Innovative controls for renewable source integration into smart energy systems

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WP2 – Control Strategies for ESS

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DEFINITIONS

- Beneficiary partners of the INCITE Consortium are referred to herein according to the following codes:
  - **IREC**. Fundacio Institut de Recerca de l'Energia de Catalunya (Spain)
  - **UPC**. Universitat Politècnica de Catalunya (Spain)
  - **TU Delft**. Technische Universiteit Delft (Netherlands)
  - **VITO**. Vlaamse Instelling Voor Technologisch Onderzoek (Belgium)
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- **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

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EXECUTIVE SUMMARY

This report presents the progress of WP2 "**Control Strategies for ESS"** where three PhD researchers have been working for slightly over a year on their individual research projects but at the same time have been benefiting from exchange possibilities and meetings as much as possible to make the collaboration within WP2 a strong factor contributing to its success.

1. STATUS OF WP2

This chapter describes the status of WP2 "**Control Strategies for ESS"**.

WP objectives

The aim of WP2 is to propose low-level control strategies for ESS in smart grid contexts, develop management algorithms to integrate ESS in smart grids, and controllers that exploit the energy storage capabilities of buildings.

The research in this WP employs a more abstract view of ESS trying to generalize concepts in order to improve the performance of microgrids and smart grids in a generic sense.

WP general progress

The general progress of WP2 is satisfactory. The first year of the three ESRs was aimed at understanding the INCITE project objectives and working plans, writing their own individual research project proposals and developing mutually beneficial interactions inside the WP.

WP impact

The impact of this WP can be measured by an important number of publications accomplished in the first year of the research. It is worth noticing that this number of publications has been reached even though the students were at the beginning of their research activities. All publications are presented in Chapter 3.

2. PROGRESS OF THE IRPS

This chapter describes the progress of the four IRPs contributing to the objectives of WP2.

2.1 Energy flexible and smart grid/energy ready buildings

Project leader	Jaume Salom	
Research institute	Catalonia Institute for Energy Research	
Sub-project leader(s)	Ramon Costa-Castelló	
Early stage researcher	Thibault Q. Péan	
Period covered in this report	20 June 2016	15 October 2017

ESR2.1 first reviewed the literature on advanced control techniques for harnessing energy flexibility in buildings, especially with heat pump systems. A clear difference was observed between rule-based controls and model-based predictive control (MPC) strategies. The outcome of the literature review was submitted to a scientific journal, and the peer reviewers required minor revisions before a definitive acceptance. After this first step, rule-based controls aiming to decrease the energy costs (using variable energy prices) were developed and tuned. These controls were applied to typical Spanish buildings through dynamic simulations, and enabled to realize cost savings and to improve the energy flexibility of those buildings, sometimes at the cost of an increased energy use. These results were presented in another journal article and in a conference paper. Another conference paper was accepted, concerning preliminary experiments realized with a natural gas boiler. ESR2.1 also participated in the bi-annual meetings of the IEA EBC Annex 67 about Energy-Flexible Buildings, where he is involved in different tasks and recently presented an invited paper about how to represent daily profiles of the available flexibility capacity and efficiency in buildings.

The next steps within this IRP consist in the investigation of more advanced control strategies for energy flexibility. An MPC framework including reduced-order models will be developed and tested first through computer simulations. When concluding remarks are drawn from the simulations, experiments will be carried out in the semi-virtual environment of the laboratories: a real heat pump installed in the climate chamber will be controlled by the chosen MPC configuration to test it in more realistic conditions.

2.2 Control and management of storage elements in micro-grids

Project leader	Ramon Costa-Castelló	
Research institute	Universitat Politècnica de Catalunya	
Sub-project leader(s)		
Early stage researcher	Unnikrishnan Raveendran Nair	
Period covered in this report	3 January 2017	15 October 2017

ESR2.2 started relatively late (January 2017) but has shown impressive effort and evolution in order to ensure meeting the IPR objectives. In this regard, the major results of the project from its start and until October 2017 can be summarised as follows:

The major work done during this period has been a literature survey and proposing a suitable multilevel control architecture for the integration of the different storage elements in the micro-grid. Based on the literature survey, a three level architecture comprised of a primary, secondary and tertiary control has been proposed as the best suited architecture for the integration of storage systems in micro-grids. The primary controller acts on the converters connecting the storage systems to the micro-grid, ensuring the reference power to these storages is delivered to the grid. The secondary controller acts on the primary level, providing it with the references necessary to maintain the grid parameters (voltage, frequency) within prescribed limits under sudden load variations. Finally, the tertiary level provides set points to the lower levels, which enables an optimal operation of the entire micro-grid. The optimization performed by the tertiary level can be on the minimization of operating costs, minimizing degradation of the storage elements etc. In this work the proposed optimization will be on degradation minimization.

Another result obtained during this period has been the development of reset controllers, which will be employed at the low level control of the architecture. The reset controllers belong to the class of hybrid controllers and are capable of achieving superior performance than linear controllers. The traditional low-level controllers employed the standard PI controller to achieve reference tracking. The new controller proposed in this IRP is a PI+CI (CI being Clegg integrator), which is a slight modification of the PI. These reset controllers partially reset their states when certain conditions are satisfied, thereby achieving improved performance over their linear counterparts (PI). Based on this approach, a PI+CI controller-based control has been developed for the DC-DC boost converter which will be employed at the output of the storage devices. The proposed controller has been designed and simulated. The laboratory implementation of the same has also been done. The major results from this research will be published in journals.

2.3 Robust management and control of smart multi-carrier energy systems

Project leader	Bart De Schutter	
Research institute	Delft University of Technology	
Sub-project leader(s)		
Early stage researcher	Tomas M. Pippia	
Period covered in this report	1 June 2016	15 October 2017

The ESR involved in this project is currently in the second year of his PhD program.

ESR2.3 has written a paper, submitted to ACC 2018, which deals with optimal partitioning of time-varying linear large-scale systems. In short, the paper proposes a novel partitioning method to split linear time-varying large-scale systems into smaller subsystems. The partition is carried out with the goal of minimizing the coupling between subsystems and, at the same time, to balance the number of elements in each subsystem. The algorithm is applied to a special class of time-varying large-scale systems, in which the state and input matrices take values from a “library” of predefined matrices. Moreover, a stability analysis is provided when a decentralized state feedback control scheme is applied to the system. As an interesting application in the framework of INCITE, this research could be applied to electric vehicles, that can be considered as energy storage systems and that move around in the power network from one point to another, and are coupled to different nodes at different times. The next step of this research is to improve the partitioning algorithm and to extend the work to an online partitioning algorithm.

Apart from the aforementioned topic, the next steps within the IRP considered by the ESR are to work on robust distributed model-based control strategies for power systems with local energy storage and local energy production. In particular, the project will consider micro-combined heat and power (μCHP) plants and electric vehicles as energy storage systems. μCHPs can generate electrical power locally by converting natural gas or hydrogen to produce at the same time heat and electricity. By combining μCHPs with an energy storage system, i.e. electric vehicles, the heat demand could be decoupled from the electricity production provided by the μCHP. This would then increase the flexibility and the hosting capacity of distribution networks. Moreover, since the instants at which energy is produced and used are different, the efficiency would be increased because most of the energy produced locally could be also be used for self-consumption. This might lead to a reduced amount of power being taken from the main electrical grid, reducing at the same the losses in transportation of energy.

3. INTERNAL AND EXTERNAL COLLABORATIONS

3.1 ESR 2.1

The ESR is currently performing his first secondment at 3E, partner organisation in INCITE, in Brussels (BE). His tasks involve analysing the data recorded from MPC operation in real commercial buildings, identifying potential flaws in the control strategies or the models used, and proposing improvements to the MPC configuration.

3.2 ESR 2.2

The ESR has not performed secondments until now. They will be performed during 2018. The following visits have been performed:

- 1 week Visit to University of Murcia (ES) for collaboration on Reset controllers.
- Visits to CentraleSupélec, Paris (FR) for attending courses on Polynomial optimization and sliding mode controllers.

3.3 ESR 2.3

ESR2.3 carried out the first of the two secondments foreseen by the INCITE project at UPC in Barcelona (ES) from mid-march until mid-July. During his secondment at UPC, he started cooperating with ESR 1.1. As a result, a joint paper was developed and submitted to the American Control Conference (ACC'18). At the moment, he is working on the extension of this work to the journal version, which is expected to be ready in the first semester of 2018. His second secondment is planned for autumn 2018, at the beginning of his third year, at 3E.

4. DISSEMINATION OF RESULTS: PUBLICATIONS & CONFERENCES

This section includes all the publications already accepted or submitted, including the corresponding abstract for each paper.

T. Péan, J. Ortiz and J. Salom (2017). *Impact of Demand-Side Management on Thermal Comfort and Energy Costs in a Residential nZEB.* Buildings, vol. 7, no. 2, p. 37. DOI: 10.3390/buildings7020037

Abstract: In this study, simulation work has been carried out to investigate the impact of a demand-side management control strategy in a residential nZEB. A refurbished apartment within a multi-family dwelling representative of Mediterranean building habits was chosen as a study case and modelled within a simulation framework. A flexibility strategy based on set-point modulation depending on the energy price was applied to the building. The impact of the control strategy on thermal comfort was studied in detail with several methods retrieved from the standards or other literature, differentiating the effects on day and night living zones. It revealed a slight decrease of comfort when implementing flexibility, although this was not prejudicial. In addition, the applied strategy caused a simultaneous increase of the electricity used for heating by up to 7% and a reduction of the corresponding energy costs by up to around 20%. The proposed control thereby constitutes a promising solution for shifting heating loads towards periods of lower prices and is able to provide benefits for both the user and the grid sides. Beyond that, the activation of energy flexibility in buildings (nZEB in the present case) will participate in a more successful integration of renewable energy sources (RES) in the energy mix.

T. Péan, J. Salom and J. Ortiz (2017). *Potential and optimization of a price-based control strategy for improving energy flexibility in Mediterranean buildings.* Energy Procedia, vol. 122, pp. 463–468, Sep. 2017. DOI: 10.1016/j.egypro.2017.07.292 (poster presented at CISBAT 2017 International Conference on Future Buildings & Districts – Energy Efficiency from Nano to Urban Scale, Sept. 6-8th 2017, Lausanne, Switzerland)

Abstract: The present study proposes the implementation and fine-tuning of a rule-based control strategy aiming to improve the energy flexibility of residential buildings in the Mediterranean area. The adopted control reacts to the time-varying electricity price signal, and modulates the set-point for space heating and domestic hot water production accordingly. A parametric study on three control variables of the control algorithm was carried out, in order to choose appropriate values. The analysed outcome consisted mainly in the provided flexibility, the impact on the comfort conditions, and the evolution of the energy use and costs compared to a standard reference case. After tuning the control strategy, a decrease in energy costs of around 22 to 26% was observed, along with an important shifting of heating loads towards low energy price periods. The proposed control additionally caused an increase of energy use of 2 to 4%, without jeopardizing comfort conditions. These results emphasize the potential of residential buildings for energy flexibility in the Mediterranean area.

T. Péan, J. Salom and R. Costa-Castelló (2018). *Review of control strategies for improving the energy flexibility provided by heat pump systems in buildings*. J. Process Control, Special Issue on Efficient Energy Management, 2018 (request for minor revisions).

Abstract: The present work constitutes a review of the existing literature on supervisory control for improving the energy flexibility provided by heat pumps in buildings. A distinction was drawn between rule-based controls (RBC) and model predictive controls (MPC), given the clear differences in their concept and complexity. For both kinds, the different objectives claimed by these strategies have been reviewed, as well as the control inputs, disturbances and constraints. Notably in MPC, the monetary objective (reduction of the energy costs) has been the most utilized in the literature, therefore the authors advocate for the further study of other objectives related to energy flexibility. Further than the control strategies themselves, the different thermal storage options (necessary to activate the flexibility) have also been reviewed, the built-in thermal mass seeming more cost-effective than water buffer tanks in this regard. Based on these conclusions, recommendations for further research topics are drawn.

T. Péan, E. Fuentes, J. Ortiz and J. Salom (2018). *Performance of a gas boiler under dynamic operation conditions: experimental studies in semi-virtual environment*. In proceedings of COBEE2018 - Conference On Building Energy & Environment, Feb. 5-8th 2018, Melbourne, Australia (accepted).

Abstract: A series of experiments were performed in a semi-virtual environment to investigate the performance of a gas boiler under dynamic operation conditions. The real condensing boiler was placed in the laboratory, and connected to thermal benches which emulate the thermal loads generated by a virtual building model. The results revealed first that the boiler efficiency drops when the Domestic Hot Water (DHW) needs prevail over space heating, due to the start-up losses provoked by a more frequent switching. The heating curve control enables to save energy and reach higher efficiency levels in spring season, but this was not entirely verified in winter (full load heating). The impact of an increased thermal mass and insulation level was also experimented, as a preliminary step towards investigating energy flexibility in an nZEB-type building.

T. Péan, B. Torres, J. Ortiz and J. Salom (2018). *Representation of daily profiles of building energy flexibility.* In proceedings of eSim 2018 – IBPSA Canada biennial Conference on Building simulation to support building sustainability, May 9-10th 2018, Montréal, Canada (abstract submitted October 15th 2017).

Abstract: The representation of simulation results with regards to building energy flexibility is investigated. The chosen case study is a residential flat located in Spain, equipped with an air-to-water heat pump. From a reference simulation scenario, active demand response (ADR) events are implemented; they consist in modulating the heating set-point for a few hours. If the starting time of the ADR event is varied in time, the resulting simulations enable to produce daily profiles quantifying the different aspects of energy flexibility. Different representations of these profiles are proposed and discussed, combining the flexibility capacity and efficiency profiles, or representing different ADR configurations in a single graph. A high dependency of the flexibility profiles was observed with regards to the existing consumption profile and temperature setbacks. An ADR event of 2 hours with set-point

modulation of ±1°C provides a maximum flexibility capacity of 9.4kWh upwards and -8.6kWh downwards.

T.Péan (2017). *Controls for improving energy flexibility with heat pumps*. Oral presentation (without paper) of PhD project in the joint workshop "Heat pumps for nZEB, retrofit and energy flexibility" at 12th IEA Heat Pump Conference, 15-18th May 2017, Rotterdam, The Netherlands.

U. Raveendran Nair, R. Costa Castelló. An overview of micro-grid architecture with hybrid storage elements and its control. Proceedings del XV Simposio CEA de Ingeniería de Control, 2017.

Abstract: This paper discusses the role of hybrid energy storage systems in future grids, especially micro-grids, to improve the penetration of renewable energy sources. The storage systems are essential in the future grids to improve the power quality and maintain the grid stability under high penetration of renewable sources. The use of more than one type of energy storage elements in the grids with different response times will help in improving the efficiency and reliability of the storage systems. The different control strategies for load sharing among these storage devices are also discussed in this paper.

T. Pipia, W. Ananduta, C. Ocampo-Martinez, J. Sijs, and B. De Schutter. Partitioning approach for control of time-varying large-scale linear systems. In Proceedings of the American Control Conference , Milwaukee (USA), June 27-29 2018.

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, T. Pipia, C. Ocampo-Martinez, J. Sijs, and B. De Schutter. On the distributed control of linear large-scale systems: partitioning and stability issues. To be submitted to Systems and Control Letters, 2018 (no abstract available yet).