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Innovative controls for renewable source integration into smart energy systems

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D1.1

WP1 Annual Scientific Report

WP1 – Control Strategies for Distributed Power Generation

Grant Agreement no 675318

Lead beneficiary: TU Delft
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[2] Administrative (website completion, recruitment completion…)
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Ramon Costa Castelló (UPC)	15/11/2017	1.1	Review and changes
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Marta Fonrodona (IREC)	21/11/2017	2.0	Final version

DEFINITIONS

- Beneficiary partners of the INCITE Consortium are referred to herein according to the following codes:
  - **IREC**. Fundacio Institut de Recerca de l'Energia de Catalunya (Spain)
  - **UPC**. Universitat Politècnica de Catalunya (Spain)
  - **TU Delft**. Technische Universiteit Delft (Netherlands)
  - **VITO**. Vlaamse Instelling Voor Technologisch Onderzoek (Belgium)
  - **UniBo**. Universita di Bologna (Italy)
  - **UGA**. Université Grenoble Alpes (France)
  - **GE Global Research**. General Electric Deutschland Holding GmbH (Germany)
  - **Efacec Energia**. Efacec Energia - Maquinas e Equipamientos Electricos SA (Portugal)
- **Beneficiary**. The legal entity, which are signatories of the EC Grant Agreement No. 675318, in particular: IREC, UPC, TU Delft, VITO, UniBo, UGA, GE 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).

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
- **WPs**. Work Packages

DISCLAIMER OF WARRANTIES

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

EXECUTIVE SUMMARY

This report presents the progress of WP1 "**Control Strategies for Distributed Power Generation"** where four PhD researchers have been working since September/October 2016 on their individual research projects but at the same time have been using exchange possibilities and meetings as much as possible to make the collaboration within WP1 a strong factor contributing to its success.

1. STATUS OF WP1

This chapter describes the status of WP1 "**Control Strategies for Distributed Power Generation"**.

1.1 WP objectives

The aim of WP1 is to propose control strategies to optimise the use of distributed generation from renewable energy systems (RES). This covers the view of smart grids as self-sufficient communities (mini- or micro-grids) capable of operating independently from large distribution systems. Concepts of distributed control and large-scale systems are used to deal with the large number of agents and complexity of the grids.

The research in this WP employs a more abstract view of electrical networks, focussed on steering the power flow acting on the agents with different approaches ranging from set-point signals to economic policies.

1.2 WP general progress

The general progress of WP1 is satisfactory. The first year of the four ESRs was aimed at understanding the INCITE project objectives and working plans, writing own individual research project proposals and developing mutually beneficial interactions inside the WP.

1.3 WP impact

The impact of this WP can be measured by the high number of publications accomplished in the 1st year of the research. All the publications, including the abstract, are presented in Chapter 3. Also visits, detachments, and training as well other deliverables are shown there.

2. PROGRESS OF THE IRP'S

This chapter describes the progress of the four IRPs contributing to the objectives of WP1.

IRP 1.1 – Partitioning and non-centralized optimization-based control of dynamical energy grids

Project leader	Carlos Ocampo-Martínez	
Research institute	Universitat Politecnica de Catalunya (UPC)	
Early stage researcher	Wicak Ananduta	
Period covered in this report	14 December 2016	15 October 2017

The introduction of distributed generators, e.g., small-scale dispatchable generators and renewable energy sources, and that of storage systems have shifted power system design and operation from the centralized paradigm to a distributed one, including the design of the controllers. Some literature has pointed out that the centralized control scheme, in which there is only one central controller, is not suitable for power networks that consist of distributed generators and distributed storages. Non-centralized structures are preferable since the computational burden can be distributed among local controllers. Moreover, it is also more flexible, scalable, and reliable than its centralized counterpart.
By considering the development of power systems, the goal of this project is threefold. This project aims to develop partitioning methods for large-scale systems with time-varying topologies, specifically within the framework of power systems. Afterwards, non-centralized optimization-based controllers that are compatible with the nature of the systems will be designed. Moreover, a study on how the proposed partitioning method and non-centralized controllers interact with each other will also be carried out.

Some specific objectives of this project are as follows:

1. Study the influence of time-varying topologies of the system to the performances of non-centralized controllers.
2. Determine and/or propose partitioning methods that are suitable for systems with time-varying topologies.
3. Design non-centralized controllers based on evolutionary game theory that are suitable for large-scale systems with time-varying topologies and disturbances.
4. Determine how the proposed time-varying partitioning approach can be used to improve the performances of non-centralized optimization-based controllers.
5. Apply the methodologies developed in items 2, 3, and 4 to power networks with time-varying topologies.

The current plan in this research project is the following:

1. Stability analysis of time-varying partitioned systems with non-centralized MPC.
2. Determine and propose a benchmark case of time-varying power systems.
3. Learn toolboxes related to power system simulations.
4. Review EGT-based distributed MPC
5. Design EGT-based distributed MPC for large-scale linear systems with disturbances.

6. Study on event-driven control approaches for control.
7. Develop event-driven partitioning methods for distributed control of systems with time-varying topology.
8. Analyse the interaction between time-varying partitioning and distributed control method.
9. Research collaboration with:
   a. Tokyo Institute of Technology (January or February 2018)
   b. University of Bologna (March-May 2018)
   c. General Electric, Munich (end of 2018 or beginning of 2019).

During this report period, the following tasks in IRP1.1 have been accomplished:

- A literature survey on system partitioning methods. Various partitioning methods that have been proposed are reviewed. In most of the papers, large-scale systems are represented as a graph and the methods proposed in those papers are developed by considering the graph partitioning problem. Furthermore, currently system partitioning is carried out prior to designing the controller. However, when the controlled large-scale system has time-varying behaviour, e.g., time-varying topology, the system needs to be repartitioned during the operation. In this regard, only one paper has discussed a time-varying partitioning method.

- Proposing a partitioning approach that is suitable for systems with time-varying topology. As the first step towards online dynamic partitioning, it has been proposed that, in order to deal with time-varying topology, a library of partitions is constructed offline. Each partition corresponds to a topology, thus when the topology switches, the controller also immediately switches the partition and its control structure. Moreover, in this work, a decentralized state-feedback control method is applied. In accordance with the partitioning approach, a library of state-feedback gains is also calculated offline. Furthermore, a stability analysis of this approach is also carried out.

- A study on the impact of time-varying communication network in distributed model predictive control (DMPC) schemes. Specifically, the impact of communication failures in which some of the communication links in the network are broken is investigated. Based on this study, communication failures may result in infeasibility and suboptimality for DMPC controllers. Therefore, two communication protocols that are resilient to some extent of communication failures have been proposed. One protocol is a practical application of the standard distributed consensus approach while the other one is based on a mean dynamic, namely distributed projection dynamic.

- A review on non-centralized MPC methods, in particular DMPC methods that are based on evolutionary game theory (EGT). DMPC strategies can be classified into cooperative and non-cooperative methods, depending on whether the objective of each local controller is local or global. Furthermore, some DMPC strategies employ a distributed optimization method, which is convenient when the goal of the controller is to obtain an optimal performance. EGT-based DMPC methods that are recently developed in our group belong to the latter group. Currently, these methods are able to deal with nominal systems and therefore it is interesting to extend them such that they are able to deal with uncertain systems.

- A review on DMPC and distributed optimization methods for energy management problems in power networks. During this work, the dynamic optimal power flow problem is reviewed. Furthermore, some DMPC and distributed optimization methods that have been proposed to solve optimal power flow problems are also surveyed.

IRP 1.2 – Decentralized Control for RES by Fast Market-based MAS

Project leader	Han La Poutré	
Research institute	Delft University of Technology	
Sub-project leader(s)	Mathijs De Weerdt	
Early stage researcher	Hazem Abdelghany	
Period covered in this report	1 October 2016	15 October 2017

Future distribution grids will differ very much from what we currently define as a distribution grid. Deregulation of electricity markets, along with electrification of transportation and heating, and the shift towards cleaner renewable energy resources are all inevitable, together with their effects. Such a transition to the new distribution grid offers great advantages from the environmental, economic and energy efficiency points of view. However, disadvantages are also present, for example:

- Current distribution grids are not designed to handle bi-directional power flows.
- Demand peaks caused by EVs charging simultaneously, usually when people start returning from work, or HPs switched on simultaneously on cold days exceed the capacities of the current distribution grids.
- Uncertainties caused by RES due to weather conditions, increase the difficulty of supply/demand matching.

To deal with these challenges, Demand side management (DSM) solutions are being developed with the objective of coordinating among resources and devices on the distribution level, in a manner that achieves economic and environmental efficiency, and maintains system operability. Lately, market-based approaches for demand response received a lot of attention due to their attractive features. However, many open research problems still exist. This project aims at developing fast, scalable and efficient market-based control approaches for distributed energy resources, which allows for better utilization of renewable energy resources and efficient operation of distribution systems.

The project aims at:

1. Modelling and developing fast, scalable agent-based algorithms for decision making and planning in market-based demand response settings, taking into consideration the uncertainties in real-time operation of power distribution systems, the objective of self-interested prosumers, and the different characteristics of distributed energy resources.
2. Representing distribution network constraints and parameters, and developing market-based control approaches that are able to utilize the flexibility offered by distributed energy resources while maintaining system-wide constraints and achieving a desired overall system performance.
3. Modelling the inter-temporal objectives of distribution grid operation and developing market-based control approaches for achieving those objectives.

The project's plan is currently under development. However, the main research themes that will be covered by the project are:

- Review literature on decision making and optimal planning in dynamic pricing settings.
- Optimal operation of flexible distributed energy resources under dynamic pricing and uncertainty.
- Decentralized congestion management in distribution grids with high penetration of renewable energy resources.
- Review literature on load profile steering and peak shifting in demand response settings.
- Develop models and algorithms for ahead planning and market steering for use in real-time market-based demand.
- Collaboration with the following institutes:
    - Catalonia Institute for Energy Research (IREC), Barcelona, Spain.
    - Universitat Politècnica de Catalunya (UPC), Barcelona, Spain.

During this report period, the following tasks in IRP1.2 have been accomplished:

- A generalized model for the problem of optimal device-level decision making and planning under dynamic pricing has been formulated using Markov Decision Processes. The generalized model applies to different types of flexible distributed energy resources, and takes into account the uncertainty in real-time prices and the operational, comfort constraints. Algorithms are being developed for different types of distributed energy resources based on the model. These algorithms can be easily implemented using embedded systems with small computational power.

IRP 1.3 – Hybrid agent-based optimisation model for self-scheduling generators in a market environment

Project leader	Zofia Lukszo	
Research institute	Delft University of Technology	
Sub-project leader(s)	Remco Verzijlbergh	
Early stage researcher	Shantanu Chakraborty	
Period covered in this report	26 October 2016	15 October 2017

The high penetration of renewable energy sources (RES) in the electricity distribution grid weakens the correlation between wholesale electricity prices and network demand. Aggregators (entities that can control prosumer/consumer energy flexibility) being profit-seeking can cause high peaks in network load. This is because aggregators reacting to wholesale prices will do so in a correlated way, as they react to the same electricity price. When aggregators postpone their customer activity until the electricity price is at its lowest, they will create a peak demand at that moment. In such cases, two issues emerge. Firstly, there is a congestion created in the distribution network. Secondly, the voltage magnitudes of the distribution network are significantly affected. Managing these issues is not only costly but also difficult to implement efficiently. Thus the goal of this research is to consider different approaches by which the DSO can coordinate with aggregators for optimally managing the distribution grid in terms of managing network congestions, controlling voltage levels and minimizing the DSO's operational costs. To study these aspects, we intend to consider different configurations for integration of aggregators into the distribution network, as well as to consider aggregators of different types of technologies. These scenarios will then be applied to low voltage distribution networks.

The current plan for the remainder of the research project is as follows:

1. Analysing the impact of DSO-aggregator coordination in the low voltage distribution network in terms of congestion management, voltage regulation and network costs.
2. Analysing the impact of the coordination of DSO and aggregators of different technologies in terms of congestion management, voltage regulation and network costs.
3. Extending the application of the Exact Distributed OPF for LVDC networks to multiple-time periods and including aggregator models.
4. Applying the Exact OPF formulation to LVAC networks including aggregator models.
5. Research collaborations with:
    a. Politecnico di Torino (October 2017)
    b. VITO, Genk, Belgium (August 2018)
    c. Catalonia Institute for Energy Research (IREC), Barcelona, Spain (Beginning 2019).

During this report period, the following tasks in IRP1.3 have been accomplished:

- During the first year the focus was on the aspect of modelling low voltage DC distribution networks and account for power losses in it. For this, ESR1.3 collaborated with another Ph.D. and a M.Sc. student in developing an Exact Optimal Power Flow algorithm which is an innovative and novel approach to performed distributed optimization within a DC distribution system. The model is built upon the Consensus and Innovation approach and helps to achieve optimal solutions while considering congestion and network line losses. Earlier research available in literature dealt with an approximated DC OPF model for an AC distributed system. Also, the research did not consider losses in the distribution lines. This violates how a practical power grid would function, as transmission and distribution cables in general encounter power losses. The algorithm developed is a non-complex procedure of update equations for the various primal and dual variables of the DC system. The only exchange of information between physically connected nodes was the nodal voltage magnitudes and the LMP values. Also, the model considers network practicalities like line losses and thus, is able to obtain a more exact solution as compared to model which did not consider network losses.

IRP 1.4 – Development of intrusive and non-intrusive control algorithms for the electricity market

Project leader	Fjo De Ridder
Research institute	VITO
Sub-project leader(s)	Bart De Schutter
Early stage researcher	Jesus Lago

Period covered in this report	1 September 2016	15 October 2017

As a result of the liberalization of the electricity markets in the last two decades, the dynamics of electricity trade have been completely reshaped. In particular, electricity has become a commodity that displays a set of characteristics that are uncommon to other markets: constant balance between production and consumption, load and generation influenced by external weather conditions, and dependence of the consumption on the hour of the day, day of the week, and time of the year. Due to these facts, the dynamics of electricity prices exhibit a behaviour unseen in other markets, e.g. sudden and unexpected price peaks, the prices become more volatile, and ultimately the system stability is put at risk.
In recent years, with the penetration increase of renewable energy sources (RES) into the grid, the described behaviour has been aggravated. In particular, while there is no question regarding the contribution of RES to build a more sustainable world, several concerns have been risen regarding their influence on electricity prices and grid stability. Specifically, as the RES penetration increases, so does the dependence of electricity production with regard to weather conditions and, in turn, the uncertainty in electricity prices. As a result, as price fluctuations increase, the behaviour of market agents becomes unpredictable, sudden drops in generation and consumption might occur, and the electrical grid can become unstable.
A second problem that arises together with grid stability is the profitability of RES. Particularly, as price uncertainty increases, the price of the energy generated by RES is much more expensive than what the technology could cost in theory. As a result, the economic incentive for using RES decreases, and the profitability of RES is put at risk.

Within the described framework, the goal of IRP1.4 is to develop non-intrusive and intrusive control algorithms so that RES penetration can increase without compromising either the grid stability or the profitability of RES. In particular, the PhD research considers that, while some fields of demand response are better developed, e.g. the usage of batteries from electrical vehicles or the thermal storage capacities of buildings, the employment of accurate price forecasting across different markets to optimally allocated bids and steer systems remains yet unexplored. Based on this observation and general objective, the aim of this PhD is divided in three goals/research steps:

1. In a first step, to develop and explore new forecasting techniques that can improve the accuracy of state-of-the-art models for predicting electricity prices.
2. In a second stage and using the obtained forecasts in the first step, to develop intrusive control algorithms for specific dynamical systems, e.g. large water reservoirs.
3. In a third stage and also using the obtained forecasts in the first step, to develop non-intrusive control algorithms for general utility companies.

During the first year of the PhD, the research goal was to improve the state-of-the-art results in electricity price forecasting. This goal was achieved by exploiting DL models and market integration. In the remaining three years, in order to complete the general goal of the PhD, the research plan is divided in three sequential steps:

1. Finishing the research on forecasting techniques.
2. Develop an intrusive control algorithm for the Ecovat system.

3. Develop a non-intrusive control algorithm for a general utility company.

In the following sections, we will debrief the details for carrying the research plan and accomplishing these three goals.

Forecasting
While controls algorithms for the electricity market are to be investigated in the second year, the first 3-4 months will be still dedicated to forecasting techniques in order to achieve a complete forecasting framework. In particular, probability forecasting is a critical part of the PhD research as it will be the basis for implementing stochastic optimal control algorithms that would take into account the uncertainty in the prices. In detail, whether we steer a dynamical system or we help a utility company to perform smart bids, the control algorithm needs the probability distribution of electricity prices in order to model the desired trade-off between profits and risk. So far, only methods from the literature and the metrics to assess the quality of the forecasts have been studied. In the coming months, ESR1.4 intends to build a novel probabilistic forecasting framework based on the developed DL models. In particular, two different ideas are to be tested: a first approach that builds 4 probability forecasts using bootstrapping and the individual DL models, and a second approach that builds a single probability forecast by means of quantile regression averaging using the 4 DL point forecasts.

Intrusive Control
After finishing the research in forecasting techniques, the first control algorithm will be developed. In particular, the expected research time for forecasting algorithms is 3-4 months. After that, it is expected to start developing the intrusive and non-intrusive control algorithms.

For the intrusive control, the plan is to develop an algorithm for the Ecovat system that, using stochastic optimal control, will steer the system to maximize benefits while stabilizing the electricity market. The plan is to have a controller ready by the end of the second year of the PhD. We have initially thought of stochastic optimal control as the problem solution as we have a nonlinear dynamical system that we can model, a stochastic loss function that we need to minimize, and a system with multiple constraints. An alternative to the above plan is a solution based on reinforcement learning. However, considering that the Ecovat system can be modelled using a differential equation, we believe that a solution based on optimal control might be more suitable.

Non-Intrusive Control
At the beginning of the third year, we expect to finish the controller of the Ecovat system and start working on a general non-intrusive algorithm that can be deployed in any utility company. The algorithm to be used is not yet clear; a possible solution would be to consider a stochastic optimal control problem as done for the Ecovat system. However, considering that the model for the utility company will be a discrete black-box function and that different utility companies might require different models, a controller based on reinforcement learning might be more suitable.

During this report period, the following tasks in IRP1.4 have been accomplished:

- During this first year of the PhD, the work has focused on the first research step, i.e. forecasting techniques for the electricity market. In detail, new forecasting techniques based on deep learning algorithms have been developed and tested. These techniques were also shown to improve the state of-the-art accuracy. In parallel with this research, we also focused on setting up a large benchmark to compare the different models from the literature. The outcome of this work is, first, to obtain a better insight in the variations and predictability of these markets, and second, to have a clear understanding of the performance of difference methods.

- In addition to that, the relation between market integration and forecasting accuracy has been explored. Focusing on the day-ahead market in Belgium and the relation with neighbouring markets, we have proven that significant gains can be obtained by considering different phenomena from neighbouring markets.

- The performed research has led to two journal papers. The first paper treats the interaction between the energy prices in Belgium and France and the way these relations can be exploited. The second paper deals with a comparison between different forecast techniques and the performance of the developed of the deep learning algorithm.

- To give a brief idea about the quality of the results when combining all the different improvements, current commercial forecasts have an accuracy of typically 14 % sMAPE and the developed techniques reach 11.5 % sMAPE.

3. INTERNAL AND EXTERNAL COLLABORATIONS

Current collaborations between WP1 researchers are at a starting phase. On the other hand, some projects established collaborative links with external organisation/universities, e.g. IRP1.3 with Politecnico di Torino, and IRP1.4 has planned the following events /activities /patents:

1. Within the forecasting techniques, ESR1.4 has established links with some Belgian aggregators and market agents that are interested on commercializing the algorithms developed. IRP1.4 is currently considering two possibilities: building a framework that can be sold to the industry or providing training to the interested partners.
2. As part of the forecasting research, ESR1.4 will organize a full day workshop to disseminate knowledge to interested parties. ESR1.4 has invited around 20-30 companies that commercialize in the wholesale electricity market.
3. Also, as part of the forecasting research, ESR1.4 is submitting a possible patent.
4. For the intrusive controller research, ECOVAT intends to make use of all the techniques developed in IRP1.4. Particularly, as they have a real demand response system, all the knowledge generated in IRP1.4 will be directly disseminated to them.
5. While no talks have been performed yet regarding the non-intrusive control for utility companies, the researchers of IRP1.4 believe that there will be interested partners that will want to acquire the knowledge developed.

4. DISSEMINATION OF RESULTS: PUBLICATIONS & CONFERENCES

IRP 1.1 – Partitioning and non-centralized optimization-based control of dynamical energy grids

List of publications

W. Ananduta, J. Barreiro-Gomez, C. Ocampo-Martinez, N. Quijano, "*Resilient Information-Exchange Protocol for Distributed Model Predictive Control Schemes*", American Control Conference, 2018, submitted.

Abstract:
Distributed Model Predictive Control (DMPC) strategies require local controllers to share information among each other. Considering the importance of communication in such control strategies and the failures that may occur in the information-sharing network, this paper proposes to apply the distributed consensus algorithm as an information-exchange protocol for DMPC controllers. The advantage of the proposed protocol is twofold. First, it relaxes some communication assumptions usually made for DMPC controllers. Second, under some assumptions, it provides resilience against some communication failures such that the performance and the features of the implemented distributed controller are preserved. A case study of a microgrid system is provided as an example in which some simulations are carried out to illustrate the aforementioned advantages.

T. Pippia*, W. Ananduta*, C. Ocampo-Martinez, J. Sijs, B. De Schutter, "*Partitioning Approach for Control of Time-Varying Large-Scale Linear Systems*," American Control Conference, 2018, submitted.
**:co-first authors*

Abstract:
Large-scale systems (LSSs) are too large to be controlled efficiently by a centralized controller. Therefore, they are usually split into smaller subsystems. When LSSs are time-varying, in order to maintain a suitable performance of the controller, it is advisable to change the partition when the system is subject to a change in its dynamics. In this paper, we propose a novel approach to partition linear time-varying switched LSSs. In particular, the proposed approach produces a library of partitions that covers the possible changes in the dynamic equations of LSSs. Moreover, we provide a stability analysis for LSSs when applying a decentralized state-feedback control strategy, taking into account also the switching between two different partitions. We illustrate the proposed approach with a numerical simulation.

W. Ananduta, J. Barreiro-Gomez, C. Ocampo-Martinez, N. Quijano, "*On the Mitigation of Communication Failures in Distributed Model Predictive Control Strategies*," journal paper, 2018, in preparation.

Abstract:
Information sharing among local controllers is the key feature of any Distributed Model Predictive Control (DMPC) strategy. This paper addresses the problem of communication failures in DMPC strategies and proposes a distributed solution to cope with them. The proposal consists in an information-exchange protocol that is based on distributed projection dynamics. By applying this

protocol as a complementary plug-in to a DMPC strategy, the controllers become resilient against communication failures and relax the communication requirements. Furthermore, a discussion on the selection criteria of the information-sharing network and a reconfiguration algorithm, which is a contingency procedure to maintain the connectivity of the network, are also presented. In order to demonstrate the performance and advantages when adopting the proposed approach, a case study of a power-network control problem is provided.

Visits, detachments, and training

1. XV Symposium of Control Engineering: Plant-Wide Control, Salamanca, 09/02/2017 – 10/02/2017
2. International Graduate School on Control, Module 2: Decentralized and Distributed Control, Paris, 30/01/2017-03/02/2017
3. Science Communication Workshop, Centre for Genomic Regulation, Barcelona, 02/03/2017-03/03/2017
4. 1st INCITE Summer School and 2nd INCITE workshop, Barcelona, 26/06/2017 – 30/06/2017

Other deliverables

- W. Ananduta, C. Ocampo-Martinez, "*Partitioning and Non-Centralized Control of Dynamical Energy Grids*," Abstract, 2nd INCITE workshop, Barcelona, June 2017

IRP 1.2 – Decentralized Control for RES by Fast Market-based MAS

Visits, detachments, and training

- Poster presentation at PowerWeb day, TU Delft, June 9th, 2017.
- Participation in the INCITE workshop, Genk, Belgium, November 23rd-25th, 2016.
- Participation in the INCITE workshop, Barcelona, Spain, June 29th-30th, 2016.
- Participation in the INCITE summer school, Barcelona, Spain, June 26th-28th, 2016.
- Course on Game Theory, Coursera and Stanford Online, May 30th, 2017.
- Participation in the European Agent Systems summer school, Gdansk, Poland, August 7th-11th, 2016.
- Course on Markov Decision Processes, Dutch Network on the Mathematics of Operations Research (LNMB), September 11th-November 13th, 2017.

Media

INCITE blog contribution "*Demand-Side Management by Real-Time Market-Based Control*"

IRP 1.3 – Hybrid agent-based optimisation model for self-scheduling generators in a market environment

List of publications

J.A. Moncada, E.H. Park Lee, G.D.C. Nava Guerrero, O.Okur, S.T. Chakraborty, Z. Lukszo, "*Complex Systems Engineering: Designing in sociotechnical systems for the energy transition*", (2017) EAI Endorsed Transactions on Energy Web, 17 (11), art. no. e1, DOI: 10.4108/eai.11-7-2017.152762

Abstract: The EU has set ambitious targets for an energy transition. While research often focuses on technology, institutions or actors, a transition requires more complex coordination and comprehensive analysis and design. We propose a framework accounting for technology, institutions and actors' perspective to design in socio-technical systems. We present its application, firstly, to biodiesel production in Germany; secondly, to vehicle-to-grid contracts in Car as a Power Plant microgrid. We show how using the framework as the core in modelling can contribute to the performance improvement of these systems. Future work will elaborate on the next generation of thermal energy systems, coordination control of microgrids and implementing flexibility through demand response aggregation. Overall, designing solutions to the problems described calls for comprehensive engineers who look beyond the technical design and deal with multi actor socio-political processes including institutional consideration.

Visits, detachments, and training

- Poster presentation at PowerWeb day, TU Delft, June 9th, 2017
- Participation in the INCITE workshop, Genk, Belgium, November 23rd-25th, 2016
- Participation in the INCITE workshop, Barcelona, Spain, June 29th-30th, 2016
- Participation in the INCITE summer school, Barcelona, Spain, June 26th-28th, 2016
- Course on Deep Learning, Coursera and Stanford Online, October 2017
- TU Delft Graduate School courses in Research and Transferrable Skills

IRP 1.4 – Development of intrusive and non-intrusive control algorithms for the electricity market

List of publications

J. Lago, F. De Ridder, P. Vrancx, B. De Schutter, "*Forecasting day-ahead electricity prices in Europe: the importance of considering market integration*", Applied Energy (Under review), 2017.

Abstract: Motivated by the increasing integration among electricity markets, in this paper we propose three different methods to incorporate market integration in electricity price forecasting and to improve the predictive performance. First, we propose a deep neural network that considers features from connected markets to improve the predictive accuracy in a local market. To measure the importance of these features, we propose a novel feature selection algorithm that, by using Bayesian optimization and functional analysis of variance, analyses the effect of the features on the algorithm performance. In addition, using market integration, we propose a second model that, by simultaneously predicting prices from two markets, improves even further the forecasting accuracy. Finally, we present a third model to predict the probability of price spikes; then, we use it as an input in the other two forecasters to detect spikes. As a case study, we consider the electricity market in Belgium and the improvements in forecasting accuracy when using various French electricity features. In detail, we show that the three proposed models lead to improvements that are statistically significant. Particularly, due to market integration, predictive accuracy is improved from 15.7% to 12.5% sMAPE (symmetric mean absolute percentage error). In addition, we also show that

the proposed feature selection algorithm is able to perform a correct assessment, i.e. to discard the irrelevant features.

J. Lago, F. De Ridder, P. Vrancx, B. De Schutter, "*Forecasting spot electricity prices: deep learning approaches and empirical comparison of traditional algorithms*", Applied Energy (Under review), 2017**.**

Abstract*:* In recent years, due to market deregulation and the increase of renewable energy sources into the electrical grid, accurate forecasting of electricity spot prices has raised as one of the most important challenges to keep a balanced and stable grid. While many predictive models have been proposed to satisfy this need, the area of deep learning algorithms remains yet unexplored. In this paper, to fill this scientific gap, we propose different deep learning models for predicting electricity prices. Next, we illustrate how the novel architectures lead to improvements in predictive accuracy. In addition, we also consider that, despite the large amount of proposed methods for predicting electricity prices, an extensive benchmark is still missing. To tackle that, we compare and analyse the accuracy of 23 common approaches for electricity price forecasting. Finally, we use the benchmark results to show that the deep learning approaches obtain state-of-the-art results that are statistically significant.

<u>Visits, detachments, and training</u>

- European Conference on Computational Optimization (EUCCO), 2016, Leuven. No publication submitted.
- International Federation of Automatic Control (IFAC) World Congress, 2017, Toulouse. Publication: *Warping NMPC for Online Generation and Tracking of Optimal Trajectories*, J. Lago, M. Erhard, M. Diehl.
- Courses -Scientific Skills
  - Innovative controls for renewable source integration into smart energy systems.
  - Data Science Summer School.
  - Graph theory and large scale applications.
  - Forecasting with R.
- Courses- Transferable Skills
  - How to Write and Publish a Scientific Paper.
  - Project Management.
  - Scientific Integrity.
  - Self-Presentation: Presenting Yourself and Your Work
  - Time Management.
  - Resources for scientific writing, the external peer review process and the internal peer review process.

5. ANNEX I - KNOWLEDGE UTILIZATION POSSIBILITIES

What target groups could be interested in the results of this research?

Groups that could be interested in the results of this research are research groups focused on control of large-scale systems, optimization-based control, and power networks, transmission system operators (TSO); university students, majoring control engineering or electrical engineering. Moreover, the project provides control techniques for distribution system operators and aggregators to unlock the flexibility offered by distributed energy resources, giving them an opportunity to further integrate this flexibility into the energy markets. Thus, the expected outcomes of this project are directly useful not only to distribution system operators but also to aggregators and to end-users of electricity.

6. ANNEX II - SPECIAL DEVELOPMENTS IN THE RESEARCH FIELD

- The dynamic optimal power flow (OPF) problem is one of the emerging research themes. It is an extension of the standard OPF in which the slow dynamics of the storage systems are taken into account. In this regard, model predictive control, being an optimization-based control which can handle dynamical systems, is seen as a suitable approach to solve such problems. Furthermore, distributed approach is preferred by considering the fact that current energy grids consist of many distributed generators and distributed storages. One promising distributed MPC method is DMPC, which is based on evolutionary game theory (EGT) and can be considered as a distributed optimization method. DMPC methods based on EGT have been proposed for nominal linear systems. It would be interesting to extend this method such that it can be applied to systems with disturbances.

- Another currently emerging research topic related to the distributed solution of the dynamic OPF is system partitioning. Prior to designing a distributed control scheme, the system must be partitioned into a number of sub-systems. Considering the fact that current power networks may have time-varying topology, e.g., due to the electrical vehicles that move around and are connected to the network at different points at different time, the system partition must also be adjusted.

- Another research theme is the application of AI techniques to solve real-time decision making and planning based on Markov Decision Processes.

- Looking into the future, a DC distribution system could become an alternative approach to supply future loads connected to distribution feeders and this can be optimally controlled by an energy management system. Primary distributed energy resources such as photovoltaic systems and fuel cells have a DC power output. Energy storage systems like batteries also work on DC input/output power. This makes interconnections on the low voltage DC network easier along with minimizing cost of extra power electronic components. Hence one of the emerging research themes that we foresee is the rise of DC systems and the low voltage DC distribution networks.

- Another research theme is that of Distributed Optimal Power Flow. Distributed OPF in recent times has caught the attention of researchers due to increase in the distributed energy resources. Increase in development of low voltage distribution networks prompts the use of distributed OPF to be incorporated to optimize the system power flows while reducing overall system operational costs. Furthermore, distributed optimization is scalable and more robust towards communication failures and cyber-attacks compared to centralized approaches.

- Co-Simulation of low voltage distribution networks is another emerging research theme that we anticipate. Even though smart grids provide solutions to aging infrastructure problems, manage the increased demand and aid in reducing the CO_2 emissions, there is a limited amount of tools that can analyse the increasing complexity of such a system. Through the means of Co-Simulation we are capable of capturing interactions between different components, actor decisions (such as DSO and Aggregator) and controls at the distribution level in real-time.