratory**

The visit of the French National High Magnetic Field laboratory was a unique opportunity for the ESRs to discover one of the four facilities that produce high magnetic fields in the world. A particular focus was done on the production and use of magnetic fields (technology of coils, power plant to produce very high DC current, cryogeny for experiments, among others); which provide them a completely new field where energy, efficiency and control are of extreme relevance.

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3.3 INCITE ESR presentations

Self-Sufficient Microgrids for Decentralized Economic Dispatch of Distribution Power Networks

ESR: Wicak Ananduta

Advisor: Carlos Ocampo-Martinez

Abstract—A non-centralized economic dispatch scheme of power networks with distributed generation units is proposed using the concept of interconnected microgrids. The scheme consists of a periodical repartitioning mechanism to maintain self-sufficiency of each microgrid and a decentralized economic dispatch strategy based on model predictive control.

I. SYSTEM OF INTERCONNECTED MICROGRIDS

With the increasing penetration of distributed generation and storage units in distribution networks, modeling such a network as a system of interconnected microgrids becomes more appealing for at least the following reasons. The network might require a non-centralized control scheme due to the high computational burden, which cannot be handled by a centralized control scheme. The microgrid concept constitutes an independent operation within a microgrid, thus when some parts of the network fail, the whole network does not fail. Instead, the failures are localized.

A microgrid is regarded as a single controllable entity that consists of loads, generation units, and possibly storage units. Furthermore, a microgrid can operate in the grid-connected mode, i.e., a connection to the main grid is available, and in the island mode, i.e., it operates independently and is disconnected with the main grid [1]. In the first mode, there is an interaction between the microgrid and the neighbor microgrids or the main grid, whereas, in the second mode, such interactions do not exist.

Therefore, a non-centralized control scheme applied to a system of interconnected microgrids must properly take into account the couplings among microgrids, particularly for the grid-connected operation. This fact usually leads to a distributed control strategy where communication among the controllers is required. On the other hand, the island mode operation requires a microgrid to be able to meet its load independently. In this regards, a careful microgrid construction is required such that the microgrids in the network can operate in this mode.

II. SELF-SUFFICIENT PARTITIONING APPROACH

As reported in [2], our current work deals with the design of a non-centralized control scheme for the economic dispatch of power networks under the framework of interconnected microgrids and model predictive control (MPC). In this regard, the MPC-based economic dispatch problem of the network is formulated as a multi-agent optimization problem, where the microgrids are considered as the agents. Furthermore, two main objectives that we consider in the

controller design are to obtain self-sufficient microgrid operation, i.e., each microgrid is able to sufficiently comply with its load without exchanging power among each other, and to reduce the communication intensity among the microgrids, which is typically high when a distributed optimization algorithm is applied. As mentioned earlier, the first objective implies resiliency with respect to failures.

Additionally, it is worth mentioning that in the construction phase, an optimal microgrid construction problem [3], [4] can be solved in order to partition the power network into a group of microgrids, each of which is self-sufficient. However, with the high uncertainty of energy production from non-dispatchable generation units, such as those that are based on solar power or wind, the performance of the system of microgrids might deteriorate. Moreover, self-sufficiency of the microgrid might also be compromised.

In order to meet the objectives and to cope with the aforementioned issue, we propose a periodical repartitioning method for the economic dispatch of interconnected-microgrid systems. The method is graph-based, is performed in a distributed manner, and belongs to the class of local improvement approaches. When designing the method, we propose two objective functions, which translate into self-sufficient and efficient operations. The network is partitioned periodically since a periodical pattern of uncertain power generation as well as that of loads are observed. Furthermore, we also show analytically that by performing the proposed repartitioning method, the performance of each microgrid, in terms of self-sufficiency and efficiency, is maintained.

As the economic dispatch strategy, we formulate a local economic dispatch that can be solved by the controller of each microgrid. Therefore, information exchange among microgrids is not necessary for this scheme. As previously stated, the interaction between neighboring microgrids must be taken into account in the economic dispatch problem. However, when the microgrids are self-sufficient, such an interaction can be decoupled. As a result, the proposed approach requires less intensive communication at the expense of a suboptimal performance. Furthermore, the objective of having self-sufficient microgrids is taken care by the repartitioning mechanism.

III. CONCLUSION

With the combination of the proposed partitioning method and decentralized economic dispatch scheme, the goal of having self-sufficient and efficient interconnected microgrids can be achieved. As an ongoing work, we are extending the

partitioning method by including an event-triggered mechanism, which will replace the periodical scheme. Furthermore, we also consider combining the decentralized approach with a distributed method in order to deal with the issue when some microgrids are not self-sufficient.

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Real-time Market-based Control of Distributed Energy Resources with Uncertainty

ESR 1.2: Hazem A. Abdelghany, TU Delft

I. INTRODUCTION

Increased penetration of distributed energy resources (DERs) and integration of intermittent renewable energy sources is an ongoing trend in power systems. Some consequences of such a trend are congestion, low load factor, instability, or system in-operability at the distribution level. Such a problem requires either a great deal of investment in grid reinforcement, or efficient use of flexibility from DERs through coordination. Coordination among small, numerous, heterogeneous DERs owned by self-interested agents under uncertainty is a complex task.

In such a setting, real-time market-based control (RTMBC) is an interesting coordination approach due to features such as scalability, openness to heterogeneity, privacy preservation and simplicity. However, RTMBC generally leads to poor performance due to mutually conflicting decisions that arise from decentralization and the self-interested behaviour of agents. For example, the effect of such behaviour is shown to lead to exhaustion of flexibility in the system. The behaviour of agents submitting similar bids (i.e. bulk switching), or clustering at lower price periods can be described as “conflict games”, where the optimal decisions from the agents’ perspective conflict and lead to sub-optimal outcomes both at the agent level and system level.

II. METHODOLOGY

In this work, we propose a RTMBC approach for coordination among a set of uninterruptible time-shiftable (i.e. deferrable) loads taking into account uncertainty. Our approach relies on probabilistic forecasts to achieve near optimal coordination in terms of overall generation cost while satisfying agent level constraints (i.e. deadlines, uninterruptibility). While our approach assumes a central entity (planner) willing to achieve optimal coordination at a system level, we assume that the planner does not have access to private information of agents in the system. Moreover, the proposed approach maintains the feature of scalability, privacy preservation and openness.

In our proposed approach, the central planner makes use of probabilistic forecasts, aggregate models and be-

haviour patterns to estimate the prices corresponding to optimal system behaviour (i.e. probabilistic reference prices). These are used by agents in the process of bid formulation. Agents use a Markov decision process based optimal bidding strategy that aims at minimizing the expected cost while taking into account uncertainty and agent level constraints. Bids are submitted and the market is cleared by the auctioneer. An additional tie-breaking algorithm is required for a special case which we demonstrate.

To validate our approach, we describe the properties of a reference solution (i.e. the optimal coordination) and show analytically that this corresponds to the outcome of a Nash Equilibrium. We show analytically that our proposed approach solves the problem of mutually conflicting decisions, and we show by simulation that it leads to near-optimal behaviour over multiple time-steps despite the fact that the algorithm is run in real-time (i.e. separately for each time-step).

III. RESULTS

We simulate various case studies to show the effect of forecast errors and uncertainty on the performance of our proposed control approach. Finally, we summarize the contributions of this work as,

- 1) We show that, in settings similar to ours, the optimal coordination corresponds to the outcome of a Nash Equilibrium.
- 2) We propose a RTMBC approach for optimal coordination among uninterruptible deferrable loads.
- 3) We develop an optimal bidding strategy for deferrable load agents given our RTMBC approach.
- 4) We show that our approach achieves optimal coordination over multiple time-steps considering uncertainty, while maintaining the features of RTMBC.



Coordinating Energy Flexibility in the Electricity Distribution Grid

Shantanu T. Chakraborty, Remco Verzijlbergh, Zofia Lukszo

Abstract— The high integration of renewables into the distribution grid leads to issues of over-voltages, price volatility and increased demand ramps. To address these issues, system operators require the flexibility provided by demand-side flexible resources such as Energy Storage Systems or Electric Vehicles. These resources are able to meet system operators demands at varying time-scales ranging from seconds to hours. Within this work, we explore the energy flexibility services that can be provided from the aggregator to the DSO for the optimal management of distribution grids. Consumers at the distribution grid can also benefit from the interactions between the DSO and aggregator, by utilizing demand-side flexibility services for hedging against rapid price fluctuations. Through this work we generate insights on how the issues of voltage regulation, line losses and price volatility can be addressed through the coordination of energy flexibility between the DSO, aggregator and consumers in a future electricity grid that has a high integration of RES.

I. INTRODUCTION

The large scale integration of renewables such as solar and wind enables the pursuit of sustainability goals. However, their intermittent nature leads to a high level of variability and uncertainty in the management of the distribution grid. Price volatility [1], over-voltages and increased demand ramps [2] are a few of the issues that arise due to this variability. To address the issues emerging from the large-scale integration of RES, increasing demand-side flexibility at the distribution grid is viewed as a promising solution. Through electricity markets and bilateral contracts, that are able to aggregate flexibility provision from small-scale residential and commercial consumers, and can provide these services to system operators such as Transmission System Operator (TSO) and Distribution System Operator (DSO).

Hence, the crux of this research is to investigate the coordination of energy flexibility between DSO, aggregator and consumers in a renewable dominant electricity market. The rest of the abstract is organized as follows; Section II provides a literature review and identified research gap, Section III presents the research proposal and planned methods.

II. COORDINATING FLEXIBILITY: STATE-OF-THE-ART

From literature, previous works on coordinating energy flexibility at the distribution grid have mostly considered either the DSO perspective only or only that of the market-driven aggregator [3]. In our research, we focus on the two perspectives simultaneously. There are several knowledge gaps identified in literature regarding coordination of energy

flexibility which will be addressed in the course of this research.

Firstly, it is observed from previous works that the aggregators directs its services mostly to the Transmission System Operator, while disregarding the Distribution System Operator. In a future institutional arrangement where dynamic pricing is implemented in distribution grid markets the coordination between DSO and aggregator for flexibility management could provide hedging against price volatility an area that has received limited attention [4].

Secondly, there is limited knowledge available regarding institutional arrangements that facilitate the coordination between DSO, aggregators, and consumers, and their impacts on the distribution grid operation. Market mechanisms for local flexibility markets [5] and grid capacities [6] have been theorized, but they lack a mathematical formalism. Without a formalism it is challenging to perform a quantitative assessment of the coordination mechanism in terms of voltage profiles, grid congestions and line losses.

Finally, demand-side flexibility sources such as Electric Vehicles are capable of providing voltage regulation services [7] at time-scales of within a few seconds to minutes. This ancillary service from EVs can be aggregated and provided to the DSO, who generally plans the operation of power electronic interfaces that it controls at the interval of an hour. Hence, the DSO could benefit from the intra-hour flexibility services for management of the grid. However, research pertaining to EVs in distribution grids have mostly been focused on determining their optimal charging strategies [8] and doing so at scale. Hence, from the literature review conducted, it can be claimed that there is limited research available on the usage of EVs in distribution grids for addressing issues of over-voltages and demand ramps, while minimizing line losses and power curtailment from PV generation.

Hence, we would like to summarize our research with the main research question, “*What coordination strategies are required between DSO and aggregators in a future electricity distribution grid with high RES penetration to address issues of price volatility, voltage regulation, congestion management and accounting for line losses?*”

III. RESEARCH PROPOSAL AND PLANNED METHODS

A. Using Flexibility to Hedge Electricity Price Volatility

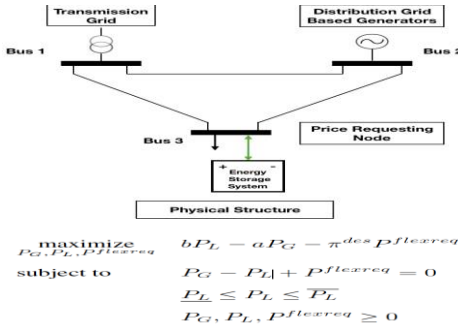
To address our main research question, we will break down the problem formulation into multiple steps. The first step, is to determine a possible strategy for coordinating flexibility

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between DSO, aggregator and consumers to hedge against electricity price volatility while accounting for energy costs and grid constraints [9].

For doing so, we constrain marginal prices which are dual variables associated with supply-demand matching. Marginal prices in recent times have become highly volatile due to the large-scale integration of RES and this volatility is undesirable from a consumer perspective. Motivated by this problem, our research conducted in [10] constrains dual variable in an optimal power flow (OPF) formulation to determine the amount of flexibility required to limit the increase of LMP. In our research, we propose an organizational structure for flexibility management, in which an end-customer can specify its maximum willingness to pay for electricity and through the coordination between the DSO and aggregator the flexibility required for satisfying the price constraints can be provisioned. A pictorial view of the problem setup is as follows:

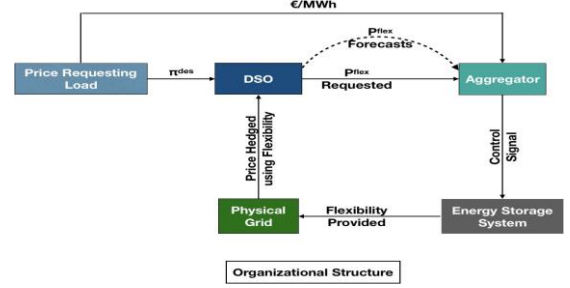


In the above equation, P_G and P_L represent the magnitude of power generation and load consumption. $p^{flexreq}$ corresponds to the magnitude of flexibility required to ensure that the LMP is less than or equal to the maximum willingness to pay for electricity of the end-customer which is specified value as “ π^{des} ”. This demand-side flexibility in [11] is assumed to be provided from an Energy Storage System and we investigate the additional economical benefit that availing information forecasts in the operation of the ESS can bring to consumers. The main novelty of this approach is that it investigates the possibility of using demand-flexibility provided by an ESS operated under Model Predictive Control to hedge electricity price volatility due to increased integration of RES. Through this formulation we are able to consider the physical characteristics of the storage devices, the impact of inter-temporal constraints on the availability of flexibility such that it can successfully account for multiple time period, and insight is drawn regarding the sizing of the ESS and its scheduling. Future work will focus on different contractual arrangements for flexibility management, including line losses in the computation of the LMP, accounting for uncertainty in forecasting and analyze the investment and associated risk for an aggregator to own an ESS to provide the hedging functionality.

B. Co-Simulation of Electric Vehicles

In order to quantify the impact of the coordination between the DSO and aggregator for voltage regulation in the distribution grid, we will use a co-simulation based approach. The aggregator in this case has control over the flexibility services which can be provided by an EV. Semi-Urban distribution grids which are able to account for both rural and

urban areas are considered in this case. These grids are medium voltage grids, and hence voltage regulation services can be provided through both active as well as reactive power control.



Our motivation for using a co-simulation based approach stems from the fact that essentially there are two time-scales that interact in this simulation, one in which the DSO plans and control the hourly operation of its power electronic interfaces and the seconds to minute power dispatch services that can be provided from EVs. The co-simulation environment will be implemented using Simulink and then executed through real-time digital simulators. Through this simulation setup we will investigate how EVs can help account for issues of over-voltages and increased demand ramps. Accompanying the Simulink implementation, we will use real-time optimization algorithm [12] which will be able to regulate EV power outputs to optimal power setpoints. The main output of this research will be smart charging and optimal active and reactive power control provided by EVs which can be implemented in both centralized and fully distributed schemes while accounting for inter-temporal constraints of the EVs state of charge.

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A 1-dimensional continuous and smooth model for thermally stratified storage tanks including mixing and buoyancy effects

Jesus Lago, Fjo De Ridder, Bart De Schutter *

I. INTRODUCTION

In the last decade, as the integration of renewable energy sources into the electrical grid has steadily increased, energy storage has emerged as one of the key components in this paradigm change. Considering that 26.3 % of the electricity consumption in EU households is destined to water and space heating, and that water and space heating accounts for 79.2 % of the total energy consumption in the same households, *thermal energy storage (TES)* systems might help fulfill some of the energy storage requirements.

One of the most important TES systems are stratified fluid tanks [1], which store energy by keeping fluid layers stratified at different temperatures. Exploiting the fact that fluid density decreases as temperature increases, they are able to stratify fluid layers where the warmest layers are displaced to the top of the tank and the coldest layers to the bottom. The scientific literature regarding modeling stratified thermal storage vessels is divided in three categories: 1D, 2D, and 3D models. While 2D and 3D models are more accurate, their computational complexity makes them unsuitable for process optimization or long-term simulation of the storage tank [1].

A. Motivation and Contribution

When considering 1D models from the literature, none of them can physically model the buoyancy effect using a smooth and continuous model. Instead, they include a non-smooth post-processing step after each simulation step that approximates the mixing of layers due to buoyancy effects. Because of this non-smoothness, these 1D models require the use of heuristic optimization methods or of finite differences and cannot be used with derivative-based algorithms that use automatic differentiation. As both heuristic methods and derivative-based optimization via finite differences require large computation times, they are not feasible methods for several applications, e.g. optimal control. In addition, as heuristic methods cannot guarantee that the obtained solution is a local minimum, the quality of the obtained solution is worse.

To tackle the problem of the models from the literature, we propose a 1D continuous and smooth dynamical model that can accurately model the buoyancy effects. To show the benefits of using the smooth model in optimization problems, we compare the smooth model against the non-smooth models in an optimization setup and show that,

the smooth model does not only obtain the best optimal solutions, but its computation costs are 100 times cheaper.

II. MATHEMATICAL MODEL

The standard 1D model for a heat storage vessel divides the tank in M segments/layers. Then, it models each layer with a *partial differential equation (PDE)* based on the heat transfer equation. In its most general case, each layer i is characterized by a state T_i representing the temperature of the layer; this state can be controlled by the input flow \dot{m}_i and its temperature T_i^{in} or by the external input heat \dot{Q}_i (heat sink or heat source) in the layer:

$$\frac{\partial T_i}{\partial t} = \alpha \frac{\partial^2 T_i}{\partial z^2} + \frac{P_i k_i}{\rho c_p A_i} (T_\infty - T_i) + \frac{\dot{Q}_i}{\rho c_p A_i \Delta z_i} + \frac{\dot{m}_i (T_i^{\text{in}} - T_i)}{\rho A_i \Delta z_i}, \quad (1)$$

where α , ρ , and c_p respectively represent the fluid diffusivity, density, and specific heat; A_i , P_i , and Δz_i the cross-sectional area, perimeter, and thickness of layer i ; k_i the thermal conductance of the isolation wall of layer i ; and T_∞ the ambient temperature.

A. Modeling buoyancy effects

The model above does not considering buoyancy, i.e. mixing of layers when a layer on top becomes colder than a layer on the bottom. As mentioned, models in the literature integrate the PDE, simulate it, and perform an post-processing step. In our approach, we propose a smooth formulation of the buoyancy that can be directly integrated in the PDE. While the details and derivation of the proposed models is out of the scope of this abstract, the dynamical model for the temperature in layer i and at time $t + 1$ is as follows:

$$T_{t+1,i} = F_i(\mathbf{T}_t, \dot{Q}'_{t,i}, \dot{m}_{t,i}, \Delta t) + \theta_{i,i-1} \frac{1}{\mu} \log(e^0 + e^{\mu(T_{t,i-1} - T_{t,i})}) - \theta_{i,i+1} \frac{1}{\mu} \log(e^0 + e^{\mu(T_{t,i} - T_{t,i+1})}), \quad (2)$$

$$(3)$$

with:

$$\dot{Q}'_{t,i} = \sum_{l=0}^i \dot{Q}_{t,l} \cdot \frac{A_i \Delta z_i S(T_{t,l} - T_{t,i})}{\sum_{j=l}^M A_j \Delta z_j S(T_{t,l} - T_{t,j})}. \quad (4)$$

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For a detailed explanation of the different notation, variables, and derivation, we refer to the original paper [2].

III. MODEL COMPARISON

To evaluate the proposed model, we compare it against the non-smooth models from the literature in the same optimization setup: an optimal control problem (OCP) where a stratified thermal storage vessel needs to satisfy a given heat demand over some time horizon while minimizing the cost of charging the tank. The goal of the controller is to find the optimal charging strategy that minimizes the cost while satisfying the heat demand.

As the non-smooth models are limited to heuristic and finite-difference methods, we consider 2 heuristics methods and 2 finite differences methods for integrating the non-smooth model in the optimization setup: particle swarm optimization (PSO), Markov chain Monte Carlo (MCMC), second-order Newton via finite differences, and first-order Newton via finite differences. For the proposed model, we use a second-order Newton via automatic differentiation.

The details of the optimization problem are out of the scope of this abstract. For full details, we refer to [2].

A. Results

The comparison results of solving the OCP via the different methods are listed in Tables I and II. Table I compares the quality of the optimal solution as the cost of buying heat and uses a baseline that represents the cost of buying heat without using the heat buffer, i.e. buying the heat demand at the actual market price. Table II compares the computation time required for each of the methods

TABLE I: Comparison of the OCP optimal solution/cost (in EUR) for different time horizons using different optimization methods. The first row represents the cost of buying directly the heat without the heat buffer. Cells with an x represent cases where the method was unable to find a feasible solution.

Optimization Method	OCP Horizon [h]			
	24	168	720	1440
No Buffer	10.1	73.3	397.0	1761.1
Smooth model	0	16.2	215.9	1108.9
Finite-diff.: BFGS	0	16.2	235.1	x
MCMC	0	19.6	343.8	x
PSO	0	38.1	2570.4	x
Finite-diff.: 2 nd order	0	x	x	x

TABLE II: Comparison of the computation time (in minutes) required to solve the OCP for different time horizons and using different optimization methods. Cells with an x represent cases where the method was unable to find a feasible solution..

Optimization Method	OCP Horizon [h]			
	24	168	720	1440
Smooth-model	0.1	0.6	5.1	34.9
Finite-diff.: BFGS	0.3	47.6	708.3	x
MCMC	26.4	137.6	571.0	x
P-Swarm	4.2	194.3	1203.6	x
Finite-diff.: 2 nd order	816.6	x	x	x

After analyzing the obtained results, the superiority of using a smooth model with a Newton-based optimization

method and automatic differentiation becomes clear. Particularly, the following observations can be made:

- The OCP solved with the smooth model is able to obtain the best solution for all possible horizons.
- Not only is the proposed approach the one with the best optimal solutions, but also the only one that outperforms the baseline across all horizons.
- The majority of the alternative methods perform poorly.
- In terms of computation cost, the method using the smooth model is by far the best: the method using the smooth model finds the optimal solution between 10 and 100 times faster.
- As the number of optimization variables increases, all the methods using the non-smooth model struggle to find optimal solutions: in the case of a 2-months horizon all of these methods fail.

B. Discussion

Based on the obtained results, it is clear that smooth models are very important if heat storage vessels are used in optimization contexts, e.g. if heat storage vessels are to be controlled optimally. In particular, when solving the OCP that provides the best charging strategy for the vessel, the smooth model provides the best yet fastest optimal solutions by using derivative-based optimization with automatic differentiation.

This gain becomes more significant for optimization problems with a large number of variables; in those situations, both heuristic methods and derivative-based optimization methods using finite differences struggle to solve the optimization problem and they use significant amounts of computational resources.

In addition to the quality of the solution and the cheap computational cost, another clear advantage of the smooth model is that it provides the only feasible alternative to be run in real time, e.g. in a model predictive control setup. In particular, a real-time control application would require computation times below the time step $\Delta t = 1$ h, and as can be seen from Table II, only the proposed model satisfies that.

IV. CONCLUSIONS

In this research, a new 1D model for stratified heat storage vessels has been proposed. The novelty of the model is that it provides a smooth and continuous 1D representation of the system dynamics while including buoyancy effects. This smoothness property is very critical when using the model in optimization problems. The benefits of using the smooth model in optimization problems were demonstrated in a case study where it was shown that the smooth model did not only obtain the best optimal solutions, but it also required computation costs that were 100 times cheaper.

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Co-simulation of Model Predictive Control (MPC) algorithms for the flexibility of heat pump heating and cooling loads

E.S.R.2.1. Thibault Péan

Supervisors: Jaume Salom (IREC) and Ramon Costa-Castelló (UPC)

I. INTRODUCTION

Model predictive control (MPC) strategies have shown consequent potential for improving the energy flexibility of building thermal loads, especially when supplied by heat pump systems. Applying these techniques to both heating and cooling in the same building has seldom been studied in the literature. Furthermore, a large majority of the published research on this topic only resorted to Economic MPC, i.e. a cost minimization strategy [1]. In the present work, different objective functions of an MPC controller have been tested, both in heating and cooling modes: minimization of delivered thermal energy, of the operational costs or of the marginal CO₂ emissions related to the electricity use of the heat pump. These strategies have been applied on a residential Spanish building through a co-simulation platform created for this purpose.

II. METHODS

A. Co-simulation framework

For testing the MPC strategies, a co-simulation framework was developed, as shown in Figure 1. The detailed dynamic building simulation is run in TRNSYS with a time step of 3 minutes to provide sufficient accuracy; it works as a ‘virtual plant’ for testing the control algorithms. Since TRNSYS does not contain suitable tools for optimization, the MPC controller is coded externally in MATLAB. Both software are connected through the Type155 of TRNSYS.

B. Model Predictive Controller

The MPC algorithm is presented in Problem 1. The state space model corresponds to a reduced order model of the building envelope and the water tank (resistance-capacity scheme, similar to electrical circuits). The building model was identified through grey-box modelling techniques, using data generated by the detailed TRNSYS model [2]. The states $x = [T_{int} \ T_w \ T_{TES}]^T$ correspond to the indoor temperature, an intermediate temperature at the inside surface of the walls, and the average water tank temperature. The controlled variables decided by the MPC are the thermal power $u = [Q_s \ Q_{TES}]^T$ respectively delivered to the indoor space and the water tank (constrained in the range $[Q; \bar{Q}]$ when ON), and the binary variables δ_s and δ_{TES} which control the operation modes of the heat pump. The vector $e = [T_{amb} \ I_H \ Q_{occ} \ Q_{DHW}]^T$ represents exogenous disturbances which are forecasted: ambient temperature, solar irradiation, heat gains from occupants and hot water tapping. The indoor temperature T_{int} must stay within comfort boundaries $[T_{int}^{\underline{}}; T_{int}^{\overline{}}]$, but these hard constraints are relaxed with the slack variable ε .

Regarding the cost function, it actually contains multi-objectives: J_ε which penalizes discomfort (excursions outside the defined comfort boundaries calculated with ε), a smoothing term $J_{\Delta u}$ which penalizes too many abrupt consecutive changes of the control actions, and an actual objective J_{obj} . The three objectives are balanced with the weighting coefficients α_i which were adjusted using Pareto fronts.

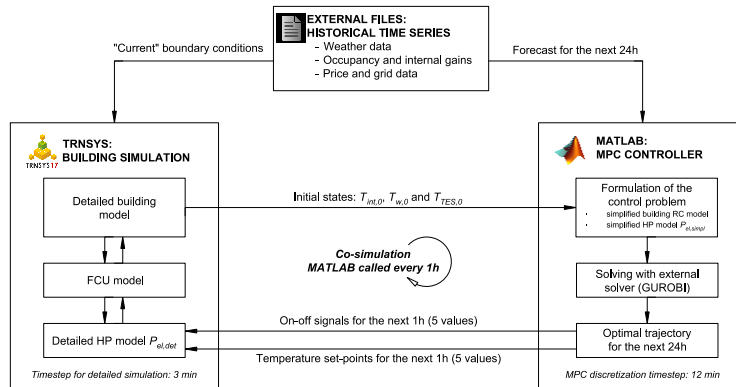


Figure 1. Co-simulation scheme.

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As previously mentioned, three different objective have been tested for J_{obj} : minimizing the delivered thermal energy, the operational costs of the heat pump or the associated marginal CO₂ emissions. The prediction horizon is chosen as 24 hours, with a discretization time step of 12 minutes (thus $N = 120$).

Problem 1 – Model Predictive Controller	
Objective:	$\min_{u, \delta} [\alpha_{\varepsilon} J_{\varepsilon} + \alpha_{\Delta u} J_{\Delta u} + (1 - \alpha_{\varepsilon} - \alpha_{\Delta u}) J_{obj}]$
Subject to:	$\forall k \in \llbracket 1, N \rrbracket$
Model:	$\begin{cases} \mathbf{x}(k+1) = \mathbf{A} \cdot \mathbf{x}(k) + \mathbf{B}_u \cdot \mathbf{u}(k) + \mathbf{B}_e \cdot \mathbf{e}(k) \\ \mathbf{y}(k+1) = \mathbf{C} \cdot \mathbf{x}(k) \end{cases}$
Constraints on the inputs:	$\begin{cases} \delta_s(k) \cdot \underline{Q_s} \leq Q_s(k) \leq \delta_s(k) \cdot \overline{Q_s} \\ \delta_{TES}(k) \cdot \underline{Q_{TES}} \leq Q_{TES}(k) \leq \delta_{TES}(k) \cdot \overline{Q_{TES}} \\ \delta_s(k) + \delta_{TES}(k) \leq 1 \end{cases}$
Constraints on the outputs:	$\begin{cases} \underline{T_{int}}(k) - \varepsilon(k) \leq T_{int}(k) \quad (\text{heating}) \\ T_{int}(k) \leq \overline{T_{int}}(k) + \varepsilon(k) \quad (\text{cooling}) \\ T_{TES} - \varepsilon(k) \leq T_{TES}(k) \quad (\varepsilon \geq 0) \end{cases}$

III. RESULTS

The co-simulation was performed with the different MPC configurations over 3 selected days in winter and summer seasons, with the Spanish residential flat as study case and data retrieved for these days (weather and penalty signals). The results are summarized in Table 1, with comparison towards a standard case (control by thermostat).

It can be observed that in general, the MPC configurations achieve their declared objectives: MPC Cost reduces the costs by 13 to 29%, and MPC CO₂ reduces the marginal emissions by 19 to 29%. This is achieved through load-shifting towards the periods of lower price/emissions, and without jeopardizing thermal comfort. It should be noted that the input penalty signals (price of electricity and marginal emissions of the grid) have an adverse behavior in general: the price peaks correspond to emissions valleys and vice versa. In heating mode, this situation favors more the reduction of the costs (load at night with low prices), while in summer it favors more the reduction of the emissions (load in the afternoon with low emissions due to solar energy).

The development and computational burden of the MPC have also been discussed. These two obstacles explain why such controllers are not widely implemented yet, despite their repeatedly proven performance. Developing the MPC required to fit simplified models of the building and the heat pump, which requires important resources. Many parameters must also be fine-tuned (the weighing coefficients α_i in particular). Furthermore, the introduction of binary variables in Problem 1 changes the nature of the optimal control problem and thus Mixed Integer Linear Programming (MILP) must be used to numerically solve it, which consequently slows down the MPC computation [3]. Since the considered systems have a high inertia, this is not a major obstacle, but the observed calculation times were consequent.

CONCLUSIONS

The present work recalls the development and test of MPC controllers with different objectives, able to function both in heating and cooling modes. The results are promising, with important costs or emissions savings while maintaining comfort conditions, and proves the benefits of predictive controllers for enhancing the energy flexibility of buildings equipped with heat pumps. The drawbacks of MPC development and computation have also been discussed. Further investigations include experimental studies in laboratory setup, to take into account the dynamics of the heat pump which were neglected in the present work (delay, ramping, actual input signals to control a real heat pump system etc.).

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TABLE 1. SUMMARIZED RESULTS OF THE DIFFERENT MPC CONFIGURATIONS BOTH IN HEATING AND COOLING SEASONS (3 DAYS CASES).

MPC objective		MPC ThEnergy		MPC Cost		MPC CO ₂	
Heating (H)/Cooling (C)		H	C	H	C	H	C
Cost variation	[€]	-0.91	+0.36	-0.92	-0.36	-0.98	-0.31
	[%]	-27.9%	+12.9%	-28.1%	-13.0%	-29.9%	-11.0%
Electricity use variation	[kWh]	-8.33	+2.03	-7.27	+1.24	-9.67	-5.15
	[%]	-25.5%	+6.5%	-22.3%	+4.0%	-29.6%	-16.6%
Marginal CO ₂ emissions variation	[kgCO ₂]	-2.31	+0.42	-2.03	+0.37	-2.64	-1.39
	[%]	-25.7%	+5.7%	-22.6%	+5.0%	-29.4%	-19.1%

Control and management of energy storage elements in micro-grids

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Abstract—Energy storage systems are becoming an integral part of the present day grids in aiding the penetration of renewable energy sources. An effective control strategy for storage systems is essential in the effective integration of such systems. An overview of the control architecture and a low level controller for energy storage systems is presented here.

I. INTRODUCTION

The paradigm shift of the electric power system from its reliance on fossil fuels as energy sources to renewable sources have been contributed by the increasing price of the fossil fuels, the various government policies, incentives and protocols for capping carbon emissions [1] [2] [3]. Therefore, modern electric network is seeing a major overhaul by shifting from the traditional centralised to distributed generation. The distributed generation through renewable energy sources (wind, solar) add varying, fluctuating power into the grid, independent of the demand, which can affect the grid stability if the supply demand balance is not met. They also reduce the inertia of the grid due to the absence of any rotational inertia making the grid more susceptible to instabilities during events of sudden load change. The increased drive to incorporate more renewable sources into the grid therefore demands integration of Energy Storage Systems (ESS) in the grid which ensures supply-demand balance, spinning reserves and improved grid inertia [5] [6].

This paper presents an overview of the work done so far in relation to the research work of ESR2.2 in the INCITE project. The objective is developing a control system that ensures stable and efficient integration of ESS in the electric grids. Some results in the primary and secondary control levels for integration of ESS in microgrids is presented here.

II. CONTROL ARCHITECTURE FOR STORAGE SYSTEMS

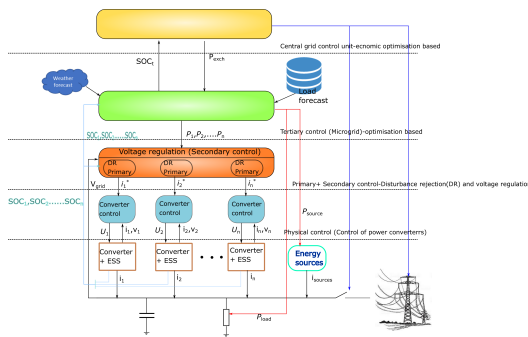


Fig. 1. Control architecture for the ESS

The Fig.1 shows control architecture for ESS considered by the ESR for the integration of ESS into grids. The

hierarchical control scheme has the system divided into three levels: physical control level, primary+secondary, tertiary and central grid control unit.

Physical control level: This level deals with control of power converters which are interfacing the ESS to grids. These converters are required to respond fast to ensure minimum variation in grid parameters. The fast flat response will be ideal to improve the power quality. The controllers at this level should be capable of such a response.

The primary level: This level is responsible for ensuring disturbance rejection in the microgrid. In an interconnected system like the microgrid sudden unaccounted load changes can cause variation in grid parameters. The primary level ensure that these variations are met and distributes it among the differnt ESS based on their characteristics. A frequency based splitting of the load will be done here.

The secondary level: It ensures that parameters (voltage, frequency etc) in the micro-grid are within the permissible range. The restoration to nominal values are achieved here.

The tertiary level The tertiary level forms supervisory level for the microgrid. This level ensures optimal power flow in the microgrid especially in islanded mode of operation. The optimal power flow problem decides the amount of power to be generated by the different sources so that some operational parameters are optimised. [7].

Central grid control unit This level supervises the operation of main grid . This level optimises main grid performance, decides which microgrid has to be connect to grid and energy exchange between different microgrids.

III. RESULTS

The initial work of the ESR focussed on developing low level controllers for power converters and voltage regulating controls for the microgrids. The ESR has then focussed on improving these controls and developing some tertiary level algorithms for the same.

A. (Low level control)

With regards to latter the focus was mostly on developing some formal stability proofs and robustness evaluation of the controls proposed in the earlier works. The reset PI+CI control was proposed in the earlier works as controller for converter systems. The control architecture is shown in Fig. 2. The reset control being a hybrid system the assessment of robustness and stability is not straightforward. The describing function (DF) analysis was considered for the same. Although it is an approximated analysis in control practice it gives an adequate characterization of both stability

margins and sensor noise effect, since the feedback loop has the necessary low-pass property.

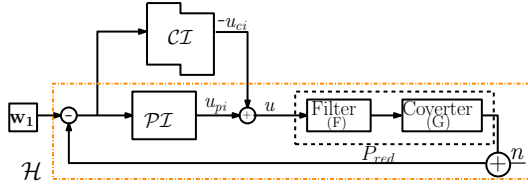


Fig. 2. Control architecture for the ESS

The DF of a PI+CI is given by

$$PI + CI(\omega) = k_p \frac{j(\omega\tau_i + \frac{4}{\pi}\rho_r) + 1}{j\omega\tau_i} \quad (1)$$

where $\tau_i = \frac{k_p}{k_i}$. The important characteristic of DF of the PI+CI controller is that the function does not depend on the amplitude of the input but solely on the frequency of input. This allows the use of frequency domain analysis tools in analysing the robustness of reset controllers. The Nyquist diagram is considered for the robustness analysis and Fig.3 shows the plots for open loop system with the DF of PI+CI (1) for different values of ρ_r . The Fig.4 shows the same but zoomed near the critical point of -1 for better understanding. It can be seen that with increasing value of ρ_r (higher reset percentage) the plots move further away from the critical point showing higher stability margins. The circle of radius 0.5 centered at the critical point has been drawn to imply the same. This ensures that there is always a gain margin of more than 2 and phase margin of 30 degrees, for all the cases. Therefore, the introduction of the reset does not destabilise the base system and ensures better stability margins.

B. Tertiary control

With regards to developing tertiary controls for microgrids, the ESR currently focuses on developing MPC based control strategies for tertiary level. The proposed control is aimed at optimising the system operation based on some pre-defined criteria while also taking into control the uncertainties that arise in the load and generation profiles. As a first step the ESR is working on a nominal model for the system with deterministic generation and load profiles. This will be extended to include stochastic nature. The initial model considered is given below for a microgrid with renewable generation from PV, loads, storage in the form of battery, supercapacitor and fuel cells.

Cost function

$$\sum_{k=0}^n p_{sc}^2 + 2 * p_{bat}^2 + 5 * p_{FC}^2 \quad (2)$$

where p_{sc}, p_{bat} , are the power supplied/absorbed by the by the supercapacitor, battery respectively while p_{FC} is the power from the fuel cell. This is a very basic cost function trying to penalize excessive drawing or absorbing from the individual storage and generating (fuel cell) units. The above

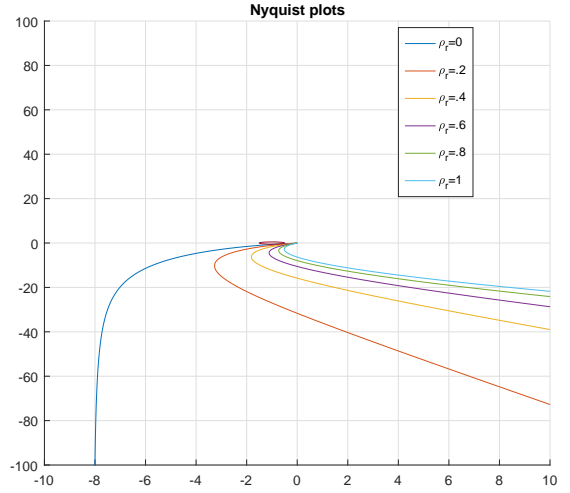


Fig. 3. Nyquist plot for the system using describing function of PI+CI controller for different values of ρ_r .

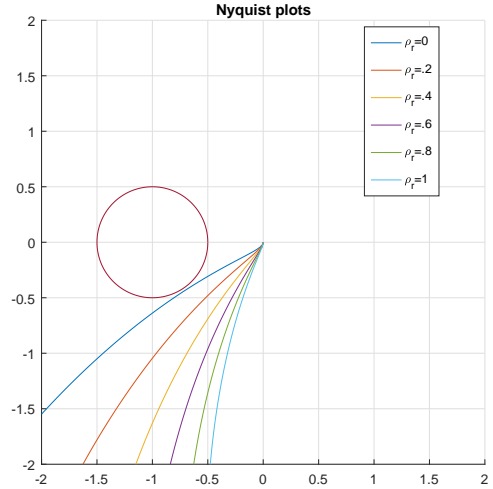


Fig. 4. Nyquist plots for the varying values of ρ_r zoomed around the critical point -1

cost function will solved in the MPC problem with the following constraints:

System model

$$\begin{aligned} SOC_{sc}(k+1) &= SOC_{sc}(k) \pm \frac{T_s p_{sc}}{C_{sc}} \\ SOC_{bat}(k+1) &= SOC_{bat}(k) \pm \frac{T_s p_{bat}}{C_{bat}} \\ SOH_{FC}(k+1) &= SOH_{FC}(k) + \frac{T_s p_{FC}}{C_{FC}} \end{aligned} \quad (3)$$

Power balance

$$p_{sc} + p_{bat} + p_{FC} + p_{ren} + p_{load} = 0 \quad (4)$$

where p_{ren} and p_{load} are the generation and power demanded at any instant

Bounds on state of charge

$$\begin{aligned} 0.2 &\leq SOC_{bat}(k) \leq 1 \\ 0.2 &\leq SOC_{sc}(k) \leq 1 \\ 0 &\leq SOH_{FC}(k) \leq 1 \end{aligned} \quad (5)$$

Bounds on power

$$\begin{aligned} p_{bat}^{min} &\leq p_{bat}(k) \leq p_{bat}^{max} \\ p_{sc}^{min} &\leq p_{sc}(k) \leq p_{sc}^{max} \\ 0 &\leq p_{fc}(k) \leq p_{fc}^{max} \end{aligned} \quad (6)$$

The simulations will be developed and tested for the same

IV. RESEARCH STATUS

The current work of the ESR carried out on two fronts. In the first the low level voltage regulation loop performance is improved with the aid of an observer based control. Along with voltage regulation low level loop will be provided with a current splitting strategy among the storages taking into account the properties of each storage system. This control loop is to work in coordination with tertiary scheme to ensure the grid stability in between the sampling instants of the tertiary controller. On the other front work is done on the tertiary level to develop more generic and close to real life models and testing them under the influence of stochastic nature of generation and load profiles.

V. ACKNOWLEDGMENTS

This work is done as part of project which has received funding from the European Unions Horizon 2020 research and innovation programme under the Marie Skłodowska Curie grant agreement No 675318 (INCITE).

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Analysis and Control of the Room Temperature in an Office Building

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I. INTRODUCTION

According to the European Union, buildings, both residential and commercial, account for around 40% of the total energy consumption [1], with heating systems representing more than half of this amount [2]. In building heating systems it is important not only to try to reduce the consumed energy, but also to reduce as much as possible the discomfort caused to occupants. In order to properly control the room temperature in a building, additional information, e.g. external temperature, solar irradiance, occupancy of the building, should be included. However, most of the currently implemented control strategies are simple rule-based ones that are not very efficient and do not include any of the aforementioned information. In this regard, Model Predictive Control (MPC) stands out as suitable control tool that can be applied efficiently to building heating systems, since it can naturally include constraints related to the heat producing devices and also to the comfort of the occupants [3]–[5]. Moreover, since in the MPC framework the control problem is turned into an optimization one, MPC allows to optimize a cost function defined in terms of economic costs and discomfort.

As said before, when it comes to control the room temperature in an office building, it is important to include data from disturbances, e.g. the external temperature. In the presence of disturbances, two different MPC strategies can be used, namely robust MPC and stochastic MPC [6]. While robust strategies guarantee that for every time instant the constraints are satisfied even in the presence of disturbances, stochastic MPC approaches consider relaxation of constraints and allow a possibility of constraint violation in the system. Which of the two strategies is more suitable for a certain system depends on the application. However, in building heating systems control, since there are no real critical constraints, the stochastic approach is generally preferred, also because a robust solution would be too conservative [3], [7]. Indeed, the main constraints are related to the comfort bounds, which can be safely violated for a limited amount of time without causing danger to people or to the equipment.

In our work, we focus on a stochastic MPC application to an office building in Brussels. Due to the fact that the model of the systems is nonlinear, as stressed in [7], we adopt a randomized approach, i.e. the so called Scenario-Based MPC (SBMPC). The main idea of this approach is to consider a several amount of disturbance realizations, called scenarios, and satisfy the constraint while minimizing the average cost for each of the scenarios. SBMPC is able to deal well with

both nonlinear systems and probability distributions obtained empirically, making it a very suitable tool for a building heating control problem. Before we implement a SBMPC controller, we need to verify which are the disturbances that influence the most the cost function, in order to focus our attention on them in the control part.

In this abstract we show the preliminary steps towards the implementation of a SBMPC controller, in cooperation with 3E, starting first from a data analysis point of view, including a sensitivity analysis of the disturbances and a scenario generation. The current implemented controller on the office building is a deterministic MPC, which makes only one forecast for each of the disturbances and assumes that the forecast is perfect.

II. DISTURBANCE ANALYSIS

The main disturbances that we consider are the solar irradiance, the external temperature, and the occupancy of the building. There is data available for the first two disturbances, but not for the third one. In this section, we analyze the influence of the disturbances on the cost of the optimal control problem in a single stage of the MPC controller. The analyzed office building is located in Brussels and its model is built through Modelica. The total cost is simply obtained as $J_t = J_e + \alpha J_d$, where J_e and J_d represent the energy and discomfort cost, respectively, and α is a weighting parameter. In order to make the disturbance scenarios more realistic, we compare the forecast profile available for certain days and the measurements available for those same days, selecting days in which the forecast is (almost) always larger/smaller than the real data. Moreover, only one disturbance is changed at a time, in order to clearly observe which is the effect of each disturbance.

The first analyzed disturbance is the ambient temperature. Through simulations, we analyze how the different costs increase when there is a change in the disturbances. One simulation is shown in Figure 1 for one day in winter, in which the measurements are almost always higher than the forecasts. As one could expect, a higher value of the external temperature makes the energy cost J_e decrease. The discomfort cost decreases as well, as long as the external temperature is not too close to the upper comfort temperature bound. We can see indeed that when the outside temperature is higher the cost J_e decreases, while the cost J_d is larger at the beginning but at the end it reaches the same value of the cost obtained with the forecast profile. The same simulation is carried out for the solar irradiance, but it is not shown here for brevity; the analysis, however, is similar.

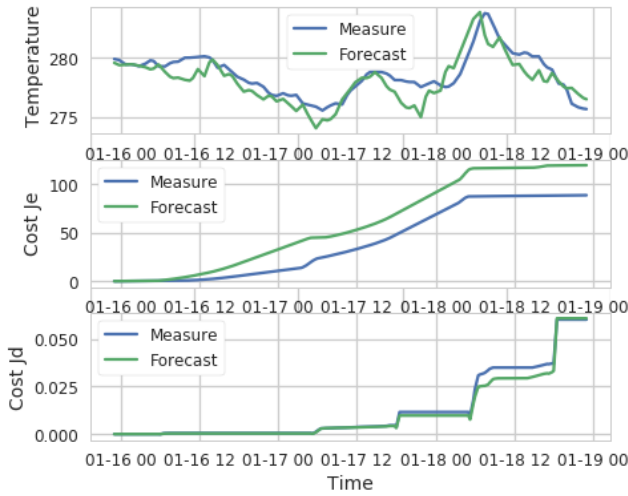


Fig. 1. Simulation with two different profiles of the external temperature.

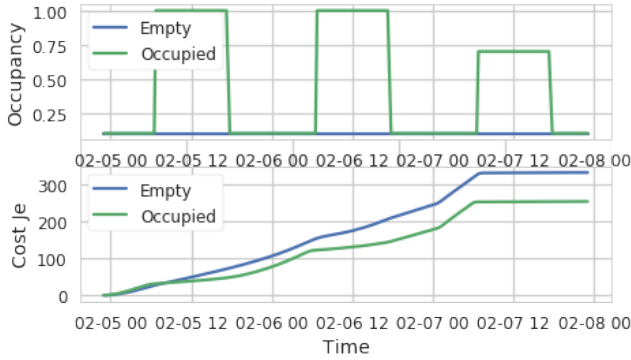


Fig. 2. Simulation with different occupancy profiles.

Lastly, we analyze the occupancy profile. Since we do not have measured data for the occupancy, we choose two different profiles, one in which the building is always empty and one in which the building is full during working hours and empty in the remaining part of the day. The profile and the cost J_e is shown in Figure 2. It can be observed that with a higher occupancy the energy cost J_e decreases. This can be explained by the fact that when more occupants are inside the building, its thermal inertia is higher, thus it can hold the internal temperature for a longer time. When instead the building is empty, the controller has to provide more heat to keep the room temperature within the comfort bounds.

III. SCENARIO GENERATION

One of the requirements of an SBMPC controller is to generate statistically meaningful scenarios related to the disturbances. Using the collected past data, we can generate scenarios adopting the method proposed in [8]. The algorithm relies on a point forecasting method, e.g. a neural network, and a probabilistic forecasting one, e.g. quantile regression. An example of generated scenarios with a horizon of 3 days is shown in Figure 3, where the real measured data is plotted in black color. It is possible to see how

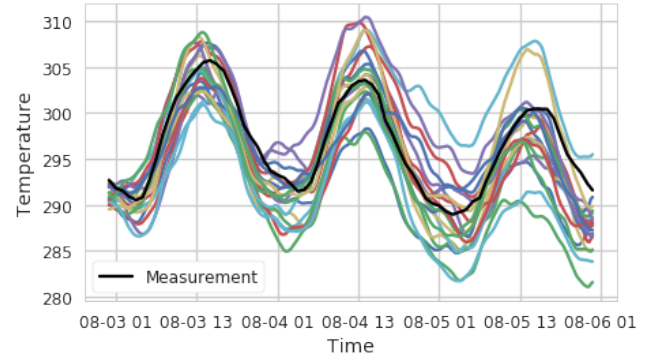


Fig. 3. Generated scenarios for the ambient temperature with a horizon of three days.

the scenarios are closer to each other at the beginning of the prediction horizon and farther at the end, due to the forecasting errors.

IV. CONCLUSIONS AND FUTURE WORK

We presented an analysis on the influence of different stochastic disturbances acting into a building heating system. Due to the stochasticity of the uncertainties, we will develop a stochastic MPC controller, which relies on the aforementioned scenario generation algorithm. The next steps are the implementation of the controller, having as starting point the analysis and the scenario generation method presented here.

ACKNOWLEDGMENTS

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An Integrated Approach to Understanding Interoperability Issues in VSC-HVDC Networks

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Abstract—An approach to study the impact of control systems and network in an interconnected system is presented in this paper. An integrated method is considered to model the entire network and the impact of feedback control on global responses. The methodology provides a high-level assessment of the impacts of independently tuned local control on global behaviour. Results show that although local subsystems are often optimally designed, the interconnection results in sub-optimal behaviour due to lack of information about the network and other active subsystems.

Index Terms—

I. INTRODUCTION

In the near future, high voltage multi-terminal DC (HV-MTDC) grids based on voltage source converters (VSCs) are expected to play a central role in the transmission of energy. Today, nearly all implementations of high voltage DC (HVDC) systems are based on point-to-point schemes supplied by the same manufacturer. Interconnection of these existing point-to-point links could potentially be the first step in expansion to MTDC grid [1].

However, interoperability issues are expected to arise due to the interconnection of independently designed controllers. That is, different controllers of different HVDC links may be designed with different objectives at the initial stage, such that interconnection with other links may result to conflicting behaviours. As network topology becomes complex, the influence of interactions between these controllers through the network would pose a significant threat to secure operation. From the system-level point of view, couplings in HVDC links are mainly dependent on electrical distances and complexity of controls (in each terminal) which is often designed by the same entity with explicit knowledge.

There is lack of literature on methods to understand these issues, particularly from a physical approach and system-level perspective. This is not unusual as these issues are only starting to emerge as manufacturers and system operators are collaborating on potential issues. The source of the challenge lies in power electronics being tightly controlled devices that

employ complex strategies that result to interaction when more than one device is interconnected [2], [3]. Motivated by these challenges, the academic and industrial communities have been applying several methods for studies involving integration of power electronic converters. One method gaining significant attention is the impedance-based modelling framework [4]–[7].

In this paper, we present a tractable methodology based on the impedance framework to understand the impact of independently tuned control systems and network on the global behaviour. It is demonstrated in the context of networked multivariable systems how controls implemented at a terminal influences the behavior of other terminals through the network. Finally, the potential of multivariable control methods in partially decoupling the system is presented.

II. IMPEDANCE-BASED FRAMEWORK

At the lowest level, the physical system is made up of impedances. For tightly controlled power converters, the control systems can be viewed as a dynamic impedance. Thus, during disturbances, the control imposes a virtual impedance that interacts with the physical impedances. Therefore, the equivalent impedance of each distinct control system, or distinct combination of control strategies (generic or specially designed) as is typical can be derived to form a single subsystem at the terminal-level. For several cases where controllers do not directly fit into the impedance framework, linearization can be carried to fit into the framework without losing important information. Conveniently, the entire system including the network, passive, and all active devices are subsequently represented as impedances.

III. METHODOLOGY FOR UNDERSTANDING INTEROPERABILITY ISSUES

Subsequent to the derivation of impedance equivalents at the terminal or subsystem level, aggregation must be done at system level. For a three terminal HVDC, Fig. 1 depicts the overview of interconnected voltage controlled VSC network where Z_{oc} are dynamic impedances and Z_{Ln} are the cable impedances. Without loss of generality, the control can be any of power, current (as is possible), or hybrid combination of any

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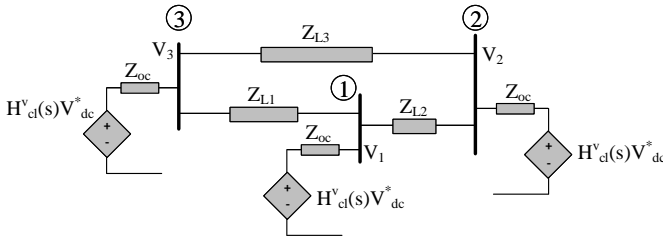


Fig. 1. Circuit schematic of a Voltage controlled VSC meshed network

of voltage, current, and power control. However, these can be transformed to equivalent voltage controlled system, in this case, current or power dependent voltage controlled system.

Considering that the DC voltage is the most important dynamic variable in the DC grid, an aggregation is carried out considering the behaviour of nodal voltages. Therefore, the closed-loop impedance matrix of the system can be obtained in the form such that

$$\underbrace{\begin{pmatrix} \Delta V_1 \\ \Delta V_2 \\ \Delta V_3 \end{pmatrix}}_{\Delta \mathbf{V}} = \underbrace{\begin{pmatrix} Z_{11}^{dc}(s) & Z_{12}^{dc}(s) & Z_{13}^{dc}(s) \\ Z_{21}^{dc}(s) & Z_{22}^{dc}(s) & Z_{23}^{dc}(s) \\ Z_{31}^{dc}(s) & Z_{32}^{dc}(s) & Z_{33}^{dc}(s) \end{pmatrix}}_{\mathbf{Z}_{bus}^{cl}(s)} \underbrace{\begin{pmatrix} \Delta \Sigma I_1 \\ \Delta \Sigma I_2 \\ \Delta \Sigma I_3 \end{pmatrix}}_{\Delta \mathbf{I}_{bus}(i \neq j)} \quad (1)$$

where $\Delta \mathbf{V}$ is the dynamic responses of voltages at all terminals for disturbances anywhere in the system, $\mathbf{Z}_{bus}^{cl}(s)$ is the closed-loop impedance matrix that holds the global information about the system considering the network and all controls, and $\Delta \mathbf{I}_{bus}$ are the bus currents that reflect any disturbances. The elements in $\mathbf{Z}_{bus}^{cl}(s)$ are impedance transfer functions as seen by each terminal. It is important to note that $\mathbf{Z}_{bus}^{cl}(s)$ is a coupled multiple-input multiple-output (MIMO) matrix rather than a collection of single-input single-output functions. Therefore, $\mathbf{Z}_{bus}^{cl}(s)$ holds the global information on the behaviour and interaction of subsystems in the HVDC grid and can be treated as a single-entity. Also, it can be manipulated to suit additional control objectives such as robustness and damping of network oscillations as it explicitly include all necessary information. Additionally, explicit knowledge of the internal structure of control systems at the terminal-level are not required considering manufacturers are often wary of sharing information. Fig. 2 depicts the overview of the impedance structure for meshed HVDC systems.

IV. CONCLUSION

This paper describes a generalized methodology to model the global impact of network and independently modelled control systems with the impedance framework in an intuitive manner. The method explicitly includes all necessary subsystems and might be key to understanding the impact of myriad devices on the overall system responses and coupling in as many distinct grids.

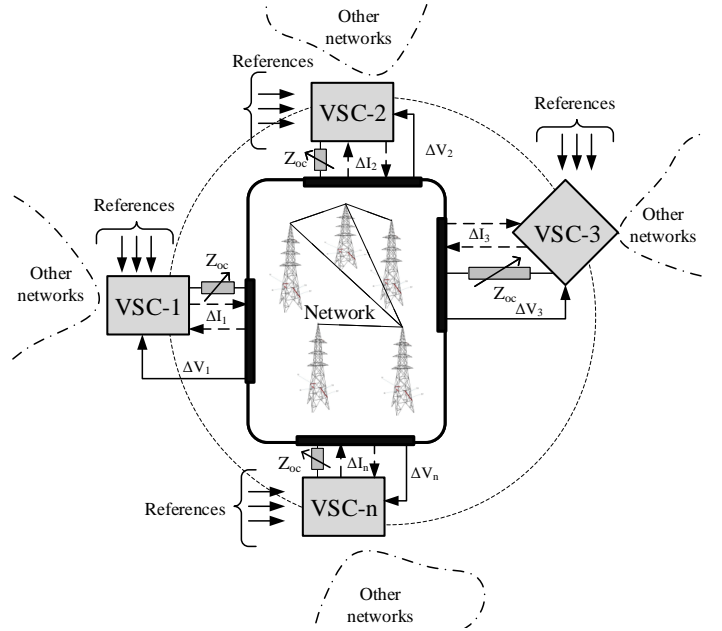


Fig. 2. Schematic overview of the Impedance Structure

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IRP32: A new modeling approach for stabilization of smart grids

Felix Koeth, Nicholas Retière

Abstract—Synchronization and stability plays a vital role in the design and operation of the power system. An important phenomenon observed in the dynamics of power system is coherency, where certain regions of the power system exhibit identical behavior. This behavior is investigated with regards to parameters and topology of the network.

I. INTRODUCTION AND MODELING

The power system, vital for the modern lifestyle, is the largest man made structure in the world. To combat climate change, the creation of energy has to change from fossil sources to renewable energies, changing the topology of the system and increasing intermittency of energy sources. This leads to possible problems with stability, which have to be resolved. A interesting phenomenon of power system stability which is linked directly to the design as well as the operation of the power system is coherency [1]. Here, some regions in the power system will have identical frequency response in certain modes. This coherency can be studied in simplified power system models, such as the structure-preserving model for the phases θ_i , given as [2], [3], [4]:

$$M_i \ddot{\theta}_i + D_{G,i} \dot{\theta}_i = \omega_i - \sum_j a_{ij} \sin(\theta_i - \theta_j) \quad i \in \mathcal{V}_G \quad (1)$$

$$D_{L,i} \dot{\theta}_i = \omega_i - \sum_j a_{ij} \sin(\theta_i - \theta_j) \quad i \in \mathcal{V}_L \quad (2)$$

Where the generators/loads G/L are in $\mathcal{V}_G/\mathcal{V}_L$. In [1], the damping D_L and D_G is assumed to be zero. Linearization around an operating point yields and considering the free-response system yields the following quadratic eigenvalue problem (QEP) for the eigenvectors x and eigenvalues λ [5]:

$$(\lambda^2 M + \lambda D + L)x = 0 \quad (3)$$

The small signal dynamics of this system are then given by the eigenvalues λ_k and the eigenvectors x_k . The entries of x_k indicate coherent behavior. The i -th entry of x_k correspond the the i -th node in the power system. All nodes which have, for a given mode, the same (or similar) eigenvector components will exhibit coherent behavior for this mode.

II. EXPERIMENTAL RESULTS

We are investigating the results of the QEP from equation (3) for the IEEE 145 (50 Bus dynamical test case) system [6]. Calculating the matrices M , D and L , as well as ω is done with the software given in [7].

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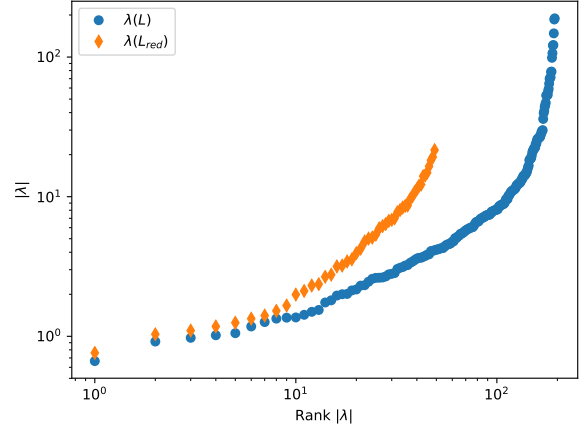


Fig. 1. Spectrum of Laplacian Matrix L and reduced matrix L_{red} .

A. Eigenvalues

a) *Laplacian matrix*: The topological properties can be observed at first by the eigenspectrum of the Laplacian matrix, calculated from equation (3) with $M = 1$ and $D = 0$, shown in figure 1. A separation of scales can be observed. While the first few (around 10) eigenvalues are relatively small and only increase slowly, larger eigenvalues increase much faster. The first eigenvalues correspond to the more global dynamics of the system, while higher modes describe the behavior of individual nodes in the system. W

b) *Undamped system*: While the Laplacian matrix helps identify purely topological properties, the influence of the dynamics and local parameters have to be investigated. In accordance to [1], the undamped system will be investigated from equation (3), with $D = 0$. It should be noted that for this calculation, the Shur complement of the Laplacian matrix with regards to the load-nodes L_{red} can be used, as shown in [1]. The calculation of the Shur complement is mathematically identical to a removal of all load nodes in the system via the Kron-reduction.

In figure 2, the original spectrum system M_0, L_{red} is perturbed by choosing a inertia matrices M_i . The spectra of the two matrix-pencils is shown in figure 2.

From the graph, it is clear that especially for lower ranked eigenvalues, the underlying topology of the network dominates the spectrum in this range. For higher ranked eigenvalues, the differences in the spectra increase. As mentioned earlier, the higher ranked eigenvalues correspond to localized dynamics. Here, the influence of the nodal properties in M_i

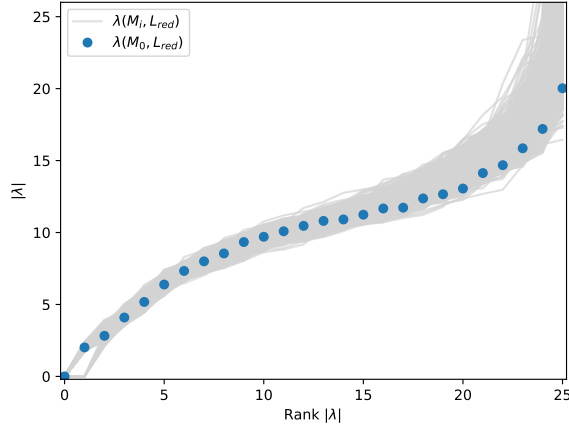


Fig. 2. Spectrum of eigenvalues of matrix pair (M, L) for IEEE 145 system with randomly perturbed inertia M , showing the original parameters and perturbed spectra.

are dominating.

c) *Damped system*: A logical extension of the theoretical results from [1] is the introduction of damping in the system. Especially the damping of oscillators is very important for power system stability [7]. In the damped system, the eigenvalues from the quadratic eigenvalue problem are generally complex numbers (while they were purely imaginary before). In accordance to the damped oscillator, transitions to overdamped and undamped behavior can be found. Figure 3 shows the imaginary and real-value of the eigenvalues for the matrix pencil $(M_0, \alpha D_i, L_{red})$ with the damping matrix $D_i = \alpha_i D_0$ and a real number α . Clearly, beyond the critical value α_0 , the imaginary parts vanish and the system stops to oscillate. In the real parts, an interesting behavior of three different inclinations can be observed. A primarily explanation is that the largest inclination corresponds to the damping of the whole system and the almost constant lines to individual node damping.

B. Coherency

The coherency is given by the eigenvector components. Similar components correspond to coherent behavior. In general, lower nodes should show more coherent behavior. For the test case, figure 4 shows the coherency of the matrix pencil M_0, D_0, L_{red} . Obviously, higher modes have very localized behavior where most nodes are zero. In lower modes, a larger activation can be observed at all nodes, as well as clusters where the values are very similar.

III. DISCUSSION AND OUTLOOK

This abstract shows experimental results on the spectrum and coherency of the eigenvalue problem related to the synchronization of power systems. The specific influence of the parameters, especially on the coherency has to be further investigated, using for example perlocation theory. Also, the theoretical work is extended.

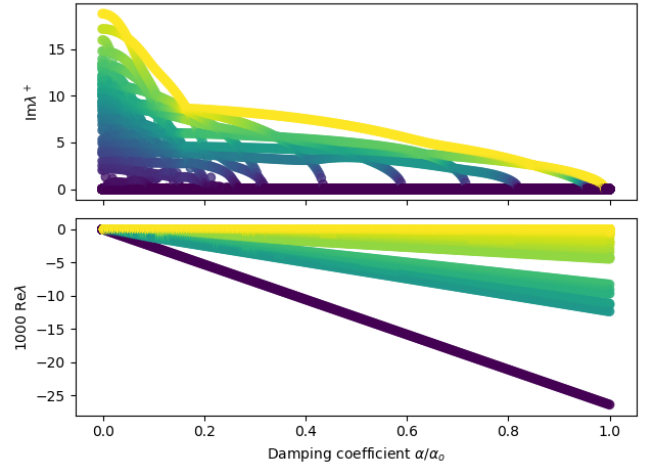


Fig. 3. Positive imaginary parts and real parts of eigenvalues for matrix pencil (M, D, L) with different damping coefficients α .

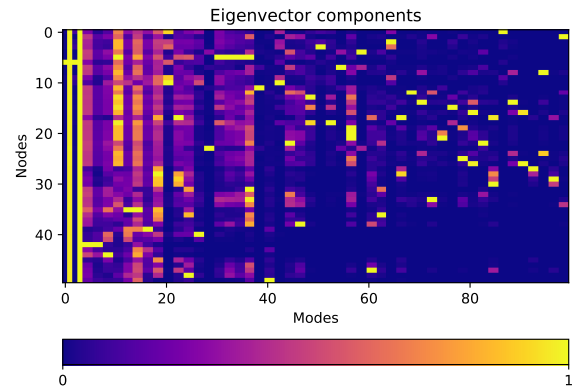


Fig. 4. Eigenvector components $|v_{ik}|$ for different modes k at nodes i .

IV. ACKNOWLEDGMENTS

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A distributed wind farm control strategy for enhancing primary frequency support

Sara Siniscalchi-Minna, Mikel De-Prada-Gil and Carlos Ocampo-Martinez

I. INTRODUCTION

In the last decade, relevant research effort has been witnessed in the field of wind energy production due to the ever-growing participation of wind energy in electrical power system. Advanced control strategies along with the improvements achieved in power electronics have pushed the wind energy generation targets further ahead towards a better employment of the wind source to ensure grid support. Wind turbines in a wind farm commonly operate to extract the maximum kinetic energy embedded in the incoming wind field without take into account the information from the other turbines. However, in the current contest of enhancing grid support, the power generated by a wind farm should ensure specific objectives (e.g. power tracking, frequency and voltage supports), thereby enabling cooperation among the turbines in large wind farms allow to optimize performance and improve the reliability of the electrical network.

When the incoming wind interacts with the rotating mass there is a reduction of the wind speed in the downstream wake and, as a result a turbine standing in the wake of an upstream one experiences a reduction of available wind power. Therefore, as the number of turbines increases such phenomenon becomes more important, so that a proper wind farm controller should take into account the aerodynamic couplings due to the wake effect, which no longer guarantee the local optimal operating point of each turbine [1]. A possible solution to optimize the performance of the power generated by large wind farms is to develop control strategies allowing the wind turbines to exchange information among the turbines. This justifies a growing interest in cooperative methods to control wind turbines belonging to large wind farms [2]. Among those methods, distributed optimization and control provide a framework for efficient computation of large-scale systems reducing the computational and communication burden. Indeed, a large wind farm can be defined as a multi-agent system, where its wind turbines represent the system agents coupled by the wake interaction [3]. Distributed optimization for wind farm con-

trol has been proposed in literature [1]. However, complex aerodynamics interactions and large timescales make this a challenging problem. Recently, a limited-communication distributed model predictive controller designed to track a power reference signal has been proposed by [4]. This algorithm uses a simplified linearized wake model to describe turbine interactions, allowing for scalability. However, this method is difficult to extend to power maximization or load minimization being the objectives highly non linear. Wind farm distributed PSO-based control accounting the wake interaction among the turbines has been considered in [5] in order to maximize the overall power generation. However, the main drawback of this approach is the slow convergence to a solution of the optimization problem due to the increasing number of direct communications among the wind turbines with the growth of the aerodynamic couplings. Additionally, the PSO strategy is not able to guarantee that the solution obtained is optimal due to the implementation of a heuristic optimization method..

This work presents a distributed optimization framework to enable fast convergence to a solution reducing the optimization time required by the centralized model-based architecture [6]. The control strategy is proposed to ensure primary frequency support by maximizing the power that can be injected into the grid in order to reduce the frequency drop. This power is called *power reserve* and it is defined as the difference between the maximum power that the wind farm can generate and the power demanded by the grid [7]. Therefore, a possible approach to maximize the power reserve is to improve the overall available power of the wind farm by reducing the wake effect among the turbines. As main contribution of this work, a novel non-linear distributed model predictive control (MPC) is stated to solve an optimization problem to track the power demanded by the grid and minimize the wake effect by including in the optimization framework the non linear dynamics of the wake propagation among the turbines.

II. DISTRIBUTED CONTROL STRATEGY

A wind farm can be represented as a directed network [6], wherein each turbine represents a node in the network and the aerodynamic interactions between turbines due to the wake effect can be represented as edges. According to the Park's wake model, each wind turbine is physically coupled to the upstream turbines (notice that the vice versa is not true). The strength of such coupling is assigned based on the physical distance among the downstream and upstream turbines and the mean direction of the freestream wind

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speed, which affects the overlapped area $A_{s,i}$ (see Figure 1). Based on these strengths, a wind farm can be divided

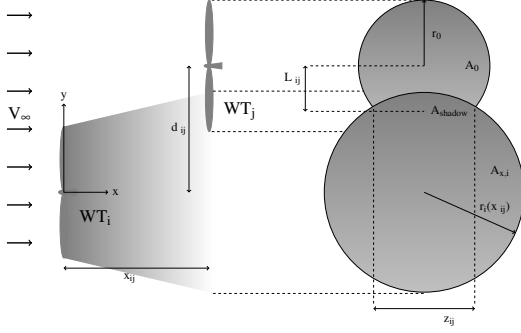


Fig. 1. Wake expansion.

into subsets which are time-varying as a consequence of being the wind direction function of time. The partitioning problem is stated to find the optimal set of partitions such that the following objectives are ensured: 1) Minimize the edges between different partitions; this may be ensured maximizing the couplings among the turbines caused by the wake propagation. 2) Minimize the physical distance among the turbines belonging to the same partition. Notice that this objective is required to ensure unique solution when no wakes affect the downstream turbines. 3) Minimize the difference between the amount of turbines in the partitions. The aforementioned objectives are hierarchically prioritized to find the optimal partition by solving a mixed-integer multi-objective optimization problem.

Once the optimal partitions are found, at each subset is required to ensure the power set-point sent by the PI controller. As shown in the control scheme in Figure 2, the PI distributes the power set-points proportionally to the number of turbines in order to sum up to the power demanded by the grid or to the maximum power available for the wind farm (i.e. $P_{r,tot} = \min(P_{dem}, P_{av,tot})$). Since the power required by the grid can change quickly (time-frame of seconds) the PI updates the set-points every second. Meanwhile, the problem of maximizing the power reserve is addressed using distributing MPC controllers for any sub-sets. The objective of the local controllers is to maximize the sum of the wind speeds over the number of turbines in the partition. The non linear dynamic propagation of the wind flow field through the wind farm is modeled using the discretized version of the Jense's wake model [8]. In particular, the sample time used to discretize this model is set equal to $\tau = s/0.8U_\infty$, being s the separation among the turbines and U_∞ the freestream wind speed [2]. The optimization problem is constrained by non linear constraints added to ensure the tracking of the power set-point sent by the PI controller and the power limits imposed by the turbine manufacturing. As a results of the optimization problem, a vector of optimal scalar variables $\beta^* = [\beta_1^*, \dots, \beta_{n_t,i}^*]$ is obtained for each turbine j in the partition i , with $j \in \{1, \dots, n_{t,i}\}$ and $i \in \{1, \dots, n_c\}$ with n_c number of partitions. This scalar values are then used to optimally distribute the induction factors, which set the

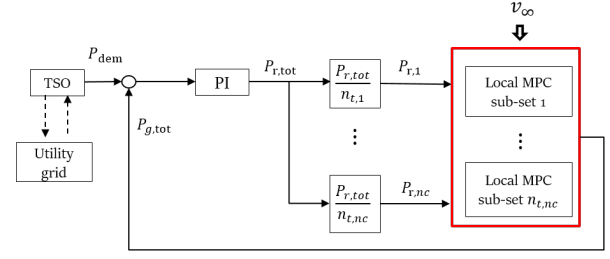


Fig. 2. Wind farm control scheme. P_{dem} power demanded by the grid, $P_{r,tot}$ power required by the PI, $P_{r,i}$ power set-point for the sub-set and $P_{g,tot}$ total power generated by the turbines.

operating conditions of the turbines.

The proposed control strategy has been evaluated for a wind farm with 30 benchmark NREL-5MW wind turbines. The results show that the mean value of power reserve obtained with the proposed approach results to be increased about 11,5% with respect to the centralized strategy.

III. ON-GOING WORK

Preliminary results have indicated that additional benefit can be obtained with distributed control strategy. In this case, the computational cost when compared to solving a fully centralized optimization can be reduced providing similar power gain results. Moreover, in [9] it has been shown that the presented optimization-based control strategy could also add an additional cost function to minimize the electrical power losses in the electrical connections among the turbines; thus, an additional step of the present work is to compute both active and reactive power flows to evaluate such losses.

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Day-ahead Scheduling of a Local Energy Community: An ADMM Approach

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Abstract— The work deals with the day-ahead operational planning of a grid-connected microgrid of a local energy community (LEC) consisting of several prosumers equipped with generating units, local loads and battery storage systems. The problem is addressed by designing a specific distributed procedure based on the adoption of the alternating direction method of multipliers (ADMM). The ADMM model provides the scheduling of the batteries to limit the balancing action of the external grid. Results obtained for various case studies are compared with those obtained by a centralized approach.

Keywords— local energy community, energy management, alternating direction method of multipliers, mixed integer programming, distributed optimization.

I. INTRODUCTION

We consider a local energy community (LEC) as a set of residential or small industrial sites connected to the same distribution network, each acting as a prosumer and being equipped, in general, with generation and storage systems other than local loads. In a LEC, each prosumer operates the available energy resources in cooperation with the others to minimize the power exchanges with the utility grid. The economic justification for the formation of a LEC is mainly due to the difference between the price of the consumption from the utility grid and the price recognized to the local producer as a reward for the energy provided to the utility grid. This difference can be significant, e.g. due to the costs of the ancillary services.

The operation of a LEC requires the implementation of an energy management system (EMS) for the optimal exploitation of the available resources, with reference to the storage units.

This paper focuses indeed on the scheduling of the battery storage units in a day-ahead EMS assuming that all generation units of the LEC are photovoltaic (PV) panels. The structure of the EMS can be extended to include also dispatchable generators. The EMS scheduling is based on the forecast of both the PV unit productions and local loads during the following day.

The EMS function can be structured as a centralized optimization problem or as a distributed procedure. The centralized approach is the typical one and needs the knowledge of all the operating characteristics and the forecasts. The distributed approach is generally considered as more reliable and it reduces the need for each prosumer to expose all characteristics and forecasts of each own units. Moreover, a distributed procedure is more appropriate for implementing new transaction method based e.g. on blockchain [1], [2] or, more generally, on distributed ledger technologies.

The structure of the paper is the following. Section II is devoted to the description of a centralized approach based on a MILP model. Section III presents the proposed distributed approach based on the ADMM method. Section IV illustrates some of the results obtained by several numerical tests. Section V concludes the paper.

II. PROBLEM FORMULATION – CENTRALIZED APPROACH

Fig. 1 illustrates the scheme of a typical LEC. The connection to the utility grid is represented by the medium voltage (MV) – low voltage (LV) distribution transformer. The grid meter M_g , positioned at the point of common coupling (PCC), is bidirectional to measure the net energy exchanged (bought or sold) by the LEC with the utility grid in the time interval.

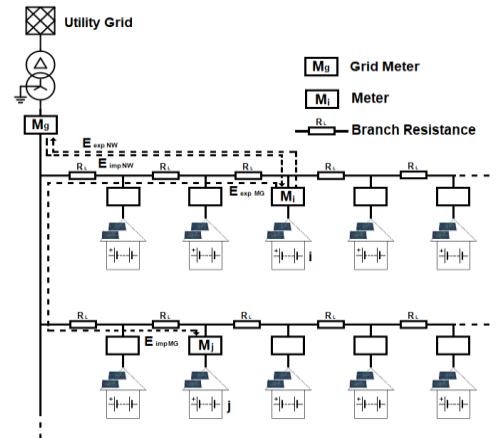


Fig. 1. Residential-small industrial Microgrid with two feeders, ten prosumers. Adapted by [3].

The aim of the LEC is to minimize the need to buy or sell energy to the grid to balance the local generation (assumed here provided by PV panels) and load profile. Each prosumer trades energy according to a peer to peer trading scheme, without the DSO intermediation, with other prosumers and the utility grid.

The day ahead scheduling dealt with in this paper provides a plan of the optimal use of the LEC energy resources during the next day, with particular reference to the energy storage systems, and calculates the prices of the energy transactions between prosumers. The prices of the exchanges with the utility grid are assumed to be fixed.

By denoting as $\Omega = \{1, 2, \dots, N\}$ the set of N prosumers index and as $T = \{1, 2, \dots, t_{end}\}$ the set of periods of the optimization horizon, the Objective function (OF) (1) minimizes the total cost associated with the power exchanged

with the utility grid in time horizon T : parameters π_{imp}^t and π_{exp}^t are the prices (in €/kWh) of the energy bought from and sold to the utility grid, respectively

$$OF = \min \sum_{\substack{t \in T \\ i \in \Omega}} (\pi_{buy}^t P_{buy_Grid\ i}^t - \pi_{sell}^t P_{sell_Grid\ i}^t) \Delta t \quad (1)$$

$$\sum_{\substack{j \in \Omega \\ j \neq i}} (P_{buy\ j,i}^t - P_{sell\ i,j}^t) = 0 \quad \forall t \in T \quad \forall i \in \Omega \quad (2)$$

III. PROBLEM FORMULATION – DISTRIBUTED APPROACH

ADMM is one of the most frequently adopted consensus methods [4] and it has been recently investigated for the solution of scheduling problems in microgrids (e.g., [5], [6], and references therein). In particular, both [5] and [6] deals with similar multi-microgrid systems as this paper, with the presence of local generation and battery energy storage (BES) systems and the possibility to exchange energy with an external utility grid. Moreover, [6] addresses the uncertainty of renewable energy, load consumption, and energy prices through a robust optimization approach.

Assuming the centralized model as reference, the distributed approach is based on the ADMM. The optimization is iteratively carried out by each prosumer k . At each ADMM iteration, the power bought or sold by each prosumer calculated in the previous iteration is made known to all the prosumers. These values are considered as parameters in the optimization problem solved by prosumer k at the current iteration and they are denoted by a hat in the model described in this section.

The objective function of prosumer k is

$$OF_k = \min \sum_{t \in T} [(\pi_{buy}^t P_{buy_Grid\ k}^t \Delta t - \pi_{sell}^t P_{sell_Grid\ k}^t \Delta t) + \sum_{\substack{j \in \Omega \\ j \neq k}} \lambda_j^t P_{buy\ k,j}^t \Delta t - \lambda_k^t \sum_{\substack{j \in \Omega \\ j \neq k}} P_{sell\ k,j}^t \Delta t + m \cdot \rho \left(\sum_{\substack{j \in \Omega \\ j \neq k}} (\hat{P}_{buy\ j,k}^t - P_{sell\ k,j}^t)^2 + \sum_{\substack{j \in \Omega \\ j \neq k}} (P_{buy\ k,j}^t - \hat{P}_{sell\ k,j}^t)^2 \right)] \quad (3)$$

Equation (3) is obtained by the decomposition for each prosumer k of the Lagrangian that incorporates OF (1) and the constraints (2), each multiplied by the relevant Lagrange multiplier λ_i^t , augmented by the squared norm of the same constraints multiplied by positive penalty parameter ρ and fixed scale factor m .

IV. TEST RESULTS

The test system is composed of two LV feeders, each with five prosumers connected. Each prosumer is equipped with a PV system, local load and a BES unit. All the calculations refer to a time window of 1 day, split in 96 periods of 15 min

each.

Table I shows the execution time of the algorithm, the values of OF , for both the centralized and distributed approach and both the two stages. The number of ADMM iterations is 18.

TABLE I - COMPARISON BETWEEN CENTRALIZED AND ADMM

	CPU time (s)	OF (€)
Centralized	10.45	18.341
ADMM	116.86	18.506

To illustrate the convergence behavior of the ADMM procedure, Fig. 2 shows the average value of the primal residuals R calculated in the 96 periods, the values of OF and the value of the part of OF due to the energy bought from and sold to the utility grid, at each iteration.

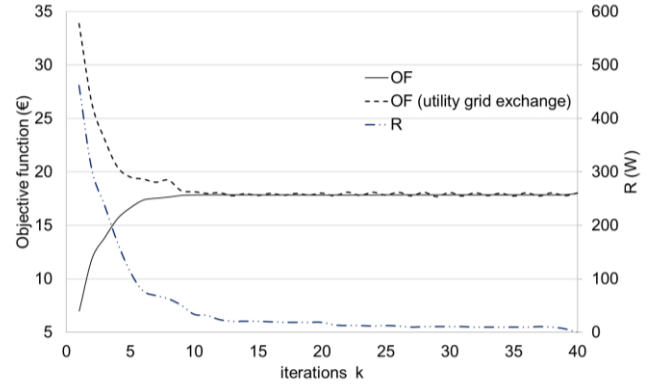


Fig. 2. ADMM convergence: total OF, part of the OF corresponding to the power exchange, average in 96 periods of primal residuals R .

The comparison between the OF values obtained with the centralized and the ADMM procedures shows that the total energy exchanged by the LEC with the utility grid are quite similar for the two approaches, and as confirmed by Fig. 3.

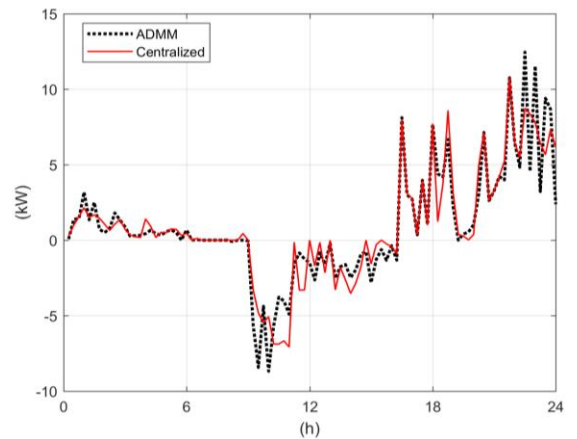


Fig. 3. Comparison of the total energy exchanged with the utility grid (solid line: centralized system, dashed line: decentralized system).

V. CONCLUSION

The results obtained by using the proposed distributed optimization procedure that avoids the presence of a central coordinator have been compared with those from a centralized

approach based on a MILP model. The distributed approach is based on the ADMM algorithm and allows to minimize the private information that each prosumer is required to provide to the other prosumers.

For the typical number of prosumers in a LEC, both centralized and ADMM-based distributed approaches provide comparable results with an acceptable computation effort.

The structure of the day-ahead scheduling procedures is consistent with the billing scheme and the metering units of the LEC.

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Part I: A fault detection and localization method for LV distribution grids

Nikolaos Sapountzoglou*, ESR 4.2, Bertrand Raison* and Nuno Silva**

Abstract—Following the method described in the previous deliverable D6.6, some recent results are presented in this abstract.

Index Terms—Fault detection, Fault localization, LV grid

I. INTRODUCTION

Recent advances include: extension of the sensitivity analysis of fault resistance up to $1\text{ k}\Omega$, a comparative analysis between the available voltage measurements and their suitability depending on the fault type, an heterogeneity analysis of the grid and its influence on the fault localization method and a preliminary study of less available measurements.

II. HETEROGENEITY ANALYSIS

Eleven different types of conductors in terms of resistance and reactance connect the nodes with each other with lengths ranging from 35 to a maximum of 210 m thus attributing to the grid an heterogeneous nature. A study was done without any load and microgeneration present in the grid in order to investigate the effect of the heterogeneity of the grid on the method. One parameter was kept unchanged: the distance of the fault from the beginning of each feeder. Two fault cases were studied: single-phase to ground SC faults at a distance of a) 270 m and b) 400 m from the beginning of the feeder. Different distances were chosen since an increase of the fault distance would include a bigger variety of conductors per branch.

Two basic conclusions were drawn. First of all, depending on the composition of a branch and how heterogeneous it is, a cost of a maximum of 5% in the accuracy of the method is possible; the further the fault was located from the beginning of the feeder the bigger the part of the conductors composing the branch were and hence the greater the risk of losing in precision if the conductors composing the branch were of quite different type. Secondly, it should be underlined that since there were no loads or microgeneration units participating in this case the slope of the curve after the faulty sector was exactly equal to zero in every case and thus the increase of the fault resistance did not affect the localization method in any way.

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III. FAULT LOCALIZATION RESULTS

Both the phase voltage measurements and the positive sequence component were used for all the different single-phase to ground fault cases and scenarios. For the three-phase fault case only the positive sequence component was considered as a viable option. In Table I the results for both methods are presented. It is demonstrated that the phase rms voltage measurements were more suitable for single-phase to ground faults since they lead to a higher precision rate in identifying the faulty branch which is the most important step of the method. Moreover, the phase voltage method was more accurate in estimating the fault's distance from the beginning of the feeder by 2.6% which was also reflected in low impedance faults with a difference in accuracy of 4.43%.

TABLE I: Localization method accuracy

	Accuracy (%)					
	Overall		Less than 50 Ω			
	1 ph	3 ph	1 ph	3 ph	1 ph	3 ph
	Vphase	Vpos	Vpos	Vphase	Vpos	Vpos
branch	75.00	66.88	75.00	91.67	89.58	100.0
sector	58.61	82.87	87.50	81.82	99.53	100.0
distance	89.33	86.73	95.21	93.11	88.68	96.03

IV. LESS AVAILABLE MEASUREMENTS

The last thing that was studied was the case of less available measurements in the grid. A preliminary analysis was made for single-phase to ground SC faults in two different fault locations. A limitation of the method is that it needs at least three distinct sectors in order to work, meaning a minimum of four measurements per branch; at least the first and the last two. The following strategy of sensor placement was developed: a) voltage sensors should be spread throughout the branch so that the voltage curve would be a good approximation of the ideal case and b) nodes with big loads and/or microgeneration units connected to them should be prioritized taking into account all three phases. To summarize, with a reduction of 30% of the available measurements for the two studied fault cases, an increase of approximately 10% of the distance estimation error was noticed maintaining an accuracy of distance estimation higher than 81%.

Part II: A review of fault diagnosis techniques in fuel cells

Nikolaos Sapountzoglou*, ESR 4.2, Bertrand Raison* and Ramon Costa-Castelló**

Abstract—An overview of the available fault diagnosis techniques based on a preliminary literature review is presented in this abstract in the context of the beginning of the second Incite secondment at Universitat Politècnica de Catalunya (UPC), Barcelona and the study case of fault detection and isolation techniques on proton exchange membrane fuel cell systems (PEMFCs). Current progress and future plans are also described.

Index Terms—Fault detection, Fault diagnosis, PEMFCs

I. INTRODUCTION

Polymer electrolyte membrane or proton exchange membrane fuel cells are the most popular among other fuel cell technologies (alkaline, phosphoric acid, molten carbonate and solid oxide) for their simplicity, variability, quick start up capabilities and their suitability for a wide range of applications [1]. As PEMFCs are becoming more and more popular their monitoring and safe operation is of paramount importance.

Monitoring of a PEMFC is a non-linear, multi-fault source with different time-scale problems especially because of all the chemical reactions taking place inside the fuel cell [2]. Its complexity is underlined in the first fuel cell law: *A change of one parameter will affect at least two others of which at least one will have an opposite effect of the expected outcome* [1]. It is thus clear that classification of faults in or obtaining unique fault signatures is a challenging task.

II. FAULTS IN FUEL CELLS

Faults in fuel cells can be divided in three big categories [3]:

- 1) Permanent faults:
 - membrane deterioration
 - absence of catalyst
 - CO poisoning
 - reactant leakage
 - fuel cell aging
- 2) Transient faults:
 - flooding
 - drying
- 3) External faults:
 - humidification
 - power electronics

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- cooling system
- air supply system
- hydrogen supply system
- air exhaust
- sensor network

From this extensive list of faults only a few will be studied. One fault inside the fuel cell, a short-circuit fault of the electrodes at the output of the fuel cell and power electronic faults similar to the ones previously studied in the GCPVs.

III. FAULT DIAGNOSIS METHODS FOR FUEL CELLS

There are five categories of fault diagnosis methods for PEMFCs: 1) model-based methods, 2) knowledge based methods: a) artificial intelligence (neural networks, fuzzy logic and neural-fuzzy method) and b) statistical methods (linear and non-linear feature reduction and Bayesian networks), 3) signal processing methods (Fast Fourier Transform for stationary signals and Short-time Fourier Transform and Wavelet Transform for non-stationary signals) and 4) hybrid methods since there is not a single method that can monitor the fuel cell system in its full complexity [2]. In this case, signal processing tools will be used in an attempt to relate previously developed methods for grid connected photovoltaic systems (GCPVs) with the fuel cell system. In [2] a list of monitoring signals is presented associating them with certain faults while in [4] a list of operations is provided in order to simulate several faults.

IV. CURRENT AND FUTURE WORK

The development of an extremely sophisticated fuel cell system model that takes into account all the chemical reactions inside it, falls out of the scope of this 3 month secondment. A model developed to serve the simulation of the selected faults is currently under development. Once the model normal operation is validated, the simulation of the faults will follow. Another goal of this study is to experimentally validate part of this work if possible.

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Efficient Convex Optimization for Optimal PMU Placement in Large Distribution Grids

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I. INTRODUCTION

The small amount of measurements in distribution grids makes their monitoring more difficult. Topological observability [1] may not be possible, and thus, pseudo-measurements [2] are needed to perform state estimation [3], which is required to control elements such as distributed generation or transformers at distribution grids. Therefore, we consider the problem of optimal sensor placement to improve the state estimation accuracy in 3-phase coupled, unbalanced distribution grids. This is an NP-hard optimization problem whose optimal solution is unpractical to obtain for large networks. For that reason, some work [4] focuses on developing convex optimization algorithms to compute a lower bound on the possible value of the optimal solution, and thus check the gap between the bound and heuristic solutions. We propose an approach to compute this bound in large-scale distribution networks, such as the standard IEEE 8500-node [5].

II. TWO-STEP STATE ESTIMATION

As presented in the previous work [2], SE can be separated in two parts: First, using the pseudo-measurement estimations or predictions for the loads S_{pseudo} , solve the power-flow offline to obtain a prior estimate V_{prior} ; then, using this estimate and the real-time measurements z_{meas} , a posterior solution V_{post} can be obtained using a linear filter:

$$\begin{aligned} V_{\text{prior}} &= \text{PowerFlow}(S_{\text{pseudo}}) \\ V_{\text{post}} &= V_{\text{prior}} + K(z_{\text{meas}} - C_{\text{meas}}V_{\text{prior}}) \end{aligned} \quad (1)$$

where C_{meas} is the matrix mapping state voltages V to measurements z_{meas} , and the gain matrix K is obtained by minimizing the expected error covariance $\Sigma_{\text{post}} = \mathbb{E}[(V_{\text{post}} - V)^*(V_{\text{post}} - V)]$: $K = \arg \min_K \text{tr}(\Sigma_{\text{post}})$. By defining Σ_{prior} and Σ_{meas} , the expected error covariance of the prior estimate V_{prior} and the real-time measurements z_{meas} respectively, the resulting posterior expected error covariance is then:

$$\begin{aligned} \Sigma_{\text{post}} &= (\Sigma_{\text{prior}}^{-1} + \sum_i (C_{\text{meas}})_{i,\bullet}^H (C_{\text{meas}})_{i,\bullet} (\Sigma_{\text{meas}}^{-1})_{i,i})^{-1} \\ &= (\Sigma_{\text{prior}}^{-1} + \sum_i x_i (\tilde{C}_{\text{meas}})_{i,\bullet}^H (\tilde{C}_{\text{meas}})_{i,\bullet} (\Sigma_{\text{meas}}^{-1})_{i,i})^{-1} \end{aligned} \quad (2)$$

so that Σ_{post} is a function of x , where $x_i \in \{0, 1\}$, $x_i = 1$ if the physical quantity i has a sensor measuring its value,

0 otherwise; and \tilde{C}_{meas} is the special case of C_{meas} with all possible measurements of all types (bus voltage, bus current, and line current) for all nodes and lines in each phase.

III. OPTIMAL SENSOR PLACEMENT PROBLEMS

In order to improve the accuracy of the SE, the problem of optimal sensor placement consists in minimizing $\Sigma_{\text{post}}(x)$ in (2), according to a metric $m(\cdot)$ and under a set of constraints $h(\cdot)$ to limit the number of sensors or the total cost:

Definition 1. *Optimal Sensor Placement problem:*

$$\min_x m(\Sigma_{\text{post}}(x)) \text{ s.t. } h(x) \leq 0, x_i \in \{0, 1\} \forall i \quad (3)$$

For simplicity, we define: $f(x) \equiv m(\Sigma_{\text{post}}(x))$.

A. Metrics for sensor placement

In the context of optimal design of experiments [6] different metrics can be considered, such as:

- *A-optimal*: $f_A(x) = \text{tr}(\Sigma_{\text{post}}(x))$. This corresponds to minimizing the sum of the eigenvalues of Σ_{post} .
- *D-optimal*: $f_D(x) = \log \det(\Sigma_{\text{post}}(x))$. This corresponds to minimizing the product of eigenvalues of Σ_{post} .
- *E-optimal*: $f_E(x) = \lambda_{\max}(\Sigma_{\text{post}}(x))$. This corresponds to minimizing the maximum eigenvalue of Σ_{post} .
- *M-optimal*: $f_M(x) = \max_i (\Sigma_{\text{post}}(x))_{i,i}$, which corresponds to minimizing the highest diagonal term of $\Sigma_{\text{post}}(x)$.

When relaxing x_i in (3) to be continuous, i.e. $x_i \in [0, 1]$, the metrics are all convex in x [4].

B. Solutions under a budget constraint

For $h(x)$ in (3) we consider a budget constraint limiting the total cost of the deployed sensors. The optimal sensor placement problem can then be expressed as:

$$x_{\text{opt}} = \arg \min_x f(x) \text{ s.t. } \sum_i c_i x_i \leq b, x_i \in \{0, 1\} \forall i \quad (4)$$

where b represents the budget and c_i the cost of installing a sensor at location i . A convexity-based lower bound can be found by relaxing $x_i \in \{0, 1\}$ in (4) to $x_i \in [0, 1]$, with solution x_{convex} and value $f(x_{\text{convex}}) = f_{\text{convex}}$. However, x_{convex} will not necessarily be feasible to (4). A feasible solution x_{feas} (with respective value $f(x_{\text{feas}}) = f_{\text{feas}}$) can be built using the convex solution x_{convex} , by selecting the sensors corresponding to the elements of x_{convex} with the highest values. Another way to create a feasible solution would

be using a forward greedy sensor selection, which in every iteration adds the sensor with the lowest ratio of objective function improvement divided by sensor cost. We denote this solution as x_{greedy} , with value f_{greedy} . See [7] for more details on the construction of x_{feas} , x_{greedy} . Then, since x_{feas} and x_{greedy} are feasible suboptimal solutions of (4), the following holds for all metrics:

$$f_{\text{convex}} \leq f_{\text{opt}} \leq \min(f_{\text{greedy}}, f_{\text{feas}}) \quad (5)$$

IV. OPTIMIZATION METHOD

Since we are considering large networks as the 8500-node feeder in [5], which translates into having a large number of optimization variables and constraints, standard optimization methods, such as second-order or dual Lagrangian methods, are not well suited to solve the convexified version of the problem (4). Therefore, we take advantage of the structure of the constraints to propose an approach based on first-order projected subgradient methods to get the optimal solution:

$$\begin{aligned} x^{(k+1)} &= \Pi_{\mathcal{X}}(x^k - \alpha^k \nabla f(x^k)) \\ \mathcal{X} &= \{x \mid \sum c_i x_i \leq b, x_i \in [0, 1]\} \end{aligned} \quad (6)$$

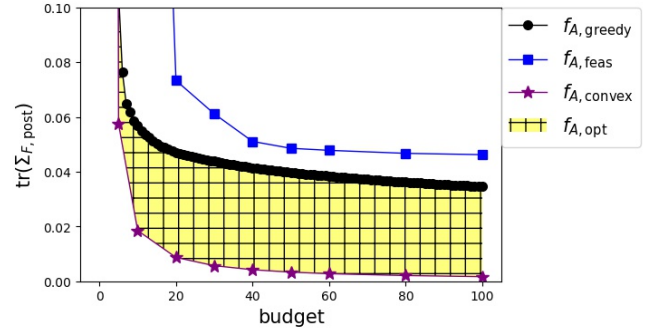
where $\Pi_{\mathcal{X}}(\cdot)$ denotes the projection on \mathcal{X} . See [7] for details on the computation of the subgradients $\nabla f(x^k)$ and the efficient projection algorithm $\Pi_{\mathcal{X}}(\cdot)$.

V. TEST CASE

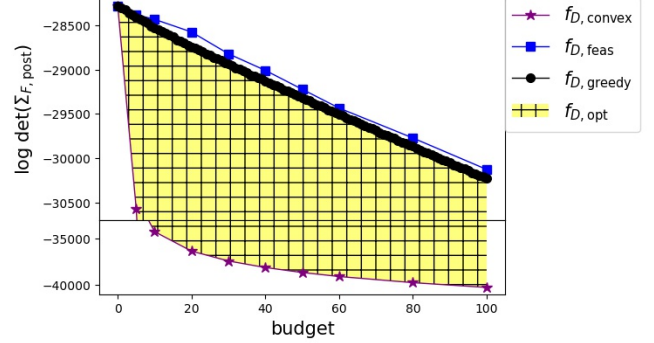
We have tested the algorithms on the 8500-node test feeder [5] for the different metrics. We assign random normal distributed costs: $c_i \sim \mathcal{N}(1, 0.1)$. The algorithms are coded in Python and run on an Intel Core i7-6700HQ CPU at 2.60GHz with 16GB of RAM. Fig. 1 shows the bounds for the 8500-node test feeder. It can be observed is that for all metrics, the feasible solutions $f_{\{A,D,E,M\}, \text{feas}}$ perform worse than the greedy ones. For the A,E,M-optimal metrics the convexity-based bound $f_{\{A,E,M\}, \text{convex}}$ is relatively close to the greedy solution $f_{\{A,E,M\}, \text{greedy}}$, especially for the E-optimal metric. This means that the performance of the greedy solutions is close to the performance of the optimal one. For the D-optimal metric, the convexity-based bound is far away from the greedy and feasible solutions. Therefore, this bound does not inform about the quality of the greedy and feasible solutions.

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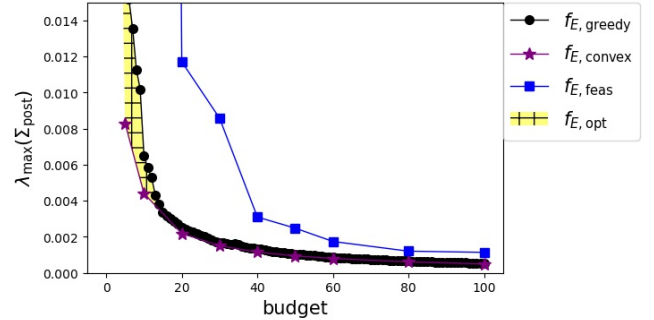
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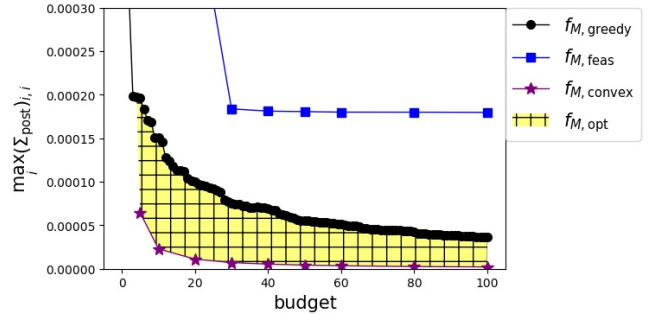
(a) A-optimal



(b) D-optimal



(c) E-optimal



(d) M-optimal

Fig. 1: Plots for the A,D,E,M-optimal metrics under a budget constraint, showing the lower bounds based on convex relaxations and the upper bounds given by the greedy and feasible solutions. The yellow shaded area with horizontal and vertical lines shows the possible locations of the optimal values $f_{\{A,D,E,M\}, \text{opt}}$.

A multi-period Optimal Power Flow scheme for Low Voltage Distribution Networks & Operation algorithms for Smart- Charging within different business models

ESR 4.4 Advanced functionalities for the future Smart Secondary Substation

Konstantinos Kotsalos and Nuno Silva

Abstract—Presently, the penetration of residential distributed energy resources (DER) that produce (rooftop photovoltaics usually bundled with battery system, small sized wind generators) or consume (electric heat pumps, controllable loads, electric vehicles) electric power, is continuously increasing following an uncoordinated trend. Yet, DER could provide certain degree of flexibility to the operation of distribution grids, which is generally assigned with temporal shifting of energy to be consumed or injected into the grid. Such temporal flexibilities need to be included to control algorithms along with proxy constraints. This work proposes a horizon optimization control scheme for the coordinated operation of multiple DER. The methodology leans on a three phase multi-period Optimal Power Flow (OPF) addressed as a nonlinear optimization problem. Additionally, a binary genetic algorithm is proposed for the management of charging points. The description of this algorithmic approach is implemented within different business models regarding the management of charging points.

I. INTRODUCTION

The increasing integration of DER along the distribution networks pose several technical challenges, which can be addressed by the active management of such resources. Distribution System Operators (DSOs) are currently increasing the observability and controllability of the grids, envisioning the active management of the DERs for ancillary services, throughout new operation stages.

Previous implementations of the ESR were focused on the scheduling of the controllable units based on a three-phase OPF which was executed sequential scheme [1]. This tool provided a coordinated operation of the resources ensuring voltages within the admissible limits.

This paper is organized in two sections, providing two distinct scopes, as follows:

Section II

- A multi-period OPF framework based on the exact formulation of the non-convex power flow equations, where computational complexity is alleviated by the introduction of the Jacobian of the nonlinear constraints and the Hessian of the Lagrangian problem.
- Presents a coordinated operation instrumented by a central entity in order to involve inter-temporal constraints (i.e. providing the limitations of each type of DER) and the counterpart inter-temporal cost dependencies.

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- A flexible operational tool, which provides support to the Distribution System Operator (DSO) with expandable objectives.

Section III

- Implementation of the management of charging point based scheduling on a reference signal received by a central controller (i.e. Advanced Distribution Management System -ADMS-) or the Aggregator.
- An optimization framework -with the use of a genetic algorithm- for the management of charging points.

II. COORDINATED DER OPERATION

The centralized coordinated operation of the DER is hereby proposed through a multi-period three phase OPF where the different periods are coupled with inter-temporal costs and the DER are assigned with inter-temporal constraints accordingly.

In this section, the multiperiod three-phase OPF is stated for an horizon of operational planning H_t . The main objective (i.e. \mathcal{O}_1) of the scheme is to minimize the operating costs assigned with all the controllable assets provided their coordination and based on their availability. Additional objectives (i.e. \mathcal{O}_2) can be assigned such as cost functions for the degradation of DSO assets. More careful assignment of objectives dependent on the state vector (i.e. \mathcal{V}) such as minimizing of unbalances and power losses, since conflicting objectives need to be addressed multi-objective disciplines (e.g. goal attainment).

In this work all buses are considered to have three terminals, where each one represents the phase connection point, a, b, c . The latter implies that for bus j , the voltage magnitude is given by the real vector $v_j \in \mathbb{R}^3$, $v_j = [v_{j,a}, v_{j,b}, v_{j,c}]^T$, and accordingly the voltage angles by the real vector $\theta_j \in \mathbb{R}^3$. For the multiperiod formulation, assuming that the decision variables at the time instant τ is correspond to the vector x_τ , which is defined as follows:

$$x_\tau = \begin{bmatrix} \Theta \\ \mathcal{V} \\ P_g \\ Q_g \\ \mathcal{Y} \end{bmatrix}_\tau, \forall \tau \in \mathcal{T}, x_\tau \in \mathbb{R}^{(2*3n_b+2*n_c+n_y)} \quad (1)$$

where n_b refer to the number of buses and n_c the controllable units. The real vector $\mathcal{V} = [v_1, v_2, \dots, v_{n_b}]_\tau^T$ corresponds to the voltage magnitudes for each bus (each bus has three terminals) at each time instant τ , and respectively Θ to the voltage

magnitudes. The sets $\mathcal{N}, \mathcal{J}, \mathcal{T}$, denote the buses, branches and the horizon of the multi-period scheme. The last set of variables defines the auxiliary variables for the framework such as dis-/charging for Batteries and EVs and the variables for the voltage relaxations. Let us consider the set of controllable assets $\mathcal{U} := \{u_1, \dots, u_{n_c}\}$, described by the control vector u , comprised by active and reactive power set points, P_g, Q_g .

Therefore, for the overall optimization problem the decision variables correspond to the matrix $X = [x_0, x_1, \dots, x_{H_t}]^T$.

$$\min_u \sum_{\tau=1}^{H_t} \left\{ \underbrace{\sum_k^{n_b} ([c_k(\tau)]^T \cdot u_{k,\tau})}_{\mathcal{O}_1} \right\} \Delta\tau + c_V \|\epsilon_V\| + \mathcal{O}_2 \quad (2)$$

subjected to

$$G_j(x_\tau, u_\tau) = 0 \quad \forall j, \tau \in \mathcal{N}, \mathcal{T} \quad (3a)$$

$$H_i(x_\tau, u_\tau) \leq 0 \quad \forall i, \tau \in \mathcal{J}, \mathcal{T} \quad (3b)$$

$$V_{\min} - \epsilon_V \leq v_j(x_\tau) \leq V_{\max} + \epsilon_V \quad \forall i, \tau \in \mathcal{N}, \mathcal{T} \quad (3c)$$

$$h_\xi(x_\tau, u_\tau) = 0 \quad \forall \xi, \tau \in \mathcal{U}, \mathcal{T} \quad (3d)$$

$$g_\xi(x_\tau, u_\tau) \leq 0 \quad \forall \xi, \tau \in \mathcal{U}, \mathcal{T} \quad (3e)$$

where the constraints in (3a) set the power balances at each bus of the network; the second constraint poses the nonlinear constraint for the constrained lines; the boxed constraint in (3c) to respect all nodal voltages to range strictly within the admissible bounds. The additional positive variable ϵ_V is used to relax the voltage constraints and avoid infeasibility. The constraints (3d)-(3e), correspond to the operational limits of the controllable DER.

The gradient of the objective, the Jacobian of nonlinear constraints and Hessian of the Lagrangian are implicitly provided to the optimizer, by expanding the calculations presented in [2]. This supports the acceleration of the convergence time. The initial point is calculated either with power flow executions or by searching in historical decisions variables.

The power flow constraints over all periods, are posed as a nonlinear equality constraint as presented in equation 3a, which is hereby expressed in discrete version due to the complex nature of power flows as follows

$$G(X) = S_{bus} + S_d - C_g S_g \quad (4)$$

$$G(X) = \begin{bmatrix} \Re\{G^c(X)\} & \Im\{G^c(X)\} \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} \quad (5)$$

This centralized optimization scheme needs forecasted data are implicitly taken into account in the real-time control. In the particular case that lack of information appears, worst case profile data can be derived from the local database of the central controller. Future work of the ESR targets on the maximization of the flexibility by relaxing further the voltage constraints of the proposed scheme.

III. EV SMART CHARGING ALGORITHM

The increasing adoption of Electric Vehicles is leading to a fast transition on electrical distribution networks, where charging stations are being deployed on a large scale to accommodate the EV users needs [1]. Several strategies in the literature have proposed advanced optimization techniques referring to a centralized management the EVs charging [3], [4].

In this part of work, an efficient management of load supply to Electric Vehicle Charging stations (EVSE) will be proposed, throughout different algorithmic approaches depending on the infrastructure management. While on the Operator perspective the Distribution System Operator (DSO) can have access and control most of network assets, on the Charging Point Operator (CPO) perspective the DSO does not have access to EVSE [5]. In some business cases the DSO might have limited access via the CPO infrastructure to the EVSE.

Within this part of the work, a conceptual suggests for the DSO perspective business model, a tool for the efficient management of EV charging points. A centralized management control optimizes the operation of the LV distribution by providing certain control set-points for controllable DER, including EV charging points. The centralized decision are derived by the tool proposed in section II.

Among the controllable DER hereby are the EV charging point or group of charging points in a condominium. The core of the proposed management tool is based on a binary genetic algorithm which receives a power reference signal by the Advanced Distribution Management System (ADMS -multiperiod OPF procedure-) and attempts to optimally allocate the demand of the EVs for the upcoming hours accordingly. The tool is capable of finding a sub-optimal solution for the scheduling of the EV on demand. The proposed tool is additionally able to cope with microgeneration connected at the premises of the charging point. The objective of the management of the EV charging will be to emulate at the charging points the power reference signal (scheduling the charging according to this), which corresponds to a signal either send by the DSO through the ADMS or through the CPO.

$$\min \sum_{t=1}^{H_t} |P_s(t) - P_D(t)| = \min \sum_{t=1}^{H_t} \left\{ \left| P_s(t) - \sum_i^{nrEV} (\delta_i(t)) \cdot P_{ev_i} \right| \right\} \quad (6)$$

where $P_s(t)$ corresponds to the power reference signal and $P_D(t)$ is the expected demand at charging point at time t .

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