Innovative controls for renewable source integration into smart energy systems

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DEFINITIONS

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  - **UPC**. Universitat Politècnica de Catalunya (Spain)
  - **TU Delft**. Technische Universiteit Delft (Netherlands)
  - **VITO**. Vlaamse Instelling Voor Technologisch Onderzoek (Belgium)
  - **UniBo**. Universita di Bologna (Italy)
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  - **Efacec Energia**. Efacec Energia - Maquinas e Equipamientos 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) and Tokyo Institute of Technology (Japan).

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 3rd INCITE Workshop, which has been organised by EFACEC and has been held in Porto, Portugal, on 21-23 February 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.

1. INTRODUCTION

The 3rd INCITE Workshop took place in Porto (Portugal), 21-23 February 2018. The host of the event was EFACEC and it was held at EFACEC premises in Porto.

This Workshop was focused 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 floating offshore wind turbines, and a visit to EFACEC's EV production facilities. Complementary skills training, on the other hand, focused on Intellectual Property and Start-ups, which are of great relevance for the ESR career development.

2. PROGRAM

Nº	*Topic*	*Speakers*	*Time*
	Wednesday 21/02/2018		*Auditorium TRP*
1	**Welcome & Introduction**	Nuno Silva - Joana Santos	9:30-10:15
2	**Seminar I: Smart, Distributed and Micro Grids - the challenges and impacts**	Prof. João Peças Lopes	10:15 – 11:30
	Coffee break		11:30 – 12:00
3	**IRP 2.1 - Energy flexible and smart grid/energy ready buildings**	Thibault Péan	12:00 – 12:30
4	**IRP 2.2 - Control and management of storage elements in micro-grids**	Unnikrishnan Raveendran Nair	12:30 – 13:00
	Lunch		13:00 – 14:00
5	**IRP 2.3 - Robust management and control of smart multi-carrier energy systems**	Tomas M. Pippia	14:00 – 14:30
6	**Seminar II: An Overview of the Smart Grids Concept**	Paulo Delfim Rodrigues	14:30 – 15.15
7	**Seminar III: From Intellectual Property to Business**	Prof. Catarina Maia	15:15 – 16:00
	Coffee break		16:00 – 16:30

8	**Seminar IV: Venture Capital and startups**	HCapital	16:30 – 17:15
9	**Seminar V: Visit to the EV production facilities**	Vitor Ferreira	17:15 – 18:00
	End of Day 1		18:00

Nº	*Topic*	*Speakers*	*Time*
	Thursday 22/02/2018		*Auditorium TRP*
10	**IRP 4.4 – Advanced functionalities for the future smart secondary substation**	Konstantinos Kotsalos	9:30 – 10:00
11	**IRP 4.2 – Fault detection and isolation for renewable sources**	Nikolaos Sapountzoglou	10:00 – 10:30
12	**IRP 4.1 – Integrated simulation and design optimisation tools (Intro to project)**	Camilo Orozco	10:30 – 11:00
	Coffee break		11:00 – 11:30
13	**IRP 3.2 – A new modelling approach for stabilisation of smart grids**	Felix Koeth	11:30 – 12:00
14	**IRP 3.3 – Distributed control strategies for wind farms for grid support**	Sara Siniscalchi Minna	12:00 – 12:30
15	**IRP 3.1 – Control strategies for hybrid AC-DC grids**	Adedotun Agbemuko	12:30 – 13:00
	Lunch		13:00 – 14:00
16	**IRP 1.2 – Decentralised control for RES by fast market-based MAS**	Hazem Abdelghany	14:00 – 14:30
17	**Seminar VI: Floating offshore wind turbines: challenges and opportunities**	Mikel de Prada (IREC)	14:30 – 15:30
	Coffee break		15:30 – 16:00
18a	**Supervisory Board Meeting**	Meeting room TBD	16:00 – 17:30
18b	**ESR Interaction**	Auditorium TRP	16:00 – 17:30
	End of Day 2		17:30

Nº	Topic	Speakers	Time
	Friday 23/02/2018		*Auditorium TRP*
19	**IRP 1.4 – Development of non-intrusive and intrusive energy-management**	Jesus Lago Garcia	9:30 – 10:00
20	**IRP 1.3 - Hybrid agent-based optimisation model for self-scheduling generators in a market environment**	Shantanu Chakraborty	10:00 – 10:30
21	**IRP 1.1 - Partitioning and optimisation-based non centralised control of dynamical energy grids**	Wicak Ananduta	10:30 – 11:00
	Coffee break		11:00 – 11:30
22	**INCITE Dissemination + Q&A**	Marta Fonrodona	12:30 – 12:45
23	**Wrap-up and closing**	José Luis (IREC)	12:45 – 13:00
	End of the meeting		13:00

3. ABSTRACTS

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

i. Complementary skills training:

- From Intellectual Property to Business (C. Maia, INESCTEC)
- Venture Capital and startups (HCapital)

ii. Scientific training:

- Smart, Distributed and Micro Grids - the challenges and impacts (J. Peças Lopes, U. Porto)
- An overview of the smart grids concept (P.D. Rodrigues, EFACEC)
- Floating offshore wind turbines: challenges and opportunities (M. De Prada, IREC)

iii. INCITE ESR presentations:

WP1. Control strategies for distributed power generation

- IRP1.1 – Resiliency of Distributed Model Predictive Control Approaches (W. Ananduta)
- IRP1.2 – Decentralised Control for RES by Fast Market-based Multi-agent Systems (H. Abdelghany)

- IRP1.3 – Coordinating Energy Flexibility in the Electricity Distribution Grid (S. Chakraborty)
- IRP1.4 – Short-term forecasting of solar irradiance without local data (J. Lago Garcia)

WP2. Control strategies for energy storage systems

- IRP2.1 – A Case Study of Model Predictive Control for HVAC Systems in an Office Building (T. Péan)
- IRP2.2 – Control and management of energy storage elements in micro-grids (U.R. Nair)
- IRP2.3 – Modeling and Control Methods for Large-Scale Systems and Microgrids (T. Pippia)

WP3. Control strategies for RES integration

- IRP3.1 – An Impedance-based Approach to Modelling of Large-Scale Hybrid ac/dc Grids (A. Agbemuko)
- IRP3.2 – A new modelling approach for stabilisation of smart grids (F. Koeth)
- IRP3.3 – Wind farms control strategies for grid support (S. Siniscalchi Minna)

WP4. Monitoring tools and secure operation of smart grids

- IRP4.1 – Comparison Between Multistage Stochastic Optimization Programming and Monte Carlo Simulations for the Operation of Local Energy Systems (C. Orozco)
- IRP4.2 – Fault detection through monitoring of the AC variables in Grid Connected PV systems (N. Sapountzoglou)
- IRP4.4 – Advanced functionalities for the future smart secondary substation (K. Kotsalos)

3.1 Complementary skills training

From Intellectual Property to Business

Catarina Maia
INESCTEC

Entrepreneurship is a skill that needs to be exercised. In today's world and focusing on the PhD programme, the potential for creation of ideas that are more or less disruptive, more or less applicable in the near-term future, more or less adequate for today's regulatory and business models. Why does my technology matter, and how can I make an impact with it? This was the main focus of the complementary skills training where topics such as understanding who the customers of the inventions may be and how to specifically detect and address their needs were approached in a provocative way to create interaction with the audience. The value creation through technology and innovation by using knowledge to solve a problem is a topic that, from the PhD perspective, is rather difficult to address since there may be a considerable gap between the developed control, algorithm or methodology and the eventual application on a "real" context. For this, the T-P-M (Technology-Product-Market) linkage was explored and exercised with examples.

Venture Capital and startups
HCapital

In the process of researching and developing new solutions to address problems, the post-PhD phase of scientists may turn out to be as entrepreneurs and creating a startup. Statistics show this context is favorable and, if properly managed, a relation with investors can result in significant (sometimes exponential) growth. This relationship needs however to be properly addressed and depends on the maturity stage of the startup, the product development and the market penetration. Leveraging a venture capital manager speaker, this seminar explained in detail what are the instruments available to those who may be interested in creating their own startup, where can they seek for support and what could be the right partners to invest, depending on the maturity curve of the startup. The pros and cons and do’s and don’ts were addressed so that a comprehensive view of the whole ecosystem was created on the audience.

3.2 Scientific training

Smart, Distributed and Micro Grids - the challenges and impacts
João Peças Lopes
U. Porto

Microgrids are assumed to be established at the low voltage distribution level, where distributed energy sources, storage devices, controllable loads and electric vehicles are integrated in the system and need to be properly managed. The microgrid system is a flexible cell that can be operated connected to the main power network or autonomously, in a controlled and coordinated way. The use of storage devices in microgrids is related to the provision of some form of energy buffering during autonomous operating conditions, in order to balance load and generation. However, frequency variations and limited storage capacity might compromise microgrid autonomous operation. In order to improve microgrid resilience in the moments subsequent to islanding, there is the need for innovative functionalities to run online, which are able to manage microgrid storage considering the integration of electric vehicles and load responsiveness. The effectiveness of the proposed algorithms is validated through extensive numerical simulations

Under normal operating conditions, a microgrid is interconnected with the medium voltage network; however, in order to deal with black start and islanded operation following a general blackout, an emergency operation mode must be envisaged. A sequence of actions and conditions to be checked during the restoration stage are identified and tested through numerical simulation. Voltage and frequency control approaches, inverter control modes, and the need of storage devices were addressed in order to ensure system stability, achieve robustness of operation, and not jeopardize power quality during service restoration in the low voltage area

An overview of the smart grids concept

Ivan Sousa
EFACEC

Increasing levels of small scale generation units connected to lower voltage levels are causing problems on distribution network operation. The implementation of smart grids enables the operator to have an extended view over the system operational parameters and even to control active participants (loads and generators). Voltage profile volatility is one of the main problems associated with DG units connected to LV networks and led to the development of several solutions to help utilities tackle tis problem in a cost efficient way. This presentation showed how the product development is made in industry and what are the current solutions within the smart grids context so that the INCITE ESR could understand how to manage the integration of (distributed) controls into industrials solutions and how to face the real-world problems of lack of information, non-ideal communication and controllability options.

Floating offshore wind turbines: challenges and opportunities

Mikel De Prada
Power Systems, Catalan Institute for Energy Research (IREC)

Nowadays, more than 91% of all offshore wind capacity is installed in European waters, mainly in the shallow waters of the North, Baltic, and Irish Seas. However, since shallow waters are scarce, it becomes necessary to develop technical solutions to unlock the abundant wind resources of deep water areas. Floating substructures for offshore wind power plants are a promising solution that has been under development in recent years. With lower constraints to water depths and soil conditions, floating substructures enable to harness the abundant wind resources of deeper waters. This session aims to understand the current state of the floating wind industry and the key technical challenges that need to be addressed to make floating wind a commercial reality. The presentation will provide a comprehensive overview of the technology and the range of concepts currently under development as well as a market outlook based on current trends. Moreover, as a second part of the session, Lifes50+ project, which is an EU H2020 funded research project carried out by a consortium of 12 leading European institutions and industry partners, will be presented. It focuses on the development of floating substructures for offshore wind turbines in the scale of 10 MW and for water depths greater than 50 meters.

3.3 INCITE ESR presentations

Resiliency of Distributed Model Predictive Control Approaches

ESR: Wicak Ananduta
Advisor: Carlos Ocampo-Martinez

***Abstract*— Communication and cooperation among local controllers are crucial in Distributed Model Predictive Control (DMPC) schemes. Therefore, it is important to cope with communication issues, such as link failures, and adversarial behaviors that avert cooperation.**

I. Distributed Model Predictive Control

Electrical grids can be perceived as complex large-scale systems (LSSs). A grid may consist of a large number of consumers and producers. Furthermore, the increasing penetration of distributed generation units, either dispatchable units or those that are based on renewable sources, and storage systems into the grids amplifies the complexity of the grids. On the one hand, renewable generation units not only provide clean energy but also introduce some issues into the grids, such as intermittency. On the other hand, storage units that may help to solve the issues brought by the renewable generation units also have some operational constraints and slow dynamics that add another layer on the complexity of the grid. Additionally, the possibility of consumers to actively contribute to the power generation, resulting in bidirectional power flows, must also be taken into account in order to achieve an efficient operation of the grids.

Designing a controller for a complex LSS is not a trivial task. One must consider the computational burden when computing the control inputs, among others. This issue is particularly important in the context of Model Predictive Control (MPC) approach since, in general, an MPC controller must solve an optimization problem online. In this regard, classical centralized control scheme may not be suitable to be implemented for the whole network. Furthermore, such scheme is also not scalable and flexible. Therefore, non-centralized schemes are considered as more appropriate alternatives than the centralized one.

In a non-centralized scheme, there exists a number of local controllers, each of which is responsible to control a subset of the system, i.e., a subsystem. In the context of MPC, the central optimization problem must be decomposed into smaller problems. These problems are then assigned to the local controllers. Non-centralized control schemes can be classified into two broad classes, decentralized and distributed schemes. The main difference between these two classes is whether the local controllers are able to exchange information among each other. By having this feature, distributed schemes are in general more superior than the decentralized counterparts, particularly when dealing with systems, whose subsystems are not weakly coupled. Attention to the research in distributed MPC (DMPC) has been increasing in the past two decades and many DMPC methods have been proposed [1], [2]. They include methods that are based on distributed optimization and game theory. Furthermore, tube-based DMPC approaches, in which the influence of the other subsystems to the dynamics is considered as bounded disturbance, have also been proposed.

As previously stated, the existence of communication among the local controllers is the main feature that distinguish DMPC methods from decentralized ones. By exchanging information, local controllers may use the information that is received from their neighbors to compute their control actions. It has been shown that this feature is necessary to obtain an optimal and/or stabilizing control actions [1]. Moreover, many methods also rely on the cooperation of the local controllers. For instance, in DMPC methods that are based on a distributed optimization algorithm, all local controllers must agree to send certain information to their neighbors and compute their control action based on the formulation that are given. Otherwise, the control action might be suboptimal or worse, it may cause instability of the closed-loop system. Therefore, ensuring resiliency against possible communication and cooperation issues is important for DMPC methods.

II. Resiliency Against Communication Issues

Certain communication requirements must be satisfied when applying a DMPC method. In fact, in terms of their communication procedures, DMPC methods can be classified into two categories: the approaches that require subsystems to coordinate only with their neighbors, i.e., the local controllers of the other sub-systems that are physically coupled with them; and the distributed approaches that require each local controller to be fully connected with all the others [1]. Furthermore, non-iterative DMPC methods require the information to be exchanged once in one sampling time, whereas iterative DMPC methods require the local controllers to exchange information multiple times within one sampling time [1].

The above communication requirements may not be satisfied throughout the operation due to some communication issues, such as delays and communication failures, that can occur in the information-sharing network [3]. If not handled, these issues might cause that the distributed control strategy cannot be performed appropriately and result in the sub-optimality of the solution or the instability of the closed-loop scheme [3].

In order to deal with communication failures, i.e., broken communication links, we have proposed to apply the distributed consensus algorithm as the information-exchange protocols [4]. The standard distributed consensus has the following dynamics [5]:

$$\dot{p}_{i,t} = \sum_{j \in \tilde{\mathcal{N}}_i} (p_{j,t} - p_{i,t}), \tag{1}$$

where $p_{i,t}$ denotes the information state of the i^{th} local controller, $\dot{p}_{i,t} = \frac{dp_{i,t}}{dt}$, and $\tilde{\mathcal{N}}_i$ denotes the set of neighbors that are connected to the i^{th} local controller in the information-sharing network. By appropriately initializing the states $p_{i,t}$, distributed consensus algorithm can be applied to exchange information among the local controllers. Since the main requirement of the consensus algorithm is only the connectivity of the network, it is actually more relaxed than the communication requirements of many DMPC methods. Furthermore, it also means that the information can still be exchanged even though some communication links are broken, as long as the network is still connected. In [4], we show the effectiveness of the proposed information-exchange protocol in a case study of power allocation problem in an electrical energy system.

III. Resiliency Against Adversarial Behaviors

As discussed in Section I, cooperation among the subsystems are required in many DMPC strategies. However, when some subsystems perform adversarial behavior, e.g., they provide erroneous information to the other agents, cooperation is not achieved and thus the performance of the closed-loop system is in question. In this regards, it is important to discuss the cyber-security aspect of DMPC methods.

In [6], it has been identified that there are four types of adversarial behaviors that can be considered as cyber attacks to DMPC strategies that are based on Lagrangian decomposition, which are: (i) *selfish attack*, in which the adversarial subsystems modify their cost function; (ii) *fake reference*, in which the adversarial subsystems use false reference; (iii) *fake constraints*, in which the adversarial subsystems use fake constraints throughout the iterations; and (iv) *liar agent*, in which adversarial subsystems implement a different control action than the one that has been computed by the distributed algorithm. These behaviors lead to the fact that the adversarial subsystems can gain benefit in terms of their cost while the normal subsystems will suffer from higher cost. Furthermore, adversarial subsystems may also prevent the convergence of the solution when the distributed algorithm is performed. Similar behavior has been studied in the consensus problems [7]. In this scenario, the local controllers will fail to compute their control actions.

Considering the implication of cyber attacks in the system, it is then important to improve the resiliency of the DMPC strategy against such behaviors. Therefore, in this regard, we are developing methodologies to identify cyber attacks as well as to deal with them. It has been investigated that different types of attacks might need different methods to cope with. In our work, we are focusing on the attacks of *liar agent* and the attacks that prevent the convergence.

IV. Conclusion

Communication issues and adversarial behaviors may cause undesirable performance of the large-scale system that is controlled by a DMPC method. Therefore, it is important to improve the resiliency of the DMPC scheme against such issues. We have proposed an information-exchange protocol to deal with communication failures and are currently investigating methodologies to deal with some adversarial behaviors.

Acknowledgments

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IRP1.2: Decentralised Control for RES by Fast Market-based Multi-agent Systems

ESR1.2: Hazem Abdelghany, TU Delft.

Paper in Progress

I. Introduction

Future power distribution grids will face unconventional challenges caused by electrification of energy demand, decentralization of power generation, and integration of renewable energy resources. As a response, Market-based control (MBC) represents a possible approach for demand response aiming at efficient utilization of flexibility from distributed energy resources (DER), while maintaining scalability, openness, end-user privacy, and autonomy.

In a setting of real-time market-based demand response autonomous agents trade in an automated spot market on behalf of their devices with a local objective (e.g. profit maximization) and subject to local constraints (e.g. device limitations, user's comfort, etc.). In such a setting, optimal bidding by flexible DER agents is necessary to make best use of the device's flexibility over a period of time (from a prosumer's perspective) and maintain local constraints. In literature, however, there is a lack of detailed control algorithms for device agents in the context of MBC. Existing research either uses simplified models, neglects realistic parameters, uncertainty, or provides practically infeasible solutions.

We address the problem of optimal bidding by flexible DER agents over multiple time-steps with uncertain price predictions. We model the problem as a Markov decision process (MDP) and exploit different characteristics of different device types to develop optimal bidding algorithms that are practically feasible (i.e. executed online by computationally small embedded controllers).

II. Optimal Bidding by Flexible DER Agents in Real-Time MBC

Many works point out the problem of bidding in real-time market-based control. However, detailed control methods of DER devices, e.g. optimal bidding of these devices has not been sufficiently studied [1]. Sub-optimal bidding leads to inefficient utilization of flexibility over a period of time, failure to achieve local objectives, incentive clipping, violation of local constraints, or failure to maintain system operability [2]–[4]. In [4] an example of sub-optimal bidding is shown where agents bid based on historical average prices. Literature on the problem of bidding DER agents in real-time MBC usually relies on simplified models (i.e. neglecting uncertainty or using unrealistic assumptions). For example, in [5]–[7] deterministic price predictions were used in the bid formulation. In [8] Electric vehicles were assumed to charge only. Other approaches to the problem rely on complex models [9], while the problem can be solved conventional optimization solvers, the small computational capabilities of device controllers are usually challenging. Similar characteristics for each type of devices can be exploited to develop device specialized algorithms with less complexity and high scalability [6].

III. MDP Model and Device Specialized Optimal Bidding

Assuming a real-time MBC with probabilistic price predictions, DER agents are required to formulate real-time bids with the objective of maximizing expected profit/minimizing expected cost within local constraints imposed by the user or device characteristics (e.g. deadline, minimum uptime). The state of a device is represented by the energy required to fulfill the device's task and the real-time price. Special characteristics of different device types are exploited to develop device specialized algorithms for optimal bidding. Device types to be considered include uninterruptible time-shiftable device, electric vehicles, battery storage, distributed generation and heat pumps.

Developed algorithms are evaluated in terms of runtime and memory usage. Cost incurred/ profit realized using MDP based optimal bidding algorithms is compared to cases with complete information (i.e. about future time-steps) and deterministic planning (i.e. without uncertainty) to study the impact of uncertainty.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under Marie Sklodowska-Curie grant agreement No 675318

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Coordinating Energy Flexibility in the Electricity Distribution Grid

Shantanu T. Chakraborty, Remco Verzijlbergh, Zofia Lukszo

***Abstract*— To reliably operate an electricity distribution grid with a high penetration of RES, system operators need flexible resources that provide the functionalities of storing energy or modifying use, and reacting quickly to meet required operating levels. While at the industrial consumer level, demand response has resulted in significant reductions in energy demand, the provision of demand-side flexibility at the residential and commercial consumer level, remains an area of active research that is currently being explored.**

Energy flexibility through aggregator function is expected to provide services to the DSO for addressing issues of congestion management and voltage regulation at the distribution grid. Furthermore, DSOs are viewed as key players for enabling a successful energy transition, in which they are expected to guarantee distribution system stability, power quality, technical efficiency and cost effectiveness in a smart grid that has a high penetration of variable RES generators. Thus for the DSO to accomplish its goal, its coordination with aggregators is crucial and further clarity on this topic is desired. In the light of this requirement, the purpose of this project is to shed light on the coordination of energy flexibility between the DSO and the aggregator in a future electricity grid that has a high penetration of RES.

I. Introduction

In 2014, as part of the 2030 framework for climate and energy, the European Union (EU) committed to increase the share of energy efficiency and renewable energies to 27% of gross energy consumption [1]. To achieve these goals, the penetration of renewables at the distribution grid is expected to significantly increase. However, there is a high level of uncertainty and variability associated with the outputs of RES generators, which poses serious challenges to the operation of the power system. Increasing the energy flexibility at the distribution grid is viewed as one of the possible solutions to ensure stability and reliability of the system in the presence of high penetration of RES. Aggregators provide an opportunity to aggregate flexibility provision from small-scale residential and commercial consumers and offer these flexibility services to the system operators such as the Transmission System Operator (TSO) and Distribution System Operator (DSO) through markets such as ancillary service markets or through bilateral contracts.

Hence, an important cornerstone of this project is to investigate the coordination of energy flexibility between DSO and the aggregator in a future electricity distribution grid that has a high penetration of RES. 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 [2]. In our research, we intend to focus on the two perspectives simultaneously. Furthermore, 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 while the aggregators seek their objectives of maximizing profit, the impact of aggregator actions on the distribution grid are largely not considered. If the aggregators operate solely with a profit-maximizing strategy, they will cause significant voltage deviations and network congestions that will increase the operation cost of DSO.

Secondly, currently there is limited knowledge available regarding institutional arrangements that facilitate the coordination between DSO and aggregators and their impacts on the distribution grid operation. Market mechanisms for local flexibility markets [3], quota based models [4], grid capacities [5] have been theorized, but they lack a mathematical formalism, without which it would be challenging to perform a quantitative assessment of the coordination mechanism.

Finally, in the future, it is expected that more aggregators would connect to the grid. In such a distribution grid, the DSO will be required to coordinate with multiple aggregators. Previous studies on this topic have assumed a hierarchical centralized approach [6] for minimizing network operation costs and reducing network peak loads. However, in such an approach aggregators are required to share sensitive information with each other, which could compromise privacy of aggregator operations and their customer profiles. Furthermore, in previous studies, simple models of the distribution grid have been assumed which are not able to account for power losses and congestions in the distribution grid. 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 low voltage electricity distribution grid with high RES penetration to address issues of congestion management and voltage regulation while minimizing network operation costs?"*

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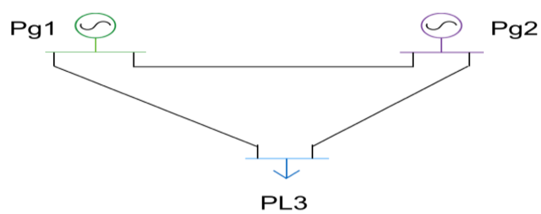
III. RESEARCH PROPOSAL AND PLANNED METHODS

A. *Directly Constraining Marginal Prices*

To address our main research question, we will break down the problem into multiple steps. Our first step in this regard is to determine possible strategies for coordinating flexibility between DSO, aggregator and consumers in the operation of the distribution grid while accounting for energy costs and grid constraints [7].

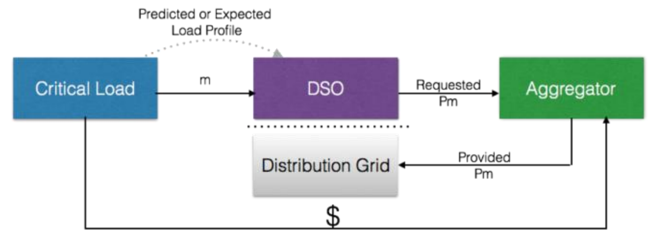
For this, we would like to consider the case of an optimal power flow (OPF), in which the dual variables represent the cost of supplying an additional unit of power to the whole system. Dual variables can be used for many additional tasks such as the analysis of system congestion and the determination of the cost of load adjustment. In a distribution grid, it may happen that critical loads such as industrial plants, data centers, hospitals, etc. might want to have control over the prices that they pay for electricity. In this regard, critical loads can announce to the market facilitator (DSO) the prices that they would prefer to pay, and through the services of flexible load aggregators they could perform the required load reduction such that their desired price is constrained lower than the nodal marginal price. A pictorial view of the problem setup is as follows:



Furthermore, to ensure that the LMP at Node 3 is less than a price value, say “m”, the following optimization problem can be setup:

$$\begin{aligned} \underset{P_G, P_L, P_m}{\text{maximize}} \quad & -aP_G + bP_L - mPm \\ \text{subject to} \quad & \underline{P_L} \le P_L \le \overline{P_L} \\ & P_G - P_L - P_m = 0 \\ & P_G, P_L, P_m \ge 0 \end{aligned}$$

In the above equation, P_G and P_L represent the magnitude of power generation and load consumption. P_m corresponds to the magnitude of load reduction required to ensure that the nodal price at node 3 is less than the consumer specified value of “m”. The main novelty of this approach would then be that it makes it possible to mathematically include explicit constraints on electricity prices in a demand response structure through which issues such as price volatility and market power can be mitigated. Previously, such approaches have not been investigated in much detail, mostly because of the fact that price is generally an output of the optimization problem and is not known a priori. Using optimization duality theory, prices can be directly constrained, which translates to required load reduction variable in the original optimization problem. To incorporate such a structure, we will further perform a comparative study in which different market mechanisms will be compared.



B. *Co-Simulation of Fuel Cell Electric Vehicles*

Using the institutional arrangement derived above, we move our focus to quantifying the impacts of this arrangement on the operation of the grid. For doing so, we intend to use a co-simulation based approach, in which we consider a fuel-cell based electric vehicle (FCEV) aggregator in the context of urban areas, that comprise of both commercial and residential loads. In this co-simulation environment, we will couple the social layer, where we implement the interaction between the various actors depicted previously, with the technical components of the grid which will be modelled through simulators for distribution grid components. The information flow among the modules, which is a critical component, will be accomplished through digital real-time simulators which facilitate real-time synchronized data processing.

C. *Distributed Optimization for Flexibility Coordination*

We next intend to extend our simulation to subsume a scenario in which we have multiple aggregators and critical loads. Here, we will address issues of scalability, ensuring privacy, and asynchronous communication during system operation. To implement this setup, we will build on the work done in [8] and use the Consensus + Innovation Distributed Optimization approach. Through the application of the algorithm on representative network models [9] we aim to generate insights on the impact of flexibility coordination on the operation of the distribution grid in terms of operation costs and technical parameter analysis.

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Short-term forecasting of solar irradiance without local data

Jesus Lago, Fjo De Ridder, Bart De Schutter *

I. INTRODUCTION

With the increasing integration of renewable sources into the electrical grid, accurate forecasting of renewable source generation has become one of the most important challenges across several applications. Among them, balancing the electrical grid via reserves activation is arguably one of most critical ones to ensure a stable system. In particular, due to their intermittent and unpredictable nature, the more renewables are integrated, the more complex becomes the grid management [1]. In this context, as solar energy is one of the most unpredictable renewable sources, the increasing use of solar power in recent years has led to an increasing interest in forecasting radiation over short time horizons. In particular, in addition to reserve activation to manage the grid stability, short-term forecasts of solar radiation are paramount for operational planning, switching sources, programming backup, short-term power trading, peak load matching, scheduling of power systems, congestion management, and cost reduction [2], [1].

II. SOLAR IRRADIANCE FORECASTING

For forecasting solar irradiance, techniques are categorized into two subfields according to the input data and the forecast horizon [3]:

1) Time series models based on satellite images, measurements on the ground level, or sky images. These methods are usually suitable for short-term forecasts up to 6 h. Within this field, the literature can be further divided into three groups.
    a) Statistical methods like ARIMA models [2] or the CARDS model [4].
    b) Artificial intelligence models, e.g. neural networks [5] or decision trees-based models [6].
    c) Cloud moving vector models that use satellite images [7].
2) Numerical weather prediction (NWP) models that simulate weather conditions. These methods are suitable for longer forecast horizons, 4-6 hours onward, time scales where they outperform the statistical models [8].

In this work, we focus on the first type of methods, i.e. time series models, to predict solar irradiance for short-term horizons (less than 6 hours ahead).

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III. MOTIVATION AND CONTRIBUTIONS

To the best of our knowledge, due to the time series nature of the solar irradiance, the statistical and artificial intelligence methods proposed so far have considered past ground measurements of the solar irradiance as input regressors [3]. While this choice of inputs might be the most sensible selection to build time series models, it poses an important problem: local data is required at every site where a forecast is needed. In particular, if we consider the geographical dispersion of solar generators, it becomes clear that forecasting solar irradiance is a problem that has to be resolved across multiple locations. If ground measurements of all these sites are required, the cost of forecasting irradiance can become very expensive. In addition to the cost, a second associated problem is the fact that obtaining local data is not always easy. As a result, in order to obtain scalable solutions for solar irradiance forecasting, it is important to develop global models that can forecast without the need of local data. In this context, while current cloud moving vectors might accomplish that, they are not always easy to deploy as they are complex forecasting techniques that involve several steps [3].

In this paper, we propose a novel forecasting technique that tries to address the mentioned problem by providing a prediction model that, while being accurate and easy to deploy, it forecast solar irradiance without the need of local data. The prediction model is based on a *deep neural network (DNN)* that, using satellite images and ECMWF weather forecasts, is as accurate as local time series models that consider ground measurements. The model, while it uses satellite images as cloud moving vector models, it is easier to deploy as it does not require complex computations, e.g. motion vector fields.

IV. PREDICTION MODEL

A key element to build a prediction model that can be used without the need of ground data is to employ a model whose structure is flexible enough to generalize across multiple geographical locations. As DNNs are powerful models that can generalize across tasks [9], a DNN is selected as the base model for the proposed forecaster. This concept of generalization is further explain in Section IV-B .The model consist of 6 output neurons representing the forecasted hourly irradiance over the next 6 hours; this horizon is the standard choice for short-term irradiance forecasting [3]. In terms of hidden layers, the model is not subject to any specific depth; instead, depending on the case study, i.e. the geographical area where the forecasts are made, the number of hidden layers are optimized using hyperparameter optimization. To select the number of neurons per layer, the same methodology applies, i.e. they need to be optimized for each geographical location.

A. Model Inputs

As indicated in the introduction, the aim of the model is to forecast solar irradiance without the need of ground data. As a result, to perform the selection of model inputs, it is paramount to consider the subset of inputs that, while correlating with solar irradiance, are general enough so that they can be easily obtained for any given location. Given that restriction, the proposed model consider three types of inputs:

1) ECMWF forecasts (weather-based forecast) of the solar irradiance at the prediction times. While weather-based forecasts are less accurate than time series models for short-term horizons, they strongly correlate with the real irradiance.
2) Satellite images representing the past radiation maps in a geographical area. For the proposed model, the input data consists of the past radiation values in the individual pixel where the forecasting site is located.
3) The clear-sky irradiance at the prediction times.

B. Generalizing across geographical sites and horizons

A key element for the model to forecast without the need of ground data is to be able to generalize across geographical sites. To do so, the proposed model is trained across a small subset of sites where ground data is available so that the model learns to generalize across geographical sites. It is important to note that, while ground data is required for this small subset of locations, the model generalizes across all other geographical locations where ground data is not needed. In particular, as we show in our case study, the number of locations where ground data is required is relatively small, i.e. 3-5 sites is enough. To further strengthen the generalization capabilities of the network, the DNN is also trained to forecast at different hours of the day. In particular, as the network forecast the hourly irradiance of the next six hours, it is trained to forecast starting at any given hour of the day.

V. Case study

In order to evaluate the proposed model, we consider 30 sites in the Netherlands during 4 years (2014-2017) and we train the model using data from 5 sites and spanning three years (2014-2016). Then, we evaluate the model using an extra year of data (2017) and the remaining 25 sites.

A. Local models

To compare the proposed forecaster, we consider four types of local models: a persistence model, an autoregressive model with exogenous inputs (ARX), a gradient boosting tree algorithm, and a local DNN. As the models are local, they are individually trained for each location, i.e. each location has a different local model. The exogenous inputs of these models are similar to the proposed DNN, but instead of using the satellite radiation maps, the models consider the historical irradiance ground measurements. As these models are to be compared with the proposed DNN, we train a model for each of the 25 sites of the test set.

B. Main Results

The proposed global model is able to obtain predictive accuracies equal or better than all the local models. In particular, using the relative root mean square error (rRMSE) as the metric of choice, the following observations can be made:

1) The global DNN has an average accuracy over the 25 sites and the 6 prediction horizons of 24.5% rRMSE. All the local models have accuracies that are above 30% rRMSE. The only exception are the local DNNs, which display an accuracy of 24.5% and perform equal to the global DNN.
2) If we look individually at every site and at every predictive horizon, this relative performance still holds. The accuracy of the global DNN is equal to the local DNNs but better than all the other local models.

C. Discussion and Conclusion

Based on the obtained results we can conclude that, without the need of local data, the proposed model is able to obtain equal or more accurate predictions than the local models. As solar irradiance has become increasingly important, obtaining ground data is expensive, and classical models require ground measurements, the proposed method is very relevant as it reduces the monetary cost of forecasting without comprising the quality of the forecast.

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A Case Study of Model Predictive Control for HVAC Systems in an Office Building

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I. Introduction

The increasing penetration of variable renewable sources of energy (e.g. solar and wind) poses potential threats to the energy grids. To help tackle this issue, unlocking the energy flexibility of the building stock is considered as a promising solution. Model Predictive Control (MPC) notably has shown effective results for implementing demand response schemes.

Before to use MPC for harvesting the energy flexibility, such control strategies can also be used simply to improve the energy management of buildings, for instance with the goal of reducing the running costs [1]. Commercial applications of MPC are already being deployed on the market[2], for instance in office buildings [3].

In the present work, such actual implementation in a real building is analyzed in details, in particular the models and forecasts that are used in its configuration. The study case is an office building of 10 000 m^2 situated in Brussels, Belgium. The MPC configuration (implemented in May 2017) aims at reducing the discomfort and the energy costs of the boilers and chiller used to condition the indoor space. Since MPC heavily rely on a simplified model of the building and on weather forecasts, it is important to understand how the accuracies of these models and forecasts can affect the overall control performance. For this reason, these elements have been studied in depth, and help understanding the functioning of the MPC. This knowledge will be beneficial when utilizing MPC for further objectives than the sole economic one.

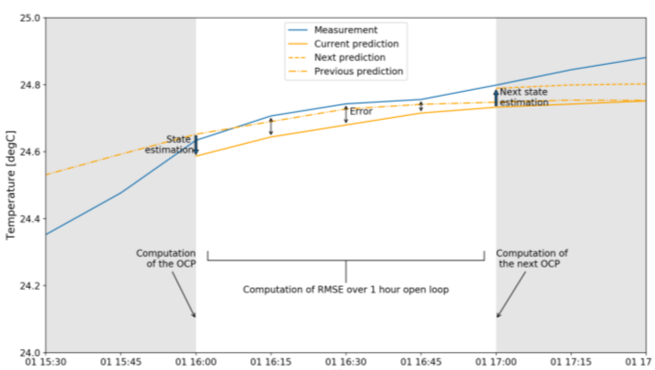

Figure 1. Principle of the analysis and the RMSE calculation.

The present study analyzes data gathered from the building operation between May and November 2017. In section II and III, the respective accuracies of the models and forecasts in use are discussed. In section IV, the interaction of the MPC with the night cooling ventilation (unknown by the controller) is presented, as well as the benefits of such operation.

II. Accuracy of the Model in Use

The principle of the accuracy calculation is shown in Figure 1. The Optimal Control Problem (OCP) is computed every hour and starts with the state estimation. During the following hour, the system runs in open loop, following the optimal plan predicted by the MPC. The Root Mean Square Error (RMSE) on the zone temperature is computed only during this open loop hour (data points every 15 min), since the model prediction is updated afterwards, starting from a new state estimation. An hourly time series of the RMSE is thus obtained, and further analyzed.

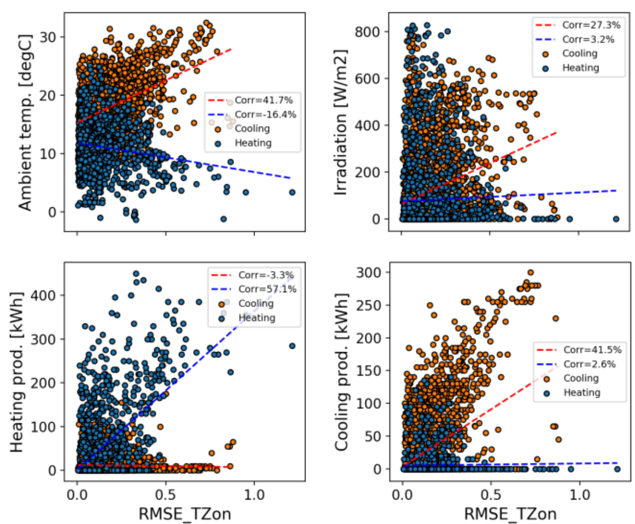

Figure 2. Scatter plots of the RMSE with selected parameters (ambient temperature, solar irradiation, cooling and heating productions)

On average, the RMSE of the zone temperature (which is the mean of temperatures measured within the whole building) is 0.16°C. The scatter plots of the RMSE values against other selected parameters are represented in Figure 2. It can be observed for instance than the model error is correlated with the cooling production: the model was fitted in heating season and should probably be re-estimated for the cooling season, using the data recorded in summer as training dataset.

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III. ACCURACY OF THE FORECASTS

The considered endogenous variables are: the ventilation profile, the occupancy factor and the Domestic Hot Water (DHW) draw-off profile. The two first were not directly measured, therefore they cannot be compared with the expected behavior. The DHW profile follows a weekly persistent model, meaning that the profile of the same day of the previous week is assumed as the prediction of the current day. This assumption proved to be sufficient, at the condition of considering bank holidays where the occupancy is different (otherwise an error is propagated during two weeks).

The exogenous forecasts considered by the MPC are the outside temperature and solar irradiation, retrieved from an external service. Their RMSE are respectively 0.6°C and 70 W/m^2, which is not negligible. The impact of the forecast error will be analyzed in further work, recomputing the MPC for every hour with a “perfect forecast” (i.e. with the actual recorded weather in the following three days).

IV. INTERACTION WITH NIGHT COOLING OPERATION

A. *Night cooling operation*

During the summer, a strategy of passive night cooling is implemented: from 1:00 to 6:00 the fans of the mechanical ventilation system are activated, with conditions on the temperatures of the outside and inside air. This strategy enables to cool down the building saving chiller energy for the next day. The temperature drop over the night reached 1.36°C on average (0.46°C) without night ventilation.

B. *Energy savings due to night cooling*

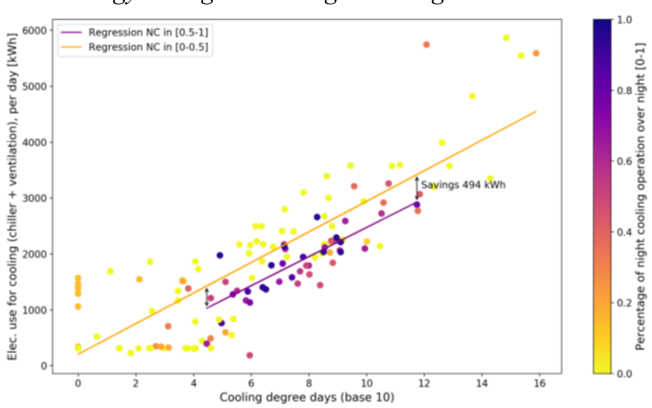

Figure 3. Savings provided by the night ventilation.

Figure 3 analyzes the night cooling operation in terms of energy savings. Each dot represents the entire energy for cooling per day, including both the chiller energy during the day and the energy of the fans during the night. The color mapping shows the percentage of night cooling operation during that night. It can be observed that on average the days with more than 50% night cooling operation (purple trend line) lead to around 494 kWh savings, compared to the days with less than 50% of night cooling (yellow trend line). This corresponds to economic savings of about 74 € per working day. The night cooling operation increases the consumption of the fans during the night (+120 kWh for full night operation) but decreases the energy used by the chiller the following day (-625 kWh on average). The overall balances is thus positive and validates the utilized control strategy.

C. *Interaction with the MPC*

Night ventilation cooling runs entirely on a rule-based control. The MPC controller that manages the rest of the building operation is not aware of this operation, and this could thus affect its predictions. The error on the zone temperature over the night (from 1:00 to 6:00, period of the potential night cooling operation) is computed. It is thus observed that when night cooling is on all night, the error can reach up to 1°C at 6:00 (overestimation, i.e. the MPC predicts a higher temperature since it does not know about the passive cooling occurring), which is a consequent value. However, since the MPC is updated every hour, the impact of such error is mitigated.

V. CONCLUSION

This work has enabled to develop a better comprehension of the functioning of an MPC controller for building climate control. In particular, the impact of the models and the forecasts in use has been analyzed. The MPC seems to operate in a robust manner: even though the building model is relatively simple and the weather forecasts contains important inaccuracies, the fact that the optimal plan is recomputed every hour enables to avoid serious consequences on the system behavior. However, the MPC only controls the overall average temperature of the building, and does not account for more specific local conditions (which are likely to vary in such a large building). The night cooling operation proved to be beneficial, with important energy savings when it is operated all night long.

Further work includes the analysis of the ideal improvements that the MPC would get if it had access to perfect weather forecasts.

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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 accelerated in the last couple of decades. The increasing price of the fossil fuels, the various government policies, incentives and protocols for capping carbon emissions have contributed to this drive [1] [2] [3]. The modern electric network is seeing a major overhaul in that it is 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 be unstable 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. The ESS ensures supply-demand balance, provide spinning reserve 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 low level controller for the converters will also be shown.

II. CONTROL ARCHITECTURE FOR STORAGE SYSTEMS

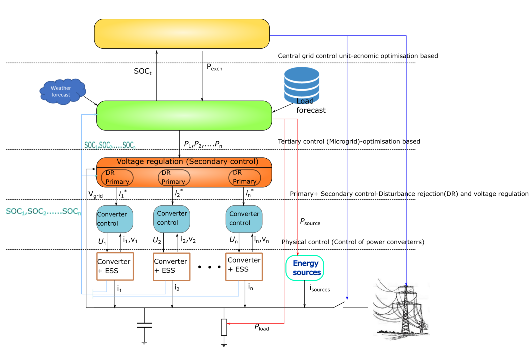

Fig. 1. Control architecture for the ESS

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. Thislevel takes care of the optimal power flow problem of the microgrid especially in the islanded mode of opration. 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 of the control architecture supervises the operation of main grid to which different microgrids are connected. This level optimises main grid performance, decides which midrogrid has to connect to grid and decides energy exchange between different microgrids.

III. RESULTS

The work of ESR has focussed on the implementation of a hybrid reset PI+CI controller for converter control. This controller ensure the reference tracking of the converter but with an improved performance over its linear counterpart (PI controller). The PI+CI controller is capable of fast flat response with no overshoot. The PI+CI controller has a PI controller with a Clegg integrator(CI) connected in parallel. The CI resets its output when the input to it is zero. This condition which causes the reset is called the reset law. The PI+CI is represented as in Fig.3. The reset ratio ρ_r shows the percentage of integral action that gets reset through the controller. Designing an appropriate value of ρ_r can ensure a fast flat response. The schematic of converter considered in given in Fig.2. The mathematical representation of such

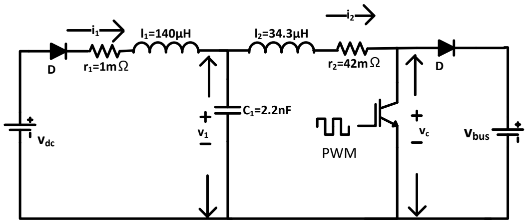

Fig. 2. Schematic of PI+CI controller

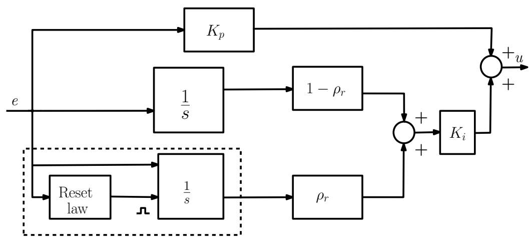

Fig. 3. Schematic of PI+CI controller

a system is given using impulsive differential equation [8]

$$\begin{cases} \dot{\rho}_r(t) = 0, \dot{\mathbf{x}}_r(t) = \mathbf{A}_r\mathbf{x}_r(t) + \mathbf{B}_r e(t), & e(t) \neq 0 \\ \rho_r(t^+) = \mathcal{P}(\mathbf{x}_r(t), e(t)), \mathbf{x}_r(t^+) = \mathbf{A}_\rho \mathbf{x}_r(t), & e(t) = 0 \\ u(t) = \mathbf{C}_r(\rho_r(t))\mathbf{x}_r(t) + \mathbf{D}_r e(t) \end{cases} \tag{1}$$

where matrices $\mathbf{A}_r, \mathbf{B}_r, \mathbf{C}_r, \mathbf{D}_r$ and $\mathbf{A}_\rho$ are

$$\mathbf{A}_r \triangleq \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \quad \mathbf{B}_r \triangleq \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \quad \mathbf{C}_r \triangleq k_i \begin{bmatrix} 1-\rho_r & \rho_r \end{bmatrix}$$

$$\mathbf{D}_r \triangleq k_p, \quad \mathbf{A}_\rho \triangleq \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$$

where $\mathbf{x}_r = [x_i \; x_{ci}]^T$ are the states of the controller defined by the integrator (x_i) and CI (x_{ci}) states, $\mathbf{x}_r(t^+) = \mathbf{x}_r(t+\varepsilon)$ with $\varepsilon \longrightarrow 0^+$, $e(t)$ is the error of the system, $\mathcal{P}(\mathbf{x}_r(t), e(t))$ is the variable reset ratio function defined as $\mathcal{P} : \mathbb{R}^2$ x $\mathbb{R} \rightarrow \mathbb{R}$ and $\mathbf{C}_r(\rho_r(t)) = k_i[1-\rho_r(t) \; \rho_r(t)]$.

The output response of the DC-DC boost converter showing the flat response for a ρ_r of 0.4889 is shown in Fig.4. The reset instance can be seen in Fig.5 which shows the control action of the controllers. The sharp reduction in the controller output for PI+CI caused by the reset action drove the system to steady state after the first reset instant.

IV. Research status

Presently the work done by the ESR is focussing on the development of a primary+secondary controller for the grid connected ESS systems which ensures disturbance rejection and voltage regulation. An adaptive observer based disturbance rejection controller is considered in this frame work. The designing, modelling of the proposed controller will be done along with the lab implementation of the same to study the feasibility of such controllers in an interconnected system of different ESS.

Thereafter the focus will be on the development of a tertiary controller for the control of microgrid. The stochastic nature of RES generation and load profiles will be considered here and stochastic MPC based controllers will be considered. It is also expected to complete the first secondment at

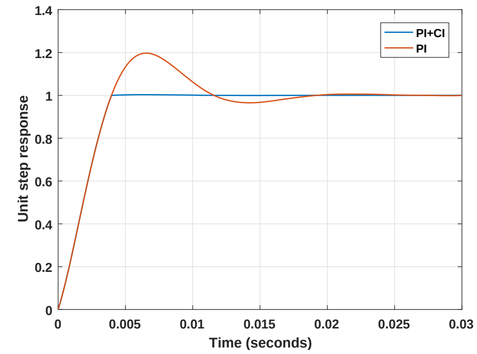

Fig. 4. Output comparison of a PI and PI+CI controller

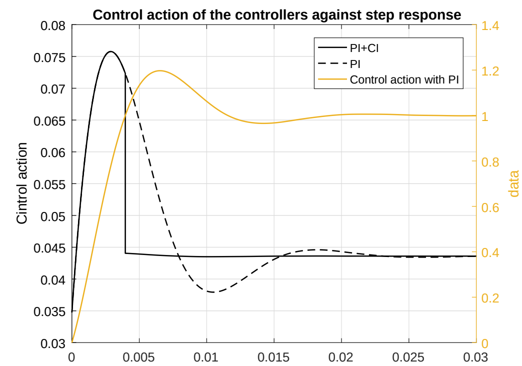

Fig. 5. Control action for the controller

EFACEC, Porto between April- July where he will continue working on the development of supervisory control levels.

V. Acknowledgments

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

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Modeling and Control Methods for Large-Scale Systems and Microgrids

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I. Introduction

The changes in the power networks in the recent years have created new opportunities but also new challenges to face. Elements such as energy storage systems, renewable energy sources, and electric vehicles are new elements in the grid that must be considered both in the design and control of the power grid. Moreover, these elements may have a time-varying nature. For instance, consider electric vehicles, which are elements that can be considered as energy storage systems that move around in the network from one point to another, or topologies of the power network that can change in time due to broken links, i.e. links between different nodes in the network that are temporarily not working. Another new feature in the power grids is the fact that the power produced by renewable energy sources cannot be controlled directly, therefore there is now less flexibility from the supply side and control actions must face this problem.

Energy storage systems have also been included recently in microgrids, in order to increase the flexibility of the system. When considering a microgrid operation optimization problem, energy storage systems can be included in order to store energy when the production is higher than the consumption, so that the stored energy can later be used in the opposite case. Control strategies that aim at optimizing the operation of a microgrid by minimizing an economical cost, must then take into account the dynamics of energy storage systems in order to achieve optimal performance.

These new elements included in smart grids must be considered during the controller design phase. Here we propose two different solutions to control problems related to power networks: a partitioning approach for time-varying linear systems and a microgrid operation optimization approach.

II. Partitioning approach for time-varying systems

Large-scale systems (LSSs) are systems in which the number of elements acting in the system are large in number and they are geographically widespread. When it comes to control them, in some cases, applying a centralized controller might be difficult or even impossible to realize, especially in cases in which there exist communication issues, e.g. the communication infrastructure is not reliable or there are delays in the communication, or when the high number of elements of the network leads to a high computational complexity. A standard approach is therefore to split them into several subsystems, such that a non-centralized control action can be applied [1]. Then each subsystem would have its own controller that uses local information only to compute the control action. In a decentralized setting, only the information of the subsystem under control is used, while in distributed control the information on the subsystems of the neighbors is considered too.

Apart from splitting the network into subsystems, the goal of the partitioning process is to reduce the coupling between subsystems, so that a non-centralized controller can obtain good performance even without directly taking the coupling into account. Moreover, the subsystems should also be balanced, i.e. they should have a similar number of elements, so that the computational effort of each controller is similar.

Although many solutions have been proposed in the literature for network partitioning [2]–[4], so far little or no interest has been given to partitioning of time-varying systems. This is important to consider because, as explained in Section I, power networks may have time-varying elements that change the topology of the network. We propose therefore a new partitioning algorithm [5], inspired by multi-step graph partitioning methods [2], [3], in which we predefine the number of subsystems, making sure that each subsystem has at least one input. This feature makes our algorithm different from other global methods, e.g. recursive bisection methods [4]. We apply the partitioning approach to a special class of time-varying systems, i.e. switching systems, and we assume that the different modes of the system are known. Then, for each of the modes, we apply the proposed partitioning approach offline, so that to every mode we associate an optimal partition.

After the partitions have been computed, we apply a decentralized state feedback control scheme, computing also the gain matrices offline. The gain matrices are computed in such a way that the closed-loop centralized system is asymptotically stable for each mode. By applying an adapting previous results from the literature [6], [7], we are able to guarantee exponential stability of the closed-loop system. Moreover, we also apply our proposed approach to an automatic generation control problem in a network with different generators, inspired by [8]. In the simulations we show that our approach is able to stabilize the system even when some links of the network are temporarily broken. Lastly, we also show that if the partition is not changed during the simulation even after the topology of the system changes, i.e. the partition is not adapted to the changes in the system, the system might become unstable. This therefore motivates our time-varying partition scheme.

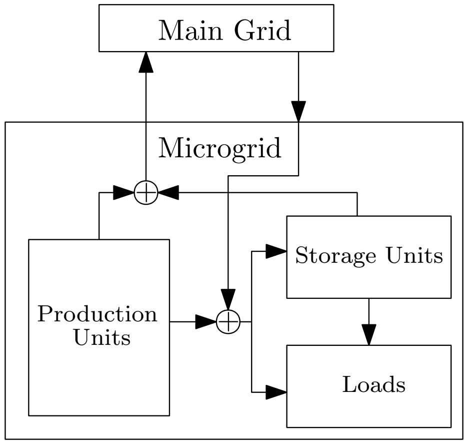

Fig. 1. Microgrid scheme considered for our work.

III. Microgrid operation optimization

Recently the microgrid operation optimization problem has received an increased amount of attention in the field of control [9]–[11]. In these works, the goal is to minimize an economical cost by managing the components of the microgrid in a grid connected mode, i.e. local production units, local loads, energy storage systems. To this purpose, a suitable control approach is Model Predictive Control (MPC), since it allows to convert the control problem into an optimization one, thus naturally allowing to include constraints and a cost function in the control problem. The optimal setpoints for power exchanged with the energy storage systems and with the main grid and the power produced by the generators are then obtained.

Some papers [10]–[12] consider a two-level hierarchical controller, where a centralized controller, which has a higher sampling time, computes the optimal setpoints for a lower level controller that has the task of leading the system to the desired setpoints. With this kind of approach, there is the need to introduce an extra level of control and more communication is also needed. Moreover, more computational power is required, since two different problems have to be solved in parallel.

Therefore, we propose an approach with a single-level MPC controller, where the controller uses two different models to predict the future states and outputs. In particular, one of the two model includes 'fast' dynamics, while the other one includes 'slow' dynamics. This not only means that the two models have different sampling times, but also that they may have a different number of states. Indeed, the predictions that are far from the current time instant are related to the steady state of the system and therefore the fast dynamics can be disregarded. Therefore, for prediction purposes, we use the model with 'fast' dynamics only until a certain time instant and thereafter we use the simplified model with 'slow' dynamics. This approach is also referred to as *multi-scale* modeling, meaning that different models with different time scales of the system under control are used. The main benefit of this approach is a reduced computational complexity, since a simplified model is used for predictions that are far from the current time instant. Moreover, since the sampling time is also bigger, extra computational complexity savings can be achieved.

As a case study, We consider a microgrid with two different kinds of energy storage systems, i.e. batteries and ultracapacitors, critical loads, dispatchable and non-dispatchable generators, connection to the main grid, and a variable price scheme. The resulting control scheme can be found in Fig. 1. The task of the controller is therefore to manage the power flowing in the microgrid in order to minimize the economical operational cost. The expected outcome is to obtain similar results with respect to current solutions in the literature, with a decreased amount of computational complexity.

Acknowledgments

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An Impedance-based Approach to Modelling of Large-Scale Hybrid ac/dc Grids

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***Abstract*—In a rapidly changing energy landscape, large-scale hybrid systems are expected to be the backbone of future power systems. Such a large-scale system, with myriads of uniquely different devices requires a systematic approach to modelling. This paper presents a method of modelling hybrid ac/dc grids to any detail required, in an effective and systematic manner, based on known modelling paradigms. At a physical (low-level) level, irrespective of size, structure or grid (ac/dc), the system is inherently made up of impedances. Therefore, this methodology exploits this idea, by modelling every identified subsystem with its representative impedance in s-domain. Meanwhile, all input devices; that is, all controlled devices in the system are represented by an impedance that includes the effect of control. All subsystems that make up the entire system are connected together in their physical structure for aggregation. This results to a tractable method for which multivariable control theory can be applied. Sequel to this, formal methods in control systems theory can be applied for investigation and studies.**

***Index Terms*—Impedance modelling, multi-scale systems, hybrid ac/dc grids**

I. Introduction

Power system literature on emerging issues over the last decade have been offering glimpse on the potential structure of future power systems, considering the impact of renewable energy integration, and changing energy landscape [1], [2]. A general consensus in the power engineering parlance is the expected role of power electronic converters and hybrid ac/dc grids. The rapid advances in the field of power electronics have opened up potentials for a vast hybrid ac/dc based on VSC (voltage source converter) technology [3], that could potentially span regions, power markets, and national borders.

It is widely expected that, whilst dc grids and domination of converter based generation are a close reality, operation would still be in connection with the existing ac network, potentially with some synchronous generation and their control present [4]. This practice is already changing the dynamics of the well-know conventional power system. System wide interactions are expected between the power electronic devices and devices in conventional power systems.

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It is a well known fact that the dynamics of the ac grid is different from that of the dc grids. This has complicated efforts to model both systems to considerable detail efficiently. This is as a result of the different tools available. AC grids have well demarcated dynamics in time-scale that allows for application of different tools for various dynamics based on their associated time constants [5]. On the other hand, dc grid dynamics are orders of magnitude faster than the ac grid in general, and depending on the control implemented, dynamics could be slower potentially causing interactions with ac grid. This has necessitated the need for new tools capable of combining both ac and dc grids simultaneously and with sufficient details for the most important studies. Developed tools should be capable of providing valuable insights for designing the most ideal control systems for secure and reliable operation.

Literature on tools for hybrid ac/dc grids are insufficient in the least as this is a relatively emerging issue in literature. Nevertheless, motivated by the expected domination of power electronic converters, the academic community has been exploring the impedance-based modelling paradigm. The impedance methodology has been introduced to cater for the unique peculiarities with power converters [6]. This methodology has been widely applied from the device perspective [6], [7] to analyse stability amongst other issues. The impedance modelling methodology has been further extended to analyse the resonance and stability issues of wind power plants connected via converters [8], [9]. In general, one converter has been the focus of study in most of the works. On very few works, impedance method has been applied to two converters connected in a point-to-point HVdc, particularly to the dc sides [10].

In this paper, we aim to go one step further by applying the impedance-based modelling for subsystem modelling by considering the entire system as a feedback. Sequel to this, the system is aggregated to obtain equivalent impedances. This includes both dc and ac grids. Such a method could be key to understanding the interactions between devices on the dc side and between the ac and dc sides on a multivariable scale. Thus allowing the application of multivariable control theory and techniques therein.

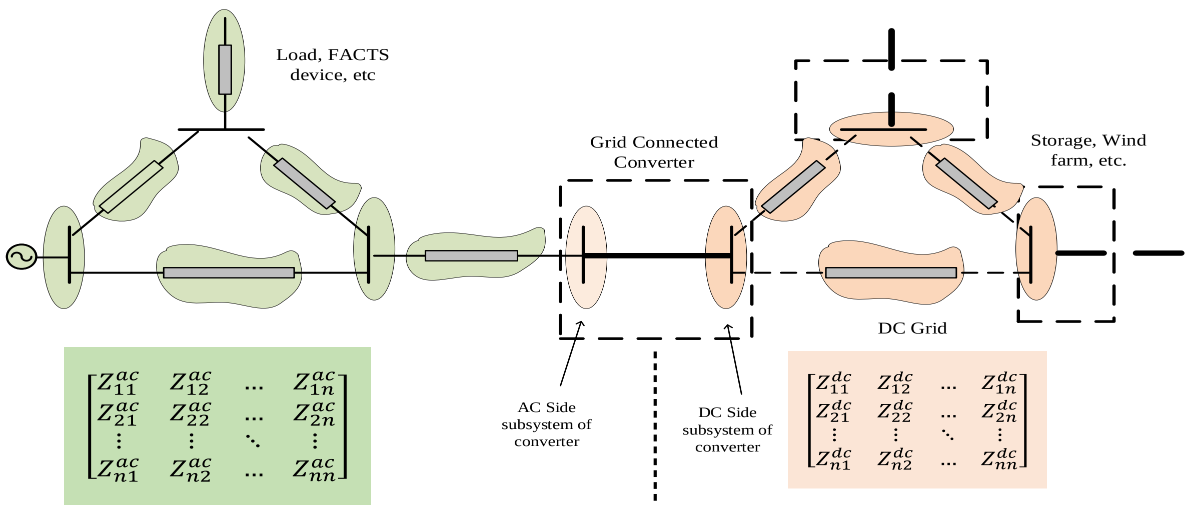

Fig. 1. Schematic diagram of Potential Structure of Future Power Systems

II. Impedance-Modelling of Subsystems

Impedance (admittance) is a fundamental property of the physical power system and its corresponding electrical circuit. In this paper, circuit components of each subsystem are represented by their s-domain equivalents and subsequently, the equivalent impedance (with sufficient details for the study at hand) that represent each subsystem is derived. For subsystems that are controlled devices, the impedance is modelled in a feedback approach. Sub-systems include, the dc cables/lines, ac cables/lines, filter (inductive and capacitive), transformers, loads, generator, converters, and as many components in the system.

Fig. 1 depicts a system level schematic of a potential hybrid network structure. This figure is only for illustrative purposes and does not depict any real system. The most important subsystems are the converter, its controls, and the synchronous generator with excitation control. More important is the converter with its often complicated control systems and varying modelling methods depending on the study in question. Both converter and generator are modelled in such a way as to obtain the closed-loop impedances representative of the converter, on each side (ac and dc). Control system may include the hierarchical control loops, the PLL (phase-locked loop), and other auxiliary control systems as required by study. For slow interactions and small-signal studies, the hierarchical control loops may be sufficient as is implemented in this work.

III. The Z_{BUS} Concept

The Z_{bus} is simply the bus impedance matrix widely applied in power system analysis. The elements of the Z_{bus} matrix is synonymous with the Thevenin equivalents as seen from each terminal and between terminals. In this work, these Thevenin equivalents includes the controls of each converter and generator in the system, and how each contribute to the dynamics of the others. Thus, such matrix is a dynamic matrix as opposed to its traditional application. A matrix is constructed for each of ac and dc grids, with each matrix containing individual and shared dynamics. Studies can be carried out on each matrix by simplifying or eliminating shared dynamics, or on both matrices for studies that involve both sides.

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INCITE Workshop Feb 2018 - Deliverable 6.5

IRP32: A new modeling approach for stabilization of smart grids

Felix Koeth

Abstract— **We investigate the linearization of a simplified power system model, resulting in a quadratic eigenvalue problem. We investigate the dynamical behavior by identifying clustering in and analyze how different system parameters influence this clustering and thus the dynamics of the system. We also compare the results with theoretical results obtained by a simplification of the model, which results in a generalized eigenvalue problem.**

I. Objective and Methodology

The aim of this work is to investigate the synchronization and stability of simplified power system models. We aim to better understand how the structure of the network and the systems parameters influence the stability, to guide the construction and regulation of power systems. We start by simplified power system models. In this models, synchronization has been observed and sophisticated conditions for synchronization have been proposed [1]. Starting from an synchronized equilibrium solution, we linearize the system to investigate its small signal stability. We investigate how the system evolves in the synchronous state, focusing on finding coherent behavior in clusters of connected nodes.

II. Power system modeling

We investigate the stability of the power system with the structure preserving (SP) model. A detailed explanation of different, simplified power system models and their deviation can be found in [2]. The corresponding equations are given in (1).

$$\begin{aligned} M_i\ddot{\theta}_i + D_i\dot{\theta}_i &= P_{M,i} - \sum_j B_{ij}V_iV_j \sin\left(\theta_i - \theta_j\right) \quad i \in \mathscr{V}_G \\ D_i\dot{\theta}_i &= P_{L,i} - \sum_j B_{ij}V_iV_j \sin\left(\theta_i - \theta_j\right) \quad i \in \mathscr{V}_L \end{aligned} \tag{1}$$

Here, $\mathscr{V}_G$ and $\mathscr{V}_G$ are the set of generators and loads, respectively, M_i are the generators inertia, D_i the generator and load damping (including control effects), $P_{M/L,i}$ are the mechanical input or load demand, V_i are the voltage magnitudes, B_{ij} is the imaginary part of the bus admittance matrix Y_{bus} and θ are the voltage phases. The system is said to be synchronous when $\dot{\theta}_1 = \dot{\theta}_2 = \dots$ and the maximum phase difference between connected buses is bounded [3].

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III. Linearization and analysis

We can linearize the right-hand side of both equations around a synchronous solution θ_i^0. Using $\tilde{M} = \operatorname{diag}\left(M_1, \dots, M_{|\mathscr{V}_G|}, 0_1, \dots, 0_{|\mathscr{V}_G|}\right)$[1] we arrive at the linearized system of (2).

$$\tilde{M}\ddot{\theta} + D\dot{\theta} = P_M - L\theta \tag{2}$$

The linearized system can be solved using $\theta = \sum_j \psi_j \exp\left(\lambda_j t\right)$ with ψ_j, λ_j being the solutions to the quadratic eigenvalue problem (QEP) $\left(\lambda^2 M + \lambda D + L\right)\psi = 0$. The dynamical behavior of the system is governed by the eigenvalues of the system and the eigenvectors. The dynamics of nodes are the same of the notes are dominated by the same eigenvalue and the corresponding eigenvectors have similar entries. This clustering is called slow/exact coherency and, for the case of $D_i = 0$, investigated in [4]. Important results from this thesis are summarized below:

- Load nodes (where $M_i = 0$) do not influence the dynamic directly and there behavior is only affected by the neighboring generator nodes.
- Strongly connected clusters[2] show slow coherency in the fastest modes (smallest eigenvalues).

Our aim is to investigate whether and how the damping effects this results. Also, we want to apply this results to realistic test cases.

IV. Computational results

To study how the simplification of neglected damping influences the results given in the previous chapter, we investigate system (2) for different parameters M, D, L and P_M. In the following, the IEEE 30 node test case is considered. The dynamical parameters are obtained as described in [5]. The QEP results in $2n = 60$ eigenvalues and corresponding eigenvectors. The eigenvalues are real or come in complex conjugate pairs [6], the eigenvector components can be complex, too. It should be noted that it is difficult to rank complex numbers. We are usually interested in the second smallest eigenvalue of graphs (the smallest eigenvalue is zero, as observed in the QEP). If we need to rank the eigenvalues, we will usually consider the absolute value of the complex number[3]

[1] Which is a singular matrix!

[2] Strongly connected clusters are of order $\mathscr{O}(1)$, while the intra-cluster connections are of order $\mathscr{O}(\varepsilon)$.

[3] Multiple complex number can have similar absolute values. In this work, especially complex conjugate pair have identical absolute values.

A. Definition of a cluster

We define a cluster of the Graph G of the system (with $a_{ij} = B_{ij}V_iV_j$ being the (weighted) admittance matrix of G) as the set of nodes C with:

- The eigenvector components corresponding to the nodes of C for a given mode are similar [4].
- The subgraph induced by C on G is connected.

We define the size of a cluster as the number of distinct clusters per mode (maximal n) and the size of the clusters as the number of nodes in each cluster.

B. Eigenvalue sensitivity

The coherency is mostly dependent on the eigenvectors of the system. Obviously, the eigenvectors depend on the corresponding eigenvalues. The perturbation theory of eigenvectors is directly related to the eigenvalues of the problem [7]. We can investigate the influence of different parameters of the system to gain an understanding of the behavior and identify the important parameters and parameter ranges.

C. Eigenvector sensitivity

In figure 1, the average number and size of clusters found in system (2) for different damping coefficients (for now, $D = \operatorname{diag}(D_0, \ldots, D_0)$ as the damping matrix) using the IEEE 30 test case is shown. Stronger damping inhibits clustering, seen by more and smaller clusters. A large jump between zero and small damping can be observed as well.

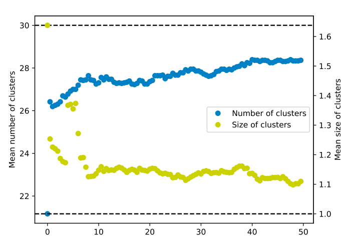

Fig. 1. Number and size of clusters for different damping coefficients.

We can also look into how the number of clusters change with respect to the modes. From the theory [4] the size of clusters should decrease with the mode. Also, for the zero eigenvalue, all nodes should be clustered, corresponding to the unified rotational dynamics of the system. The behavior is shown for two different damping coefficients in figure 2[5]. Clearly, decreasing behavior is found. Smaller eigenvalues (faster modes) show more clustering behavior, as expected from theory. A peak around a damping coefficient can be noticed. We are currently investigating the effects leading to this peak and ask whether a combination with critical damping is possible.

In figure 3, the cluster numbers and sizes with respect to a multiplicative factor for the coupling matrix L is given. We see, as expected, a small increase of cluster sizes, meaning

[4] x, y are similar iff $|x-y| \leq \left(10^{-1} + 10^{-4}\,|y|\right)$

[5] The zero eigenvalue is omitted as it would break the scale

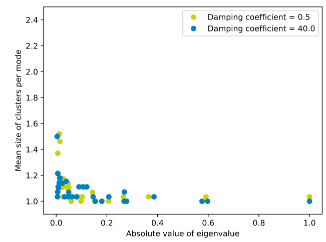

Fig. 2. Size of clusters with respect to mode for two different damping values.

stronger coupling increases the systems tendency to form clusters. But we can observe that the effect is generally relatively small.

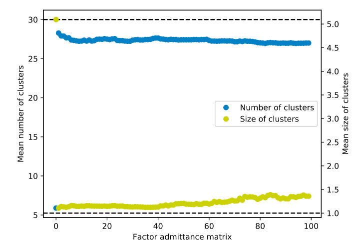

Fig. 3. Number and size of clusters with respect to multiplicative factor of admittance matrix.

V. Outlook

- Continuing investigating different IEEE and random graphs to try to see how and why clustering happens.
- Influence of the structure of the network, the order in the dynamical parameters on the clustering.
- Investigate which nodes are affected by clustering.
- Theoretical approach, based on [4], try to apply eigenvalue perturbation to extend problem to include damping.

VI. Acknowledgments

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Wind farms control strategies for grid support

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

I. Introduction

In the last decades, the electrical power systems have experienced significant changes due to the increase in the installations of renewable energy sources (RES). In 2017, the wind power capacity installed worldwide has reached 530 GW with an electrical production become relevant in a scenario previously dominated by conventional power plants [1]. Due to the increasing penetration of wind power plants (WPPs) in electrical power networks, some Trasmission System Operators (TSO) are requiring WPPs not only to satisfy the power demanded by the grid but also to provide ancillary services. Wind turbines do not inherently provide these services, but advanced control strategies have been proposed for wind farms and wind turbines to provide reactive and active power in order to participate in grid support designing voltage and frequency control actions. For example, it is required WPPs to participate in frequency control providing the power balance after frequency deviations. Conventionally, grid frequency response is divided into separate control regimes: inertial, primary and secondary responses. The wind turbines can take part in inertial frequency support releasing, within milliseconds, the kinetic energy stored in the rotating mass during the normal operation [2]. Likewise, wind farms can also participate in primary frequency control delivering extra active power within seconds by operating in de-loading mode. Thus, wind farms can meet TSO requirements and generate less power than the maximum available to guarantee the demand. In literature, wind farm control strategies are proposed to optimally redistribute such additional power, also known as power reserve, for minimizing the loads [3]. The authors in [4] propose an active power control able to estimate the wind speed to compute the power generated in de-loading operation. Finally, the secondary control restores, within minutes, the system to operational value following a power command signal set by the grid operator. This work proposes two control strategies to maximize the power reserve that a wind farm can deliver to the grid. Here, the complex problem of modelling the wake effect can be solved linearizing the model by using the Jensen's model [5].

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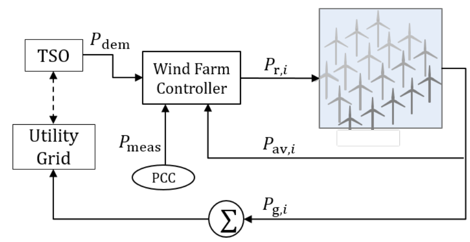

Fig. 1. Wind farm control scheme.

II. Control Strategies

The problem of delivering a power profile at the Point of Common Coupling (PCC), demanded by the TSO, can be achieved with different contributions from each wind turbine. A feedback control strategy is designed for a wind farm with n_t turbines, as illustrated in Figure 1. Here, the central wind farm controller determines a collective control policy using measurements (power demand P_{dem}, available $P_{av,i}$ and generated $P_{g,i}$) and sets the individual control signals $P_{r,i}$ to the wind turbines. In this work, the power $P_{r,i}$ is chosen to maximize the power reserve

$$P_{res,i} = P_{av,i} - P_{g,i}. \tag{1}$$

A. Strategy 1

The first approach proposes a centralized model predictive controller (MPC) [6]. This controller is based on the receding horizon principle in which a constrained optimization problem is solved using future predictions of the systems state. Due to nonlinear dynamics in a wind farm, it is challenging to obtain a dynamic wind farm model suitable for real-time control. In this circumstance, the dynamic behaviour from the power set-point to the generated power can be modelled as a first order system. In the controller, two goals can be distinguished. The control inputs need to be found as the solution of a multi-objective optimization problem stated to:

1) Ensure the tracking of P_{dem}.

2) Maximize the total power reserve P_{res}.

With the goal of considering the higher priority of tracking problem than the power reserve maximization problem, the two optimzation problems are sequentially solved with the lexicographic minimizers method as proposed in [7], which ensures a given prioritization of the control objectives. Simulations have been run using YALMIP and CPLEX under MATLAB/Simulink. Figure 2 analyzes the system behavior when the power set-point P_{dem} increases from 13 to 15 MW.

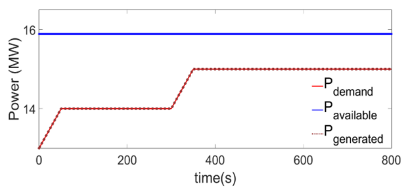

Fig. 2. System response for scenario 1: generated, available and demanded total power.

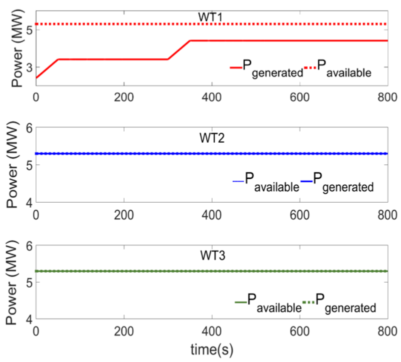

Fig. 3. System response for scenario 1: generated and available powers for each turbine.

In the top plot, it can be observed the power demand set-point P_{dem} (red line), the total generated power P_g (dashed line) and the total available power P_{av} (blue line). The generated and available powers for each wind turbine are displayed in Figure 3, with solid and dashed lines, respectively. As shown in Figure 2, the control is able to guarantee a good tracking, which is achieved by requiring the maximum power to the downstream turbines (WT2 and WT3) and minimizing the power generation of the first turbine (Figure 3).

The MPC strategy has also been tested with a medium-fidelity code The Parallelized Large-Eddy Simulation Model (PALM) [8]. The proposed MPC is applied to an aligned six turbines case with turbulence intensity of 5%. Figure 4 shows the good tracking for fast variations of P_{dem}.

B. Strategy 2

The second control strategy proposes a new power distribution to define the power contribution of each turbine in

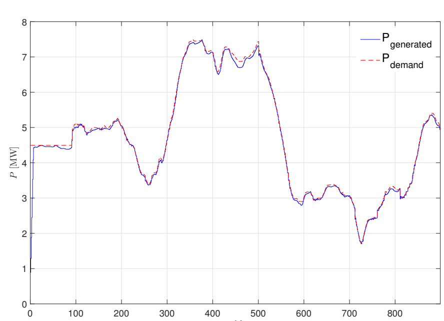

Fig. 4. Wind farm power and wind farm reference signal.

order to reduce the wind speed deficits caused by wake effects. In the proposed scheme, the contribution of each wind turbine is determined according to the main wind direction and aims to minimize the wake effect and to maximize the available power (and thus the power reserve). The main idea is to require the maximum contribution starting from the most downstream turbines (in the wind speed direction) and reducing the power generation of the usptream turbines, thus the minimum power is generated by such turbines that are facing the free-stream wind speed.

The proposed strategy has been evaluated by simulation in the case of 12 turbines under different scenarios, including low and high power demands and several wind speed conditions. The results show that this configuration minimizes the wake effect and increases the power reserve available for the provision of ancillary services.

III. Future Works

In order to reduce the massive number of communication links from a large number of turbine to the central controller a possible solution could be to split the wind farm into clusters with dedicated controllers that coordinate to produce the desired global behaviour. A partitioning approach will be developed to divide the wind farm in clusters. The way to determine the sub-systems shall consider the physical connections due to the wake effect not only generated by the turbines in the same system but also by the nearest turbines. Moreover, such partition of the WPP must consider the electrical connections among the turbines in order to reduce the electrical losses; thus, an additional step of the present work is to compute the active and reactive power flows to evaluate such losses.

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Comparison Between Multistage Stochastic Optimization Programming and Monte Carlo Simulations for the Operation of Local Energy Systems

C. Orozco, S. Lilla, A. Borghetti, C. Nucci

***Abstract*— The paper compares the application of the Monte Carlo method and the use of multistage stochastic approaches for the day-ahead optimization of the operation of a local energy system that includes photovoltaic units, energy storage systems and loads. A linear programming model is adopted in which the storage system is represented by the Kinetic Battery Model. Different methods for the construction of the relevant multi stage scenario tree are shown.**

Keywords—Energy scheduling; Local energy system; Mixed integer linear programming; Stochastic programming; Scenario reduction; Monte Carlo method; Kinetic Battery Model.

I. Introduction

This paper deals with an electric local energy system with the presence of renewables, such as the power system of an industrial site or of a residential neighborhood, including a photovoltaic (PV) unit capable to provide a significant part of the local energy consumption. The system is also equipped with an energy storage unit in order to fully exploit the available renewable energy source even for the case of a limited capability of the external utility network to which the system is connected. This scenario is realistic in many actual situations, as shown in [1],[2] and references therein. Moreover, although not considered in this paper, it is worth mentioning expected that an increased number of local energy systems will also include in the future parking lots equipped with many charging stations of electric vehicles (e.g., [3]–[6]).

We here assume that the daily operation of the battery unit is addressed as an optimization problem with a 24h horizon. The inputs are the forecasting of the PV production and of the local loads.

Since the forecasts of both PV production and load consumption are affected by significant uncertainties, either stochastic optimization approaches or Monte Carlo simulations are typical adopted to solve this kind of problems (e.g., [7]–[9]).

The aim of this paper is to compare these the two different approaches by using a linear programming model of the local energy system with the two following characteristics:

- a 15 minutes time discretization, which appears more suitable for the energy management of the local system than the usual 1 hour time step;
- the use of the kinetic model of the battery state of charge, more detailed than the simple energy balance, in order to appropriately represent the relevant operating constraints.

In order to better adapt the day-ahead solution to the actual intraday operating conditions, the stochastic optimization problem is formulated as a multistage decision problem in which the battery output set points, for each 15-minutes time interval t, are decided at the beginning of the 24h horizon (i.e., at t=0) and subsequently every 6 hours (i.e., at t=24, t=48, t=72). Therefore, the multistage stochastic optimization problem is applied to a scenario tree model and this paper will compare the results obtained by different scenario tree generation techniques.

II. Model of the Local Energy System

A typical aim of the energy management system is the minimization of the production costs associate with PV, storage units and the power exchange with the external network to feed the internal load in a time horizon T.

The use of a cost minimization objective function needs the knowledge of the values of the various prices. An alternative objective could be the minimization of the power exchange with the external power distribution network. The implemented model determines the optimum day-ahead scheduling for the battery operation as shown in Fig.1.

a) b)

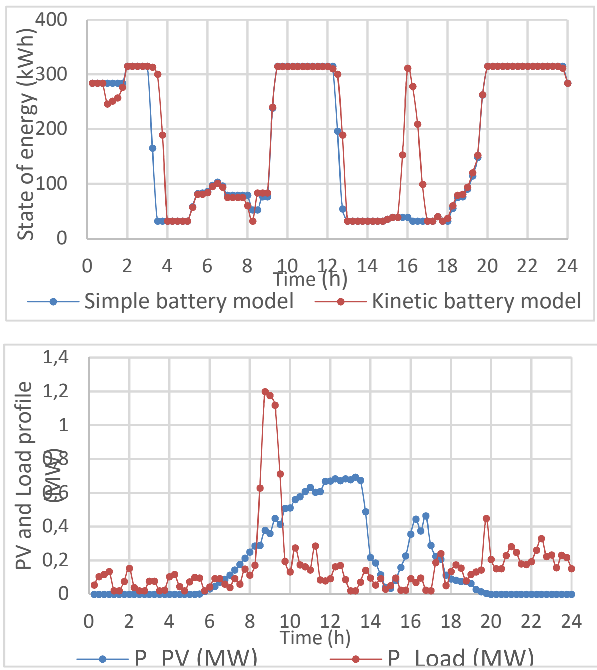

Fig. 1 a) State of charge of the battery calculated by using the kinetic and simple model, b) profiles of the load and PV production.

Fig. 1 shows the results of a deterministic solution of the optimization problem for a considered test system and compares the results obtained by using the Kinetic energy model, which uses the parameters value indicated in [10], with those obtained by the simple battery model in which the state of charge is determined by the energy balance.

III. Generation of the Scenarios and of the Scenario Tree

The uncertainties are described through stochastic processes, conveniently characterized using scenarios. For this purpose, we adopt a scenario-Generation procedure that incorporates the correlated behavior of the prediction and its hourly profile by using the properties of a Markov-Process approach [11].

In general, the number of scenarios for adequately describing this kind of stochastic process is very large and thus the associated stochastic programming problem becomes computationally difficult [12]. As mentioned, this paper compares two different approaches, namely the Monte-Carlo simulation techniques and the multistage stochastic optimization as illustrated in Fig. 2.

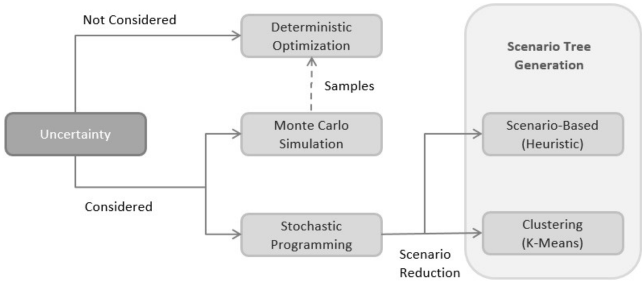

Fig. 2 Diagram of the implemented approaches.

This work includes the implementation of different scenario-reduction techniques, namely a heuristic based approach and *k*-means clustering, in order to reduce the computational effort while keeping as much as possible the information contained in the set of the original scenarios.

IV. Day-ahead Stochastic Problem Solution and Intraday Decision Function

The use of multi-stage stochastic programming motivates the development of a decision-making function. The solution proposed in this work is determined by successive consecutive decisions made at each stage. In order to accomplish this decision process in the actual operation during the day, a decision-making function is implemented based on the calculation of the Euclidean distance for the identification of the scenario of the tree closest to the actual operation scenario.

The decision making function accomplishes the following tasks:

- looks for the most similar scenario of the tree to the real state of the stochastic variables (PV generation and load);
- decides the set point values of the battery power output for each 15-minutes time interval of the following 6-hours stage.

For illustrative purposes, Fig. 3 shows the generated scenario tree and, in red, the successive decision steps provided by the decision making function for a test scenario.

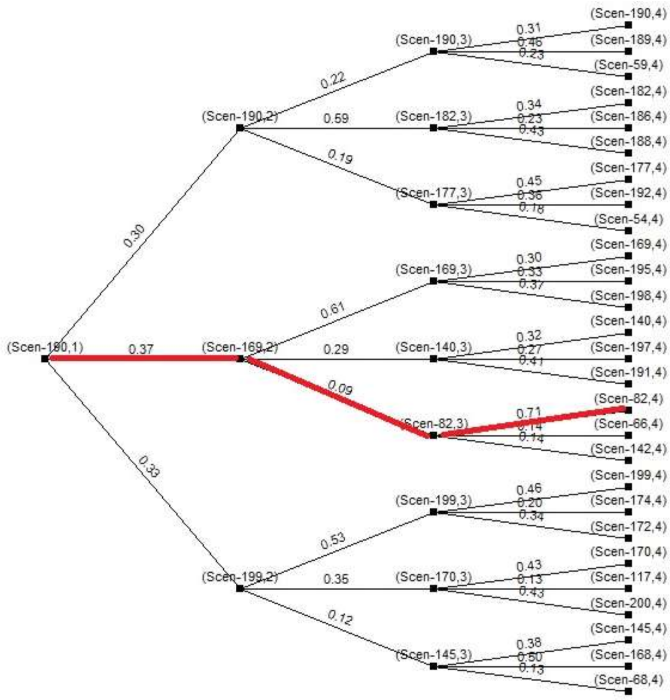

Fig. 3 Scenario tree and, in red, an example of the solution provided by the decision making function.

V. Test Results

As an example of the results, Fig. 4 shows the comparison between the solution for the objective function by using the average decision provided by the Monte Carlo simulations and the decision obtained by the stochastic optimization approach, for several different scenarios.

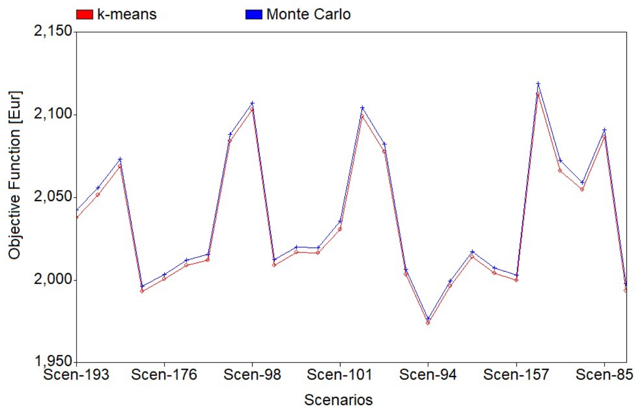

Fig. 4 Comparison between the values of the objective function for each scenario calculated by using the average decision provided by the Monte Carlo simulations and the decision obtained by the stochastic optimization approach based on *k*-means clustering technique.

As expected, Fig. 4 shows a reduction in the energy costs over the local system that represents the so-called value of the stochastic solution [12].

VI. Conclusion

The adoption of a more detailed model for the calculation of the state of charge of the battery is important in order to obtain decisions that appropriately consider the characteristics of the storage unit.

The *k*-means algorithm provides an attractive method to solve the stochastic optimization problem in local energy systems. According to the available literature, it is possible to extend and improve the algorithm through approaches aimed to define the initial centroids.

The comparison with the results obtained by Monte Carlo simulations provides useful insights on the influence of the uncertainties in the day ahead scheduling of the local energy system.

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Fault detection through monitoring of the AC variables in Grid Connected PV systems

Nikolaos Sapountzoglou, *ESR 4.2* and Bertrand Raison

***Abstract*— This document presents the necessary steps to detect and localize different types of faults in grid connected photovoltaic systems (GCPV) through the monitoring of AC electrical variables. After a short introduction to the details of the developed method, a detailed list of the studied faults is provided in Section II. In Section III, the choice of the monitored electrical variables is justified and in Section IV the fault signature concept is explained. The document concludes with some remarks on the fault diagnosis strategy.**

***Index Terms*— GCPV system, Fault detection, Fault signature**

I. Introduction

The occurrence of a fault is divided in three periods of time: the sub-transient (first cycle), the transient (5-10 cycles) and the steady-state [1]. The developed method in this study creates an alarm signal in less than $150ms$ from the occurrence of the fault, in the worst case scenario, thus detecting the fault during its transient period. Considering the vast amount of possible simultaneous faults and their complexity, the method assumes that only one type of fault is occurring at a time, focusing on the most important ones.

II. Fault types

Four main categories of faults were examined: a) faults in the PV array including shading and bypass diode faults, b) short circuit (SC) faults between the DC bus and the ground, c) faults in the power electronics devices such as SC and open circuits (OC) on switches and d) faults in the grid both close and far away from the plant, simulated as SC between phases and as direct voltage sags respectively. The complete list of faults is provided below:

a) faults inside the PV array:

[f01] shading of a number of PV modules
[f02] inverse bypass diode
[f03] short-circuited bypass diode
[f04] bypass diode breakdown

b) faults between the DC bus and the ground:

[f05] SC between the positive pole and the ground
[f06] SC between the negative pole and the ground

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c) faults in the power electronics devices:

[f07] open-circuited converter's IGBT
[f08] short-circuited converter's IGBT
[f09] open-circuited inverter's IGBT (1 IGBT in 1 leg)
[f10] open-circuited inverter's IGBTs (all IGBTs in 1 leg)
[f11] short-circuited inverter's IGBT (1 IGBT in 1 leg)
[f12] short-circuited inverter's IGBTs (all IGBTs in 1 leg)

d) faults in the grid:

[f13] SC between one phase and the ground
[f14] SC between two phases and the ground
[f15] SC between three phases and the ground
[f16] SC between two phases
[f17] SC between three phases
[f18] voltage sag in one phase
[f19] voltage sag in two phases
[f20] voltage sag in three phases

More specifically, in the shading fault case (f01), 50% of the surface of the first five modules in the first twenty out of a total of thirty strings was covered by shade which was simulated by a reduction in half of their photocurrent. Moreover, in the bypass diode breakdown case (f04), the diode was replaced by a resistance of 5Ω. Furthermore, in all SC faults, those on the DC side (f05, f06) and those on the grid side (f13-f17), the resistance was set to 1Ω. Finally, voltage sags (f18-f20) were simulated as a 50% decrease in the initial voltage.

III. Fault detection

The main objective of this study is to determine which type of fault is occurring, through the monitoring of electrical variables on the AC side. Through the three phase measurements of current (I) and voltage (V), the active (P) and reactive (Q) power were calculated. In order to complete the set of the monitored electrical variables, a phase locked loop (PLL) was used to obtain the frequency (f) from the measured voltage.

The aforementioned electrical variables I, V, P, Q and f were monitored in order to detect the occurrence of a fault. The values of the variables during normal operation of the system were compared to the values of the variables after the fault was established. A difference between the two suggests the existence of a fault under the condition that the irrandiance has not changed.

A first conclusion was that the current, the active and reactive power are all altered in each fault case. Since the active power is affected in each and every fault case, a difference between the expected active power output of the power plant - based on weather conditions (irradiance level and temperature) - and the one attained at every moment, can be used as a first indicator of fault occurrence. In order for a fault to be identified, a dedicated combination of alterations in all of the variables is necessary. However, for the majority of faults a change in all the associated electrical variables was noticed. From this last observation arose the need to further specify the detection threshold settings and inspect in what way each variable was affected.

IV. Fault localization

More detailed criteria around the current and the voltage were developed in order to expand the list of symptoms and construct the fault signature table. A first set of criteria included comparisons between faulty (FO) and normal (NO) operation values of voltage and current (i.e. $\Delta I = I_{FO} - I_{NO}$) and conclusions were drawn based on whether ΔI was negative or positive (s1) or V_{FO} was equal to zero (s3). Another aspect of changes in I and ΔV is whether they appeared symmetrically in all three phases or not (s2, s4). Furthermore, the sum of all three phase currents being equal to zero consisted an extra symptom (s5). In addition, the method of symmetrical components was used to further analyze the measured voltage. Based on the magnitude and phase alterations of the voltage, the rest of the symptoms were created; s6 and s7-s9 respectively. A list summarizing all the symptoms is presented below:

[s1] current increase $\Delta I > 0$ or current decrease $\Delta I < 0$
[s2] in how many of the three phases is $I_{FO} = 0$
[s3] voltage is equal to zero, $V_{FO} = 0$
[s4] in how many of the three phases is $\Delta V < 0$
[s5] the sum of phase currents is equal to zero
[s6] both the negative and the zero components exist
[s7] phase of the positive component, $\phi_{pos} < -25$
[s8] phase of the negative component, $-20 < \phi_{neg} < 20$
[s9] phase of the zero component, $\phi_0 > 0$, $\phi_0 > 110$, $\phi_0 < -110$ or $-110 < \phi_0 < 110$

These symptoms along with the studied fault cases, were used to construct the fault signature table, Table I. In this table, the symbol "$\surd$" is used to verify that the criteria described in this symptom are met while "x" marks the opposite. The symbol "/" is used as indicator that the specific symptom is of no interest to the associated fault. Another set of symbols is necessary to describe the changes in the current in s1; "+" is used when $\Delta I > 0$ and "−" when $\Delta I < 0$. For s2 and s4 the numbers "$0 - 3$" indicate how many of the three phases are affected; "0" is for none of the phases, "1" for one phase etc. Finally, for the s9 where four conditions apply, "++" is used to indicate that $\phi_0 > 110$, "+" is used for $\phi_0 > 0$, "−" for $\phi_0 < -110$ and "+−" for $-110 < \phi_0 < 110$.

From the fault signature table, sixteen faults or group of faults can be localized out of the total of twenty different faults. All faults inside the PV array (f01-f04), consist altogether a group of faults that present exactly the same fault signature, making them impossible to discriminate from each other. This can be easily explained since the measurement point is located far from the source of the fault and the signal is altered when it reaches the sensors. The second and last group of inseparable faults are the faults inside the boost converter (f06, f07) since they too have the same fault signature. All the other faults can be detected and localized. In the cases of f09, f10, f11, f13 and f14, the faulty phase can also be detected through monitoring of the current's behavior.

TABLE I: Fault signature table

	Symptoms								
Faults	$s1$	$s2$	$s3$	$s4$	$s5$	$s6$	$s7$	$s8$	$s9$
f01	−	0	x	0	√	/	/	/	/
f02	−	0	x	0	√	/	/	/	/
f03	−	0	x	0	√	/	/	/	/
f04	−	0	x	0	√	/	/	/	/
f05	−	0	√	3	+	/	/	/	/
f06	−	0	√	3	−	/	/	/	/
f07	−	3	x	3	√	/	/	/	/
f08	−	3	x	3	√	/	/	/	/
f09	+−	0	x	0	√	/	/	/	/
f10	+−	1	x	1	√	/	/	/	/
f11	+−	0	x	3	√	/	/	/	/
f12	+−	0	√	3	√	/	/	/	/
f13	+	0	x	1	√	√	/	/	/
f14	+	0	x	2	√	√	/	/	/
f18	+	0	x	0	√	√	x	/	+−
f19	+	0	x	0	√	√	x	/	++
f15	+	0	x	0	√	x	√	√	−
f17	+	0	x	0	√	x	√	√	+
f20	+	0	x	0	√	x	x	√	+−
f16	+	0	x	0	√	x	x	x	−

V. Conclusion

A diagnostic strategy was developed based on the unique fault signatures as shown in Table I. Further details about the threshold settings and their implementation will be given during the presentation at the 3rd INCITE Workshop at Efacec, Porto.

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Advanced functionalities for the future Smart Secondary Substation

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***Abstract*— This work aims to describe the mathematical framework of the analytical three phase unbalanced Optimal Power Flow (OPF), in order to examine its computational effort. The method lies on providing a satisfying initial point in order to improve the response of the problem's convergence. A discussion about possible linear approximations as well as extensions of the proposed technique to a multi-temporal one follows. This is justified towards the notions of implementing a coordinated operation of multiple Distributed Energy Resources (DER) in a day-ahead scale; fact which implies temporal bundling along the optimization frame.**

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.

Optimal Power Flow (OPF) is widely used by the DSOs for planning and operation purposes among numerous optimization problems, by manipulating the objective function and the respective control variables. Nevertheless, Low Voltage grids in particular, present purely unbalanced loading conditions and mainly resistive line characteristics. Therefore, the widely used DC power flow approximations in transmission grid studies, but cannot be applied due to the higher R/X ratios. The use of non-convex non-linear AC power flows in an OPF framework, can easily become computationally complex according to [1]. Convex relaxations are settled, based on e.g. semidefinite relaxations [2]; these, find solutions that are globally optimal for the original problem in many practical cases, leading though non-valid solution in some cases [3].

In this work, it is initially examined a typical iterative scheme merely based on the BFS algorithm which is incorporated in section IV in the 3-phase AC-OPF scheme.

II. NETWORK TOPOLOGY

A distribution network can be represented by a graph, let $\mathcal{G} = \{\mathcal{N}, \mathcal{J}, \mathcal{W}\}$, where the set of vertices includes the nodes-buses of the network $\mathcal{N} = \{1, \ldots, n_b\}$; the edges-pair of nodes-$\mathcal{J}$ correspond to the connectivity among buses, while the weight of the edges $\mathcal{W}$ represent the branch connection (i.e. three-phase line section impedance).

In a LV distribution network the voltage at node i lies on $\mathbb{C}^{\phi_i}$ since it is $V_i = \{\mathbf{V}_{ia}, \mathbf{V}_{ib}, \mathbf{V}_{ic}\} = |\mathbf{V}_{i,abc}|\angle V_{abc}$, where ϕ_i is the number its connected phases. The analytical model representation should include all the coupling among the active conductors (i.e. neutral conductor and possibly the earth conductor, if there is coupling with the neutral); nevertheless, the Kron's reduction technique, can adequately represent the state of the grid on the $\mathbb{C}^{3 \cdot n_b}$ domain [3].

III. THREE PHASE UNBALANCED POWER-FLOW

A three phase power flow (PF) is implemented according to the main notions described in [4]. The PF was implemented in two versions deploying also the matrix formulation proposed by [5]. The typical Backward-Forward Sweep (BFS) technique is briefly presented in pseudo-code in algorithm 1, where in the Backward stage the branch current calculation occurs, whilst in Forward Sweep stage the nodal voltage calculations. This method, unlikely to classical power flow methods, copes with a branch oriented technique rather than nodal relations. Alternatively, the PF equations were addressed as proposed in [5], which is a method that requires only the formulation of the bus-injection to branch-current matrix (BIBC) and the the branch-current to bus-voltage matrix (BVBC). Nevertheless, the algorithm 1 is foreseen more robust in large scale systems, since the only necessary input is the Y-admittance matrix. The Y-bus for a radial distribution network is a fairly sparse matrix; fact, which can be treated as efficiently treat instead of triangular matrices that imply LU factorization.

It is quite interesting to stress that such PF algorithms present quick convergence, i.e. iterations do not exceed 4 for tolerance convergence $\epsilon_t = 1e-4$. Their performance can

Algorithm 1 BFS description, merely based on [4]

procedure LOAD FEEDER
  Rank nodes, *Node-Order* procedure: Sort m^j
procedure BFS
  initialize $k \leftarrow 1$,
  $V_{j,a}^{(k-1)} = 1\angle 0$, $V_{j,b}^{(k-1)} = 1\angle \frac{2\pi}{3}$, $V_{j,c}^{(k-1)} = 1\angle \frac{-2\pi}{3}$
  do
  Node j Injections : $I_{j,n} = -\sum_{\phi \in \Phi} \left[y_{j,nn} I_{j,\phi} \right]$,
  $I_{j,abc}^{(k)} = \left(\frac{S_{j,abc}}{V_{j,abc}} \right)^{(k-1)^*} - \text{diag}(Y_{j,abc}^{\text{shunt}}) \cdot V_{j,abc}^{(k-1)}$
  Backward Sweep- Current Calculation:
  $J_{abc,n}^{(k)} = -I_{j,abcn}^{(k)} + \sum_{m \in M} J_{m_{abc}^{j}}^{(k)}$
  Forward Sweep Calculation:
  $V_{abc,n}^{(k+1)} = V_{abc,n}^{(k)} - [Z_\ell] \cdot J_{abc,n}^{(k)}$
  $k \leftarrow k + 1$
  while max $\left(|V_j^{(k)}| - |V_j^{(k-1)}| \right) \geq \epsilon_t$
  return $J_{j,abcn}, V_{j,abcn}, j \in \mathcal{N}$

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be further accelerated by the valid assertion that the angle displacement in LV distribution networks between adjacent nodes is fairly small [2], i.e. $\Delta\theta \rightarrow 0$ which arise to the conception in equation 1.

$$\Delta V_{abc}^{(k+1)} \approxeq \Re\{Z_\ell * J_{abc}^{(k)}\} \tag{1}$$

This property is further exploited in the OPF framework, as presented in the following section.

IV. Three-phase AC-OPF

In this section, the analytical (i.e. exact PF equations) single-period AC-OPF is formulated, examined in order to verify analytically its computational burden. In figure 1, the 3-phase OPF scheme is described, which consists of providing an adequate initial point provided by an accelerated (i.e. $\Delta\theta = 0$) BFS-PF performance. The objective function is to minimize the operating costs assigned with all the controllable assets providing their coordination according to their availability. The vector $[x_t]$ expresses to the state vector of the grid (i.e. voltage magnitude and angle -not critical for LV network-) at each time step t. Let us consider the set of controllable assets $\mathcal{U} := \{1, \ldots, n_c\}$, described by the control vector u, comprised by active and reactive power set points. Therefore, in a single-period resolution the AC-OPF problem is posed by 2:

$$\min_u C_{obj}(x_t, u_t) = \min_u \sum_{j}^{n_b} \left(c_{n_c}^T \cdot u_j\right) \tag{2}$$

subjected to

$$F_j(x,u) = 0 \qquad \forall j \in \mathcal{N} \tag{3a}$$
$$h_i(x,u) \leq 0 \qquad \forall i \in \mathcal{J} \tag{3b}$$
$$V_{\min} \leq V_{j,\phi}(x,i) \leq V_{\max} \qquad \forall i, \phi \in \mathcal{N}, \Phi \tag{3c}$$
$$h_\xi(x,u) \leq 0 \qquad \forall \xi \in \mathcal{U} \tag{3d}$$
$$g_\xi(x,u) \leq 0 \qquad \forall \xi \in \mathcal{U} \tag{3e}$$

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 constraint in (3c) to respect all nodal voltages to range strictly within the admissible bounds. The constraints 3d-3e, correspond to the operational limits of the controllable DER. The gradient and Hessian matrix of the objective function and the nonlinear constraints are provided to the optimization solver, by expanding the calculations presented in [6]. There is a particular concern on its performance, since the formulation of the multi-temporal planning of operation scheme will have augmented resolution time because of the multiple stages of optimization, in addition to the linkup of intertemporal constraints. More analytically, flexible assets such as battery storage systems, EVs and controllable loads, induce the capability to commit certain amount of energy and release it at another one. The complexity of the OPF scheme increases proportionally to the number of buses -including each corresponding phase- $n'_b = 3 \cdot n_b$ and the number of time steps incorporated in the resolution time horizon H_z. The AC-OPF is currently being extended to a multi-temporal framework (eq. 4) in order to efficiently coordinate the flexible-controllable resources in a day-ahead scale.

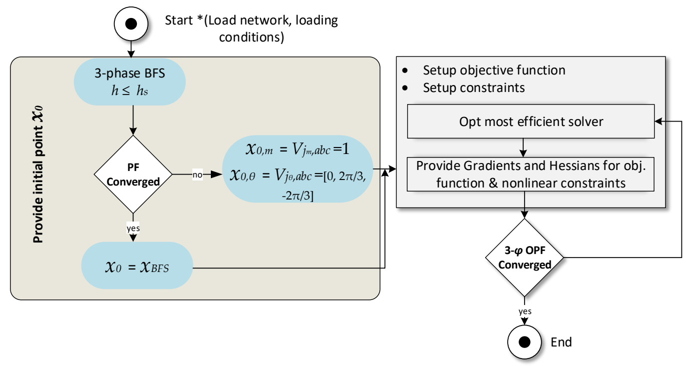

Fig. 1. Flow chart algorithm for single-period 3-phase AC-OPF.

$$\min_u \sum_{t=1}^{H_z} C_{obj}(x_t, u_t) \tag{4}$$

V. Conclusions

Currently, the work is focused on the inter-temporal expression of DER models in such way to overly verify the computational effort of the multi-temporal scheme using the exact power flow equations. Approximative relations and linearizations can be applied in order to avoid non convexities of exact power flow as well as non linear equalities and inequalities.

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