
Innovative controls for renewable source integration into smart energy systems



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First Workshop Proceedings

WP6 – Dissemination and exploitation of results

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¹ Report

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


³ Dissemination and/or exploitation of project results

⁴ Other including coordination

⁵ Public: fully open, e.g. web


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DEFINITIONS

- Beneficiary partners of the INCITE Consortium are referred to herein according to the following codes:
 - **IREC.** Fundacio Institut de Recerca de l'Energia de Catalunya (Spain)
 - **UPC.** Universitat Politècnica de Catalunya (Spain)
 - **TU Delft.** Technische Universiteit Delft (Netherlands)
 - **VITO.** Vlaamse Instelling Voor Technologisch Onderzoek (Belgium)
 - **UniBo.** Universita di Bologna (Italy)
 - **UGA.** Université Grenoble Alpes (France)
 - **GE Global Research.** General Electric Deutschland Holding GmbH (Germany)
 - **Efacec Energia.** Efacec Energia - Maquinas e Equipamentos 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).

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ABBREVIATIONS

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

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EXECUTIVE SUMMARY

This report brings together the abstracts of the scientific presentations that took place during the first INCITE Workshop, which was organised by VITO and was held in Genk, Belgium, on 23-25 November 2016.

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

Though not included in this report, complementary skills were also addressed in the workshop, which included a full day seminar on Project Management (1 ECTS) and a seminar on “The publication and reviewing process”.

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1. INTRODUCTION

The first INCITE workshop was held in Genk (Belgium) on 23-25 November 2016. The host of the event was VITO, and the goal of the workshop was three-folded.

First, it intended to provide doctoral training to the members of the research network. To accomplish that, the workshop included a full day seminar on *Project Management* and a short tutorial on “*The publication and reviewing process*”.

Second, it served as introduction and presentation of the different Individual Research Projects (IRPs). For that, each Early Stage Researcher (ESR) presented his/her line of research, a roadmap of his/her work and/or research intentions. After each presentation, the fellows received feedback from their peers in order to enhance the quality and scope of the different IRPs.

Finally, it also hosted two relevant scientific keynote speakers within the project research field. Prof. Ronnie Belmans (KU Leuven, CEO EnergyVille) and Prof. Damien Ernst (Université de Liege), who presented his work on managing distribution networks considering the increase of renewable energy sources, evolution of consumption patterns and other relevant network effects.

2. ABSTRACTS

In the following pages, the abstracts of the IRP presentation can be found:

WP1. Control strategies for distributed power generation

- IRP1.2 – Decentralised control for RES by fast market-based multi-agent systems (H. Abdelghany)
- IRP1.3 – Hybrid agent-based optimisation model for self-scheduling generators in a market environment (S. Chakraborty)
- IRP1.4 – Intrusive and non-intrusive control algorithms for the energy market (J. Lago Garcia)

WP2. Control strategies for energy storage systems


- IRP2.1 – Energy flexible and smart grid/energy ready buildings (T. Pean)
- IRP2.3 – Robust management and control of smart multi-carrier energy systems (T. Pippia)

WP3. Control strategies for RES integration

- IRP3.1 – Control of (high voltage) hybrid AC-DC grids (A. Agbemuko)
- IRP3.2 – A new modelling approach for stabilisation of smart grids (F. Koeth)
- IRP3.3 – Distributed control strategies for wind farms for grid support (S. Siniscalchi Minna)

WP4. Monitoring tools and secure operation of smart grids

- IRP4.2 – Fault detection and isolation for renewable sources (N. Sapountzoglou)
- IRP4.3 – Review of methods plus new approaches for distribution system state estimation (M. Picallo Cruz)
- IRP4.4 – Advanced functionalities for the future smart secondary substation (K. Kotsalos)

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Keynote speakers

- Prof. Damien Ernst (U. Liège) – The GREDOR project. Redesigning the decision chain for managing distribution networks

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

ESR1.2: Hazem Abdelghany, TU Delft.

I. INTRODUCTION

Today's typical electrical grid takes a centralized form, based on a SCADA system that is capable of supervision, control, and data acquisition from a central control point. However, the growing need for cleaner, cheaper and sustainable energy calls for a new control paradigm able to handle grids with flexible demand, energy storage, and numerous micro-sources owned by different, sometimes competing, parties. This project studies market-based multi-agent systems for decentralized control over such grids. The project aims to introduce decentralized market-based control approaches that are fast, robust, and with efficient complexity. The project objectives are to:

- Model smart grids with various, decentralized RES owned by different parties.
- Develop fast market-based control strategies that can act in fractions of seconds.
- Develop the required bidding languages, mechanism designs in order to establish efficient and robust market mechanisms.
- Develop the required multi-agent system including the required agent strategies and decision modules.

II. MARKET-BASED MULTI-AGENT SYSTEMS

The future electrical grid is distributed in nature. It is typically made of numerous sources (usually fluctuating), loads and energy storage devices. In an agent-based paradigm, each element of the grid is treated as an agent, these are divided into three layers [1]:

- Information layer (perception): agents responsible for gathering information from different data sources (i.e. sensors, weather forecasting, smart meters).
- Knowledge layer (cognition): agents responsible for understanding and prediction (i.e. load forecasting, generator scheduling).
- Behavioural layer (action): agents responsible for running complex algorithms, decision making and execution of actions (i.e. optimizers, actuators)

Due to the nature of the smart grids, agents often have different, sometimes conflicting, parameters, preferences and goals. These characteristics can be seen as a traditional market economy, where different entities (agents) coordinate in order to achieve personal objectives. In a manner that satisfies all parties [2].

In a market-based system, a market mechanism is used to resolve conflicts between agents and govern bidding, negotiation and decision making. Such a market mechanism consists of [1]:

- Bidding language.
- Mechanism design.

On the agent level, a bidding strategy is the main components of an autonomous agent [1], it implements the agent's task (perception, cognition, or action); the other major component is the agent's decision module. Finally, the fluctuating nature on the future electrical grid dictates that the aforementioned control system should be able to act in the timescale of seconds, or fractions of seconds.

III. EXPECTED OUTCOME

The project is expected to introduce control solutions for RES based on market-based multi-agent system, these solutions are required to be:

- Efficient in terms of computation and communication complexity.
- Able to use suitable market mechanisms to regulate and adjust resources allocation and power injection into the grid.
- Modelled, using multi-agent software prototypes, including the required agent strategies and decision modules.
- Analysed and evaluated by simulation on proper grid models and test cases.

IV. PROJECT AS PART OF THE INCITE PROGRAM

This IRP is part of WP1 and serves its objectives by modelling different sources in complex electrical networks, developing decentralized control strategies for RES in grids with distributed generation based on multi-agent systems. However, these control strategies cannot ignore input and feedback from other WPS, such as on energy storage systems, stability, voltage, and frequency regulation.

Moreover, the project aims at producing solutions that are validated by simulation using grid models and test cases as part of WP5.

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Hybrid Agent-Based Optimization Model for Self-Scheduling Generators in Market Environment

Shantanu T. Chakraborty, Zofia Lukszo

Abstract— Currently the falling prices of renewable energy systems (RES) coupled with favorable policies regulating them in the European Power Markets have resulted in an increasing number of renewables and distributed energy sources being integrated to the grid. In the residential energy sector, end-customers with RES capabilities (Prosumers) have been empowered with the ability to produce and consume their own energy which reduces their grid dependency. However, there are fundamental issues with RES that limit their growth.

The variable and uncertain nature of renewable energy poses a constraint on the efficiency and integrity of the power system. This serves as a major hindrance for their higher penetration to the grid, which necessitates the requirement of novel control and optimization methodologies to ensure the optimal operation of the power system. Through our proposed research, we aim to tackle these issues.

In our research we attempt to address the problem of power system optimization under demand uncertainties in electric grids having a high penetration of RES. To achieve effective demand response, we propose Distributed Optimization algorithms using Alternating Direction Method of Multipliers (ADMM) implemented at the Load Aggregator that spans across all its customers, in a Multi-Agent systems context. Further, to address the issue of intermittency of renewable generation, we propose the exploration of an adaptive framework for Unit Commitment based on probabilistic optimization techniques. Also, in our research, we understand the importance of communication in the operation of the electric grid, and propose the exploration of new ICT tools to enable efficient information and data flow.

By coupling the two problem statements of Demand Management and Unit Commitment, we believe that we can achieve optimal planning and operation of the power system.

I. INTRODUCTION

Favorable policies and reducing costs for Renewable Energy Systems (RES) has resulted in their increasing adoption to meet energy demands. This has led to the emergence of a new type of utility customer, who are capable of generating and consuming their own energy. However, the intermittent nature of renewables limits their widespread integration to the electric grid.

In Day-ahead Markets, large-scale integration of RES, poses great challenges to power system operators and load serving entities (load aggregators). In order to achieve the objective of minimizing cost while meeting the demand, it is imperative for load aggregators to be accurate in their load

and price forecasts to determine transactions in the power market [1]. Prosumers, with their ability to generate energy on-site, are capable of offsetting a fraction of the demand. However, the amount of load displaced is subject to weather conditions and is variable; which adds noise to the load aggregators forecasts. Hence, as predictions are not perfect, it introduces discrepancies between actual power imported and forecasted power, which are settled in the real-time operation of the power system [1]. In conditions of unmet demand, it is the responsibility of the power system operator to schedule the generators to meet this demand, which is also known as the problem of Unit Commitment. As generation costs are a major component of the whole system's operation cost, it becomes critical to derive optimal solutions to achieve economic savings [2].

In order to address the issues caused by the integration of large-scale RES, we propose a two stage approach for optimizing the operation of the power systems under uncertainty of demand and generation. First, we explore the problem of optimizing demand management systems under different price signals, by implementing Distributed Optimization using Alternating Direction Method of Multipliers (ADMM) [3] at the Load Aggregator. We then, broaden the system description to include the problem of Unit Commitment under uncertainty by designing an adaptive framework based on the methods of Stochastic Optimization, Robust Optimization and Model Predictive Control. In addition, to achieve optimal operation and planning of the power system, it is critical to have a robust bi-directional communication channel between the end-users and the electric grid. For this, we also propose the exploration of novel Information and Communication tools using an Internet of Things architecture.

This paper is organized as follows: Section II describes our proposed system description and the exploratory algorithms that we plan to implement.

II. SYSTEM DESCRIPTION

A. Prosumers

End-use customers of the electric grid, who have renewable energy system capabilities, are able to produce and consume energy on-site, and are hence known as Prosumers. In our system, we model them as agents who participate in Energy Markets. Each Prosumer has its own generation and load profile, and the difference in load is satisfied by the load aggregators. In addition, prosumers also participate in demand response programs, that are governed by price or economic signals as well as demand constraints that are imposed by the load aggregators.

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As the energy generation profile of the RES are probabilistic, there could be significant variances in the residual loads, that the load aggregators would have to satisfy. In order to obtain more accurate generation profiles, we propose the development of predictive models based on weather data that are capable of providing updates in both a day-ahead schedule as well as real-time. This would enable both the load aggregators and power system operators in their planning.

Also, while modeling prosumers, it is important to acknowledge that they are capable of having diverse load patterns. To simplify the system, a classification model can be implemented based on installed RES technology, characteristic of households and consumption behavior [4].

In the Distribution System, these Prosumer agents are capable of communicating with the Load Aggregator Agents, who are responsible for implementing effective Demand Management Systems for demand response programs.

B. Load Aggregators

The Load Serving Entities or Load Aggregators, are agents who forecast customer loads and place the bids in the Day-Ahead Market with the objective of minimizing purchasing price. For any unsatisfied demand, load aggregator need to procure the residual energy in real-time markets.

The load aggregators, also have the responsibility of implementing Demand Management Systems and controlling Energy Storage Systems, to ensure Distribution System stability. To ensure optimal operation of the Distribution System, Distributed Optimization using Alternating Direction Method of Multipliers (ADMM) is implemented at the Load Aggregator agent, spanning across all the prosumer or residential energy consumers serviced by it. The ADMM approach has been opted for due to its advantages of better robustness, convergence rate and process requirements as compared to other decomposition algorithms [3].

C. Power System Operator

The Power System Operator is the agent that is responsible for clearing all the bids that are placed by the Load Aggregators at the Distribution Systems. In power systems, that have a high penetration of RES, the forecasts that are made by the load aggregator agents can have significant discrepancies in them. For the residual energy demanded by the load aggregators, it is the responsibility of the Power System Operator to ensure their clearance in real-time.

In order to satisfy the residual energy demanded, the power system operator needs to schedule dispatchable generators in real-time. As generation costs are a major component of the whole system operating cost, it becomes critical to derive optimal solutions to achieve economic savings [2]. With this as our objective, we tackle the problem of Unit Commitment through an adaptive framework of Probabilistic Optimization and Control algorithms. Depending on the market and constraints such as reliability and system stability, we explore solutions through

the implementation of Stochastic Optimization, Robust Optimization and Model Predictive Control, to minimize generation costs.

D. ICT Tools

Traditional, uni-directional communication between the grid and residential end-customers, has been identified as one of the major issues for the emergence of Prosumers and further integration of RES. Hence, there is a need for bi-directional communication. One of the solutions to achieve this is through Smart Meter Infrastructure, which could be implemented using affordable and compact micro-computers which could be interfaced with residential areas. The Internet of Things (IoT) has already displayed immense potential in process industries, and this holds true for having better data and information flow between Transmission and Distribution Systems.

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Intrusive and non-intrusive control algorithms for the energy market

Jesus Lago Garcia

I. INTRODUCTION

In recent years, *renewable energy sources (RES)* have been gaining a large production share of the world's energy production. While there are no question regarding their contribution to build a more sustainable world, several concerns have been raised regarding their influence on price electricity. In detail, most of the goods which can be stored, energy has to be traded on the spot as their storage is unfeasible. As a result, different energy trade markets are set across the world where the price is adjusted accordingly to real-time offer and demand. With the appearance of RES in recent years, the market price has become volatile: unlike traditional fossil fuel generation plants, the production of energy from RES depends on weather conditions; as a result, when a weather forecast is not correct electricity prices change dramatically, energy imbalances occur and the electricity network might collapse.

A possible way to prevent this and safeguard the profitability of RES, is to implement non-intrusive control algorithm to produce smart bids in the energy market. In particular, by forecasting energy prices in advance, market players know when it is more convenient to trade energy; as a result, energy buyers will try to purchase when prices are low and the offer is high (high production of RES), and sellers will try to carry the opposite strategy. As a consequence, when the offer is too high (low), the demand experiences an increase (decrease), the market is balanced and prices become less volatile.

However, as shown in previous attempts to forecast energy prices [1], [2], the accuracy of the prediction is significant enough. As a result, non-intrusive control might help to reduce network imbalances, but in general are not sufficient to completely balance the energy market.

To overcome the mentioned limitations, intrusive control algorithms are able to steer some electrical system in real-time and provide demand response when the market request. Examples of such algorithms are smart houses [3], thermal storage systems [4], or electric vehicles [5], [6].

The aim of this project is to look at different approaches in both fields, and derive a new set of control algorithms that can improve even further the profitability of RES.

II. NON-INTRUSIVE CONTROL

As non-intrusive control is a very broad topic with many different applications, we will narrow our research in three different areas. First, we will look at new forecasting techniques, then, we will implement a control algorithm that takes into account interrelations of markets, and finally, we will design a toolbox for optimal selection of battery systems.

A. Forecasts of Energy Markets

The main goal of this part of the research will be to forecast the price and imbalance positions of the three markets with more presence of renewable sources (day ahead, intraday and imbalance). In particular, we will focus on the interrelations of the different markets to be able to infer/estimate the forecast:

- 1) Patterns in the allocation and prices on the day ahead market that can be used to forecast imbalance positions and imbalance prices in the imbalance market. The input information from the day ahead market will be coupled with weather forecasts.
- 2) Look at patterns in the allocation and prices on the day ahead market that can be used to forecast energy offers and energy prices in the intraday market. The input information from the day ahead market should be coupled with weather forecasts.

In order to achieve the previous goals, two different points have to be tackled:

- 1) Understand and discover the dynamics of energy markets. In particular, identify which phenomenas have more influence on price and demand fluctuations. This task does not aim at quantify the effects nor identifying interrelations between markets; instead, it tries to extract the set of features that have the biggest influence in market changes and on finding the external influences of individual markets.
- 2) Identify the set of interrelations between energy markets. Model these interrelations using different inputs, e.g. historical data or weather forecast, in couple with current prices and energy trade of day-ahead/intraday market.

B. Control Algorithm for Multiple Markets

Once the characterization of the forecast is done and interrelations between markets are established, we will aim at developing a control algorithm that will optimally allocate different energetic resources among the three different markets. There are three possible options or levels of implementation:

- 1) Based on historic data and weather forecast, a first layer of the control algorithm will determine how much energy should be allocated in each of the three individual markets. This allocation has to be obviously done considering the different discrete time intervals of each market.
- 2) A control algorithm focusing on day-ahead and imbalance market interrelations. In this case, once the

allocations of the day-ahead are done, imbalance positions can be optimized using energy storage systems; i.e. energy can be bought on low demand intervals and sold at high demand intervals using a storage system as a buffer. A possible controller algorithm to perform this task is Nonlinear Model Predictive Control (NMPC).

C. Toolbox to select/validate battery systems

The aim of this research is to create a toolbox that, given a microgrid installation with its demand and its generation, performs validation and optimal selection of battery storage systems.

- 1) A validation unit that checks whether a given installation is feasible. It receives as an input the power demand and generation of the microgrid, the price forecast of a given year, the technical specifications of a battery storage systems and other input data. With this data, it computes the return of the investment in a given horizon. Then, it uses the tool described in 2 to compare how much the setup can be optimized.
- 2) An optimization unit that finds the best battery storage system for a given microgrid. It receives as an input the power demand, the generation of the microgrid and the electricity price forecast of a given year.

III. INTRUSIVE CONTROL

In this research areas, we will look at several different topics. In the first one, we aim at finding systems that can be modified or improved to provide energy demand response. In the next one, we will look at optimal experimental design as a tool to obtain accurate models.

A. Identification of Systems with Unknown Management

There are some cases where a system is controlled by an external agent and we have no manner to identify or control the system in a direct manner. Furthermore, it is of no interest to overwrite or modify the original controller as it implements security measures and complex control tasks that have to be deployed.

However, it is also possible that the same system, while keeping the necessary and original management algorithm, could be partially modified to gain some advantage by providing energy demand response. There are two clear examples reflecting the defined case:

- 1) A building management system (BMS) or heating system controlling that a building stays in the comfort zone. The management algorithm can be very complex, unknown and can not be modified.
- 2) A manufacturing plant that is controlled by some agent that decides when to steer, that keeps security measures and that takes a set of decisions that we are not interested in modify.

In both scenarios, we aim at identifying the system controller so that we can steer the system by using virtual (non-real) inputs. In the case of the building, this would mean use virtual temperatures to adjust the heating rate of the building to provide demand response.

B. Optimal Design for Energy Allocation

Taking the role of an aggregator, we aim at identifying the demands response of individual industrial plants to a given price profile. Once the models are obtained, we could produce accurate bids in the day-ahead market.

Moreover, if the plant demand response is identified, we also open the door to intrusive control algorithms. In particular, we know that convincing companies of steer their productions is very hard and in many cases even impossible. Nevertheless, as aggregator and knowing their energy demand response, we could use virtual prices to modify individual demand responses and in turn correct imbalances.

To obtain the demand response of the plant, we will look at optimal experimental design to generate the minimum number of price profiles that are necessary to obtain a high accurate model.

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Energy Flexible and Smart Grid/Energy Ready Buildings

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Abstract — The present abstract relates the work carried out and planned within the INCITE project, in particular for the individual research project 2.1. The project is driven by the foreseen large deployment of renewable energy sources, which may seriously affect the stability of energy grids. It will therefore be necessary to control the energy consumption to match with the instantaneous energy production. In this scope, buildings and their built-in energy flexibility may be utilized for stabilizing the energy grids, since they can be controlled in order to shift their energy demand in time. The energy flexibility of a building is the ability to manage its demand and generation according to local climate conditions, user needs and grid requirements. The objective of this Individual Research Project is to investigate, propose and test control strategies to exploit the potential energy flexibility in buildings together with assessing the benefits for the future smart energy systems at building and aggregated level. The literature existing on this topic has been reviewed, in order to better apprehend the challenges of energy flexibility in buildings. Preliminary experiments and simulations have also been carried out. This achieved work constitutes the basis for defining the upcoming tasks during the remaining of the project, which will include the development of control algorithms and their testing in real-scale and laboratory environments.

I. INTRODUCTION

The increased penetration of solar and wind power in the national energy mixes might cause issues for the stability of the electricity grids in the future, because of their undispachable nature. The possible mismatch between renewable energy production and the energy load can be solved for example by demand-side management techniques or curtailment of RES power plants, but this latter option is not advisable.

Demand-side management of buildings has become a topic of great interest in the recent years, since buildings inherently contain some available storage, in the form of thermal energy (space heating, hot water storage tank for instance). The energy flexibility of a building consists in making it available for demand-side response, for example by shifting its loads towards periods where more renewable energy is available.

The current electrification of dwellings might facilitate this task. In fact, more and more energy-efficient dwellings (nZEB) are designed with PV panels and heat pumps, which makes them all-electrical. This could create issues, with an increase in electricity demand and peaks, but it should also be regarded as a chance, with a great potential for energy flexibility and electricity demand-side response of buildings. The objective of the present research project is to integrate

buildings as active nodes in the energy grid systems, in order to support the operation of those grids and facilitate the integration of RES. In particular, control strategies have to be defined in order to enhance the flexibility of buildings within the grid.

II. ACHIEVED WORK

A. Literature review on heat pump controls

As mentioned in the introduction, the electrification of dwellings and other constructions is a current trend in the building market, especially with the implementation of heat pump systems for the production of DHW, space heating or cooling. For this reason, a literature review has been carried out focusing on the different control strategies for heat pumps, aiming at improving their flexible usage.

The review revealed two main existing groups of control strategies: rule-based control (RBC) and Model Predictive Control (MPC). The former is a simpler form of operating the heat pump, based on a predefined rule, such as for example using a fixed schedule or forcing the switching of the heat pump based on the production of a PV system. The latter, MPC, is a more complicated strategy, since it requires a model of the building, and forecasts of the weather or electricity price for example. Based on the predicted reaction of the building model to the forecasted disturbance, the MPC performs an optimization over a certain control horizon, to determine the most profitable operation of the heat pump. Both RBC and MPC can be defined using different objectives: for instance reducing the energy use, the cost of electricity, the time spent in discomfort, increasing the self-consumption of the building etc.

B. IEA EBC Annex 67 – Energy-flexible buildings

The International Energy Agency (IEA), Energy in Buildings and Communities (EBC) programme is leading a joint international Annex about Energy Flexibility in buildings. In this framework, a Common Exercise was sent to the involved parties. It consisted in providing a simple building model with certain boundary conditions, and asking the participants to quantify the flexibility of this building.

A case study was investigated for the Common Exercise, with a building model from Catalonia. A set-point modulation strategy based on the electricity price signal was applied to this building. The results were analyzed using flexibility indicators from the literature, but also user-defined parameters. The analysis and methods used were compared with the ones of the other contributors of the Common Exercise during an expert meeting of the Annex 67 in Bolzano (Italy).

C. Experiment with boiler

In parallel with the aforementioned work, a small experiment is being performed in the SEILAB facilities of Tarragona. SEILAB is a semi-virtual environment which enables to connect a building simulation model with real operating devices such as a heat pump. In this case, a gas boiler was implemented in the lab, and its performance

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evaluated in different setups of the building model. One objective was also to become familiar with the experimental facilities in anticipation of a larger experiment (see III.D.).

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D. Dynamic Calculation Methods for Building Energy Assessment (Summer School in Granada, Spain)

Participation in this summer school enabled to learn about tools for statistical modeling techniques. Especially, using data measured under dynamic conditions for identifying building models has been one of the focus points, and these methods can be used for example in combination with MPC.

III. PLANNED WORK

A. Continuation of the literature review

The current literature review will be extended, including more publications on heat pump control, but also on the topic of thermal storage within buildings. A publication is considered from this review. The further aim is to identify potential control strategies that have not been studied in depth yet and that can be considered interesting to develop in the remaining of the project.

B. Development of control algorithms

Based on the results of the literature review, some new control algorithms for heat pumps will be designed. MPC could notably be developed with different objective functions than the traditional cost or energy use, for example with the aim of minimizing primary energy use.

C. Real building application (secondment in 3E)

A secondment in Belgian consulting company 3E is planned in 2017. The main objective of this internship will be to apply a MPC strategy to a real building, and measure the performance of the resulting operation. The MPC optimization problem will be coded in Python language.

D. Experiment with a heat pump in semi-virtual environment

An experiment will be carried out in the semi-virtual environment of the SEILAB facilities in Tarragona. A heat pump placed in the climate chamber will be connected to thermal test benches and a building simulation model (TRNSYS). Some of the previously developed control strategies will be tested in this setup.

IV. CONCLUSION

During this first phase of the project, the challenges and definitions behind the concept of energy flexibility in buildings have been identified. The literature about heat pump control has been reviewed, as this was a first and necessary step in the workflow of the project. Besides some additional experimental and simulation work, some tasks have also been defined for the upcoming period: development of control algorithms based on the literature review results, testing of these algorithms both in semi-virtual and real environments.

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Robust Management and Control of Smart Multi-carrier Energy Systems

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I. ABSTRACT

In the last years, the continuous increase in the share of renewable energy sources and technological improvements have dramatically changed the power grids. However, many issues still have to be solved in the field of renewable energy sources. One of them is the intermittence of the power generated by this kind of sources and thus the mismatch between production and consumption of power. A solution to this problem could be to introduce some energy storage systems into the electrical grid, thus increasing flexibility of the overall system, compensating the highly variable power delivered by renewable energy sources and trying to maintain the power balance [1]. At the same time, while previously the overall generation/distribution model was mostly based on a centralized generation with subsequent distribution and transmission, nowadays the generation of power consists in smaller generation sources that are geographically dispersed. These small-scale electricity generation systems are referred to as distributed generation; examples of these technologies are photo-voltaic systems, wind turbines and combined heat and power (CHP) plants [2]. The latter technology is able to produce both heat and electrical energy locally by combining electricity and gas networks and is referred to as the next generation domestic heating system. Both energy storage systems and distributed generation systems require new control paradigms that have to be developed in order to integrate these new technologies into the future Smart Grids and to increase their flexibility, efficiency, and sustainability. The overall scheme presented in this abstract is shown in Figure I.

Power networks are subject to various kinds of disturbances and therefore usually a simple control strategy is not sufficient. The goal of the control strategy is to guarantee the convergence of the local control agents to a set of consistent control actions even in the presence of disturbances. Electrical grids require that some magnitudes stay within specific values and that they do not exit from certain sets. For instance, the voltage is usually required to have a value around a nominal one and therefore some hard or soft constraints can be used in the optimization problem. A robust control method based on model predictive control (MPC) will therefore be developed in order to fulfill the requirements and the constraints of smart grids. This kind of control will be applied to balance demand, supply, storage, and conversion in mixed electricity/gas networks. In the literature, different approaches have been proposed for

obtaining robust control with MPC, e.g. min-max control, tube-based MPC, scenario-based MPC, or stochastic MPC [3]. The first one is usually too conservative, because although the constraints fulfillments are guaranteed even in the worst-case scenario, on average performances are low. The other approaches became popular in the last years due to their ability to achieve better performance and they will be further studied, extended, and applied to power networks in this project.

With a shift from a centralized approach to a distributed one in power networks, new controllers will have to consider the large-scale nature of these systems. Indeed, since the overall network is geographically widespread, in practice it is not feasible to consider a centralized control approach. The power network could be owned by different entities that may not be willing to give access to their data, sensors, and actuators to a centralized authority; sometimes the agents of the networks may even be in different countries, under different legislations. Even in the case in which all the parties agree on having a centralized authority controlling part of their network, this authority would encounter computational issues in solving the overall centralized control problem due to its very large size. Furthermore, the physical distances among the agents are so big that issues like delays, packet loss, jitter, etc., may arise. The best option in this case is to apply a distributed MPC strategy in which each controller solves its own MPC problem using the local model of its part of the system. The control methods will also be multi-level, which means that according to the level in which the model is used, different descriptions and time scales will be considered. Here, different models will be used at different levels, meaning that a more detailed model will be used at a lower level and a less detailed one will be used at higher level. This helps to improve the computational tractability of the overall problem, since at higher levels and bigger time scales a simpler model description will be used, allowing to control various parts of a power network more easily. Since the systems are coupled, communication among agents is required. According to how often information is exchanged, the resulting algorithm may be noniterative, if the information is transmitted only once per each sampling step, or iterative, otherwise. Furthermore, each regulator may minimize a local performance index or cooperate with other agents in order to minimize a global cost function. In [4], a distributed MPC strategy is applied to energy hubs of coupled electricity and gas networks that include also conversion and storage of different forms of energy and that use CHPs.

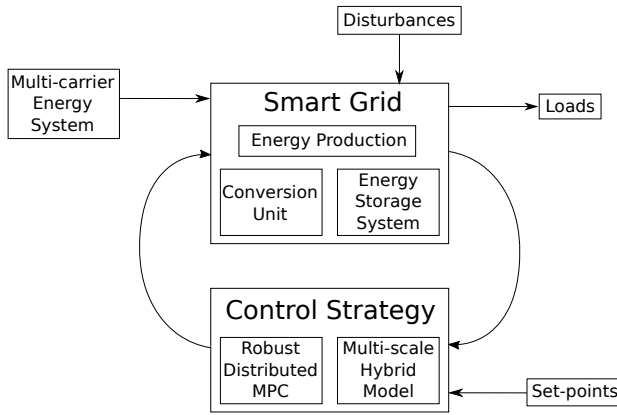


Fig. 1. Smart grid control scheme

The applied algorithm is iterative and cooperative, meaning that agents can communicate multiple times per sampling step and that the actions that are taken are optimal from a system-wide point of view in linear problems or with convex objective functions.

In general, in power systems the model description may include both continuous and discrete variables. Continuous variables include components that obey physical laws, like generators and loads, and are usually linked to differential and algebraic equations while discrete variables are linked to discrete events or discrete inputs, such as connecting/disconnecting a transmission line or loads, saturation effects, on/off switches. For these reasons, a hybrid system description is needed. In particular, we will focus on the development of a Piecewise Affine Model (PWA) or Mixed Logical Dynamical (MLD) model. The two models have been proved to be equivalent under some mild conditions, even though there are more theoretical results for PWA models. Nevertheless, hybrid MPC is a research field that still has many open challenges, especially for what concerns stability of the solution and for computational issues [5]. Indeed, when applying MPC on MLD models, the resulting optimization problem is mostly of the mixed integer linear or quadratic programming type, which is known to be very difficult to solve. When considering PWA models, the situation does not improve, because the proposed strategies either have a computational burden that grows exponentially with the prediction horizon or are once again mixed integer linear or quadratic programming problems. Therefore, some new hybrid MPC strategies will be developed during this project and applied to power networks.

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Control of (High Voltage) Hybrid AC-DC Grids

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I. INTRODUCTION

Over the last decade there has been a worldwide renewed call to drastically reduce CO₂ emissions identified to be partly responsible for climate changes. As a direct consequence of this, the European Union (EU) has taken a bold step to reduce the emission of greenhouse gases to between 80%–95% of 1990 levels by 2050. A huge step towards this goal was identified to be *zero* carbon emissions in the power sector by 2050. That is, it is required that the power system will be 100% dependent on renewable energy sources (RES). Currently, conventional power plants are being decommissioned and directly replaced by renewable power and zero emission plants and majority of new installed capacity is RES-based [1].

Wind, solar, biomass, and hydro sources have shown to be the most viable renewable sources for grid level integration. Notwithstanding the potentials, renewable energy sources (RES) are not without their inherent challenges¹, part of which this work hopes to provide insights and solutions.

Major problems of renewable sources include (but not limited to) intermittence of resource and geographic sparsity which results in a distributed nature of the resources. To take Europe as an example, large hydro resources are concentrated in the north, wind is fairly distributed, solar in the south, and biomass centrally located. As a result of this geographic sparsity, there will be a need to connect all these distributed resources in a super grid if the energy demands of Europe is to be met under the current policy of 100% dependence on RES by 2050.

The connections described will have to span energy markets, regions, and countries covering a vast area. Long distance high power transmission systems are required to connect resource locations to load centres which are typically far away from resource locations. The conventional high voltage AC (HVAC) transmission system for the aforementioned envisaged connections will be unbearably costly and technically inefficient. Currently, there is a general reluctance to invest in HVAC technology at first level transmission. The newer high voltage direct current (HVDC) technology provides immense benefits in terms of cost and is particularly suited for very long distance high power transmission connections.

In addition to the previously mentioned benefits of HVDC, other equally important benefits include, provision of access to energy markets, capability to connect diverse resources and asynchronous grids, capability to improve security with

increasing demand and system-wide stability, while offering very low losses.

As of now, the most common HVDC technology in operation all over the world is the *line commutated converter* (LCC) technology based on thyristor semiconductor technology. However, this technology has limitations and several drawbacks. Most important of these is difficulty in the implementation of multi-terminal configuration². Newer installations over the last half decade and future plans have been based on the *voltage source converter* (VSC) technology. It offers significant benefits over the former and is the current choice of technology for new connections requiring HVDC. Most importantly, VSC allows for multi-terminal connection in meshed configuration. The VSC technology will thus, allow for operation of the HVDC grid in a similar way as the conventional AC grid.

Notwithstanding the above benefits of HVDC, it will not be operated independent of the AC grid for the foreseeable future. Therefore, both grids (AC/DC) are expected to be in constant interaction with each other during operation. Coupled with the expected pervasiveness of HVDC connections based on current plans and future outlook, such interaction is expected to have both positive and negative impacts and thus the major focus of this project.

Another direct consequence of increasing power electronic (PE) interfaced renewable generation is lack of inertia of new generation and gradual loss of system inertia as conventional heavy power plants are being decommissioned. At current penetration levels of PE interfaced renewable generation, the conventional system dynamics is fast changing to the detriment of stability. In fact, with more synchronous plants being decommissioned to give room for RES, the HVDC and connected RES may have to take up the responsibility of ancillary services provisions, traditionally provided by synchronous generators.

II. BRIEF OVERVIEW OF STATE-OF-ART AND CURRENT GAPS IN LITERATURE

The HVAC has been well researched over the last four decades and focus is now towards network intelligence [2]. Over the last decade, a lot of research has been done specifically on the viability of high voltage multi-terminal DC grids (MTDC) for transmission purposes, with very promising results. Research has focused heavily on modelling and control

¹with regards to power systems

²99% of installations are point-to-point connections.

of MTDC grids (mostly exclusive of the AC grid). However, very little have been done in detail on combined of AC-DC grid based on current penetration levels, and future outlook as explained in Section I.

As aforementioned, the loss of system inertia is leading to new power systems dynamics requiring the transmission system operators (TSOs) to define new requirements, particularly ancillary to be able to maintain system stability at the current penetration levels. Similarly, there is currently no new knowledge on what the dynamics will look like in a future grid with pervasive PE interfaced renewables (much higher than today's levels)— may be DC dynamics will dominate the AC dynamics, and/or new phenomena will be observed, no new insights so far. This is one focus of this project.

An evident gap in literature is the issue of *harmonic interaction* at global system level between both grids. At the distribution level with divers power electronic loads and power quality issues, this is a well researched topic. With expected future HVDC connections, harmonic interaction will possibly be the biggest challenge at transmission level and there may be need to re-define system harmonic requirements to include the transmission system. This is a major focus of this work.

As observed from current literature, models for AC/DC system studies are non-exhaustive/oversimplified and in most cases, either the AC side is modelled in complete or considerable detail, whilst the DC side is simplified or vice versa. In cases where both sides are modelled in considerable detail (very few cases), either one or both grids are relatively small (3 terminals at best).

Another gap in literature is the lack of research effort into *static energy storage* at high voltage level³ (almost none in the context of AC/DC grid interaction). Storage will be highly instrumental to renewable dependent power systems, particularly for system ancillary support (frequency, voltage, oscillation damping), and added flexibility, (irrespective of the current state of storage technologies). In fact, several of the most challenging problems highlighted in literature can in some way be mitigated by having a static storage. Of course, both positive and negative interactions can be foreseen, this is also the focus of this project. Still under the purview of ancillary services, reactive power (in the context of AC/DC interaction) has been largely ignored in a lot of studies.

Another issue not given attention is, *inter-operability*. That is, the grid, PE converters and their controls will most likely be multi-vendor based. System and controller interactions (specifically negative) will require more understanding. Under the same issue of inter-operability, coordination has not been given enough attention as would be expected. Whatever the case may be, results of studies from above will show how coordination will be required.

There is also the possible influence of system topology on AC-DC grid interactions and possibly how it will affect coordination that has also not been given any attention (if any)

³At the microgrid level, this has been studied extensively, but both grids have inherent properties that do not allow “mechanical” transfer of technologies.

and will be a part of this project. Fig. 1 shows the possible future outlook of how a renewable dependent power system would look.

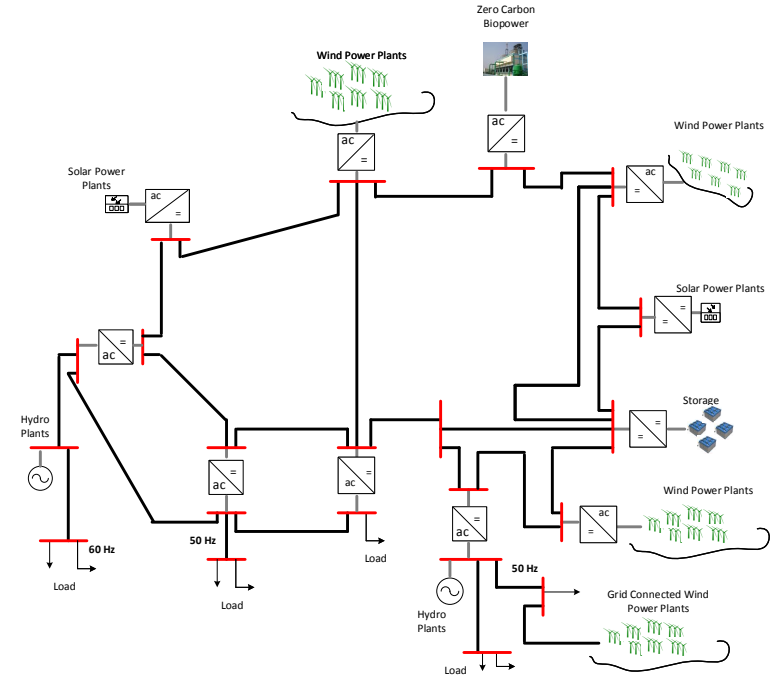


Fig. 1. Perspective of Future Power Systems

III. CONCLUSION

Considering the aforementioned gaps in literature and the results that would be obtained from further studies and research effort based on this project, there would need to propose innovative control algorithms and establish re-defined requirements the will guarantee supply security and system stability considering future perspective of the power grid. Also, there may be a need to propose new stability metrics for hybrid AC-DC grids.

The project is also expected to provide innovative solutions to ancillary services provision considering the fact this is currently the responsibility of synchronous conventional plants are expected to be decommissioned in the near future.

It is important to note that the review of literature to find gaps based on current and future outlook (of power systems) is still ongoing. As such, more studies and analysis to be studied but not included in this abstract are foreseen.

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IRP32: A new modelling approach for stabilisation of smart grids

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Abstract—This project is concerned with the stability and synchronization of power systems and the challenges arising from the transition to renewable energy. The current modeling approaches will be extended to reflect the different dynamics and challenges regarding stability. The new models will be analyzed using various methods from the studies of power systems and compared to various modern methods.

I. POWER SYSTEMS

Power systems are possibly the largest and most complex engineered system in history. The power system is responsible for the generation and distribution of electrical energy. It plays a crucial role in modern society. Almost all processes, in the industrial as well as the private sector, are impossible without electrical energy. The main role of the power system is to deliver the required electrical energy, ideally at minimal cost and resource consumption. The transition to renewable energy imposes additional challenges to the power system. More and smaller electrical generators increase the overall complexity. Energy sources like wind or solar power are less predictable and controllable as classical energy sources, such as coal power plants.

A. Stability in Power systems

A good engineered power system is able to deliver the required power even under stress or unexpected situations, such as failures of generators or transmission lines or heavy load changes. This is investigated in the framework of the stability analysis of power systems.

The power system stability problem is usually divided into three different classes. This classification makes it possible to study the various aspects of stability in detail. All classes are subject to different instabilities and lead to different methods of improving stability. The classes are [1]:

- **Rotor angle stability:** The ability of synchronous machines (generators and loads) of the power systems to remain synchronized. Depends on the balance between mechanical and electromagnetic torque in the system.
- **Voltage stability:** The ability of the power system to maintain steady voltages at all buses. Depends on the ability of the system to maintain an equilibrium between the generation and the load
- **Frequency stability:** The ability to maintain a steady frequency after a significant imbalance between load and generation

Rotor angle stability is divided into two subcategories. *Small-disturbance rotor angle stability* deals with the ability

of the power system to restore a synchronized state after *small* perturbations. As the perturbations are small, the linearized system is sufficient for analysis. *Transient stability* is concerned with larger disturbances, where linearization of the model equations will fail. The system will undergo large excursions in phase space. It is often encountered when transmission facilities fault or at a loss of generator or large loads.

To investigate the power system stability, mathematical models are developed and analyzed. These models formalize the physical processes in various components of the power system. A schematic representation of such a model is shown in figure 1. This model consists of three different parts of the power system: The generation system, the transmission system and the loads. The generation is described as a set of differential-algebraic equations, here called the individual machine reference frame. The main aspects of the generation unit are the swing equation, describing the mechanical process of turbines in the generators and the rotor circuit equations, which describe the electromagnetic processes due to the rotation. The transmission system is described with a set of algebraic equations, the so-called power flow equations. Many different versions of load modeling exist, like modeling the loads as generators with negative mechanical torque (motors) or mostly as static loads.

A full model is a set of non-linear differential equations. Analytical results for a full model are almost impossible, so numerical treatment is common. Under different assumptions and simplifications, analytical results were found.

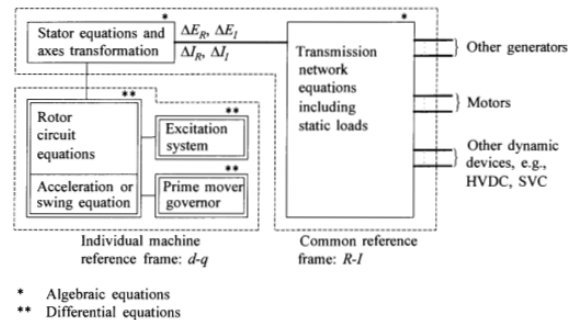


Fig. 1. Various aspects of the mathematical model for the power system. Taken from [2].

II. SYNCHRONIZATION

Synchronization is a phenomenon studied extensively in the physics community. Since the first observation of synchro-

nization in pendulum clocks by Huygens in the seventeenth century, it was investigated in many different fields and systems. The synchronized flashing of fireflies is an example of a biological system, while the synchronization of Cooper pairs in Josephson junctions is an example of solid state physics.

In general, synchronization occurs in oscillators. Coupling multiple oscillators can lead to unified motions, called synchronization. Synchronization depends on different aspects of the system, such as the local dynamics, the network topology or the coupling strength (or function). A special class of oscillators, the so called phase oscillators, are of great interest. The periodic phase oscillators are characterized by their phase and natural rotation frequency. The synchronization of these phase oscillators depends mainly on the natural frequency of the oscillators and the topology of the coupling network. The well known Kuramoto Model describes a certain kind of phase oscillators.

Phase oscillators also link the synchronization problem to the stability of power systems. Rotor angle stability can be understood as the synchronization of the generators. The swing equation, a simplified model for the dynamics of the generators, correlates to a second order phase oscillator.

The Kuramoto model was originally studied in the thermodynamic limit of infinite oscillators. A comprehensive review can be found in [3]. Recent results in [4], [5] extend the analytical results of synchronization to simplified power system models.

III. OUTLOOK

The aim of the project is to extend the current modeling approaches for stability in smart grids. Especially synchronization and the transient stability problem will be investigated using the new model. The focus will be on how the topology and local dynamics of the system may reinforce or inhibit synchronization. Special attention is given to the modeling of renewable energy sources and how they influence the stability problem.

IV. ACKNOWLEDGMENTS

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Distributed control strategies for wind farms for grid support

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I. INTRODUCTION

Wind is one of the older energy sources, in order to use this costless fuel the wind turbine (WT) size had grown to reach largest capacity up to 10 MW. The economy of scale has made it attractive to position the turbines close to each other, forming large wind farms (WFs). In 2015 in Europe, the installed capacity of wind power plant (WPP) was 142 GW, covering more than 11% of European energy consumptions, and it is predicted to achieve 320 GW in the next decade [1]. In Spain, wind energy covers more or less 20% of electrical demand (with 23 GW of installed capacity); even more Denmark can supply half of its energy consumption by using WFs. Due to the recent progress in power electronics field, over 90% of WTs are variable speed equipped with doubly fed induction generator (DFIG) or Permanent Magnet Synchronous Machine (PMSM) connected to the grid through partial or fully rated back-to-back converters. In general, variable speed WTs increase flexibility allowing independently regulation of active and reactive powers and reduction of mechanical loads.

As result of the increasing wind power penetration on power systems, it is required for the WPPs to participate actively in grid support. However, the fluctuating and uncertain nature of wind may introduce several challenges. In order to accomplish most of the required tasks from the Transmission System Operator (TSO), the literature offers different control strategies for the regulation of WF power production. As shown in Fig.1, the WPP is organised in a hierarchical structure with two different levels, a centralised control *wind farm controller* (WFC) and a localised control *wind turbine controller* (WTC).

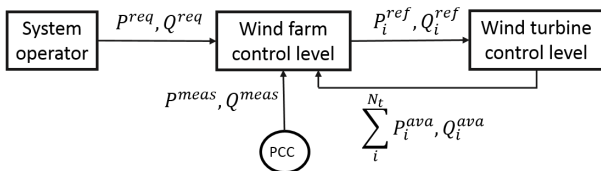


Fig. 1: Typical interaction between TSO and WPP control.

II. CONTROL ARCHITECTURE

In Fig.2 a classical WFC is shown; generally a WFC includes two control loops based on PI controllers [2]. They receive as inputs reactive and active powers requested

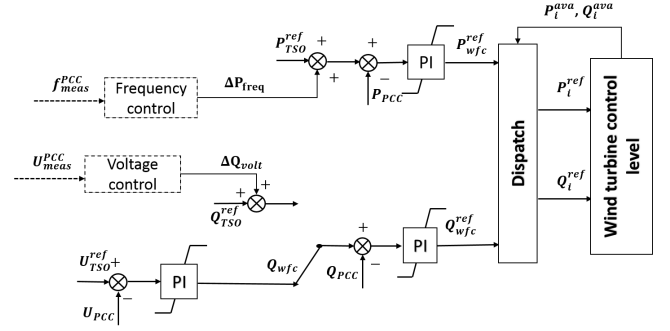


Fig. 2: Classical wind power plant control scheme.

by TSO and provide, using a dispatch function block, the reference powers P_i^{ref} , Q_i^{ref} for each turbines within the farm. The coordination between WFC and WTC ensure that $P_i^{ref} \leq P_i^{ava}$, where the latter is the available power obtained by the maximum power tracking point algorithm. The active and reactive power references are given as inputs for the WTC. This controller then translates these references in commands for the power converters (acting on the electrical generator) and pitch actuator (acting on the aerodynamic efficiency of the wind rotor).

III. CONTROL STRATEGIES

As suggested in [3], in order to reduce power overproduction, which forces to export the excess energy at low prices and use the WFs for ancillary services, the following control functions, Fig.(3) could be integrated in the WFC:

- Balance control, the active power can be adjusted downwards or upwards in steps at constant levels.
- Delta control, the WF is ordered to operate with certain constant reserve capacity in relation to its momentary possible power production capacity.
- Power ramp rate limiter, which sets how fast the WF power production can be adjusted upwards or downwards.
- Frequency control, must be able to produce more or less active power in order to compensate frequency oscillations.
- Reactive power control, the WF produce or absorb a constant value of reactive power.
- Voltage control, the WF produces or consumes an amount of reactive power in order to control the voltage.

In cases where a farm is asked to produce less than the maximum power, for example using a delta control, some turbines will need to limit their power production. This implies that they have a degree of freedom (DOF) to vary

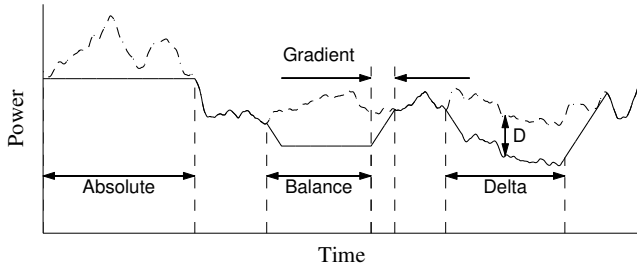


Fig. 3: Control functions for active power in modern WF

their production according to the wind speed fluctuations, thus power can be redistributed between turbines according to local wind conditions. The DOF can be utilized in different ways,

- reduce energy losses in transmission lines [4],
- reduce the number of farm-wide turbine startups and shutdowns,
- reduce fatigue loads.

In order to fulfil these objectives several proposal can be found in the literature. In [5], the WF are split into smaller groups and each group is considered separately without any loss in performance. Therefore, the control scheme is *distributed* thus each WT is only allowed to communicate with nearest turbines reducing the complexity of the *centralized* control. Other approaches to optimize the power reserve use the model predicted control (MPC) schemes. In [6] a distributed MPC, on a given prediction horizon, is proposed to evaluate the power demand set points to achieve mechanical stress reduction. Instead, in [7] different model predicted control (MPC) regulators are proposed to achieve optimal power distribution. Another relevant objective is the provision of ancillary services, such as frequency control. For instance, in [8], some operation strategies are proposed in order to maximise power reserves acting on the kinetic energy stored in the wind rotor or working in de-loading conditions.

The reactive and voltage controls have an important role in case of grid faults or weak power network. In [9] is investigated the response of WTs during a grid fault, when typically the utility disconnects the WTs to prevent a risk of voltage oscillations. The authors propose a solution by using dynamic reactive compensation for WTs equipped with DFIG, this obtained with the static synchronous compensator (STATCOM). During the grid faults, the STATCOM improves the transient voltage stability and helps the WTs to remain in service during grid faults.

IV. PROJECT OBJECTIVES

The control systems proposed in literature can follow three different strategies:

- Maximize total WF active power,
- Track given total WF active and reactive power references,
- Minimize fatigue loading for the WTs in the farm.

The first strategy aims to maximize the total energy captured by the WF. For this purpose, the control algorithms seek to operate each WT according to their particular wind condition in order to maximize the total power produced by the WF. This research project will be more focused on the second and third (in less extend) objectives. The objective is to propose distributed control strategies in order to simplify the WPP architecture in terms of communications and needed computation power and to increase reliability of the whole control system.

Using a centralized controller all the sensors and actuators are connected to one central controller; this implies a massive amount of communication links from a large number of turbines to the central controller. The fail in one link might result in the disconnection of some WTs and then in voltage oscillations in the grid. A possible solution could be to split the WF into clusters with dedicated controllers that coordinate to produce the desired global behaviour. Thus, in case of a cluster outage, the WF could continue to operate and reduce the negative effects on the grid.

The control algorithm will be developed in Matlab and tested in SimPowerSystems and PowerFactory. The use of SimWindFarm to model the wake interactions among WT is also foreseen. The HornsRev-1 wind farm, located in Denmark, is used as benchmark layout; This is a commonly used test WF consisted of 8 by 10 matrix of NREL 5MW WTs, with distance between the turbines of 7D (D rotor diameter). Different static models will be investigated starting from the approaches proposed in [6], [7] and [8] but with more interest on the reduction of the power losses then the fatigue loads.

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Fault detection and isolation for renewable sources

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Abstract— This document will try to summarize the basic concepts of fault detection and isolation methods on smart grids. The document starts with a description of the goal of this project and continues with a brief explanation of the importance of fault detection and isolation methods to the society. The self-healing smart grid is then defined and a short description of the fault detection approaches follows. This document then addresses the types of faults that can be encountered in smart grids and the impact they may have according to their location. The document concludes by indicating the selected course for further study.

Index Terms— Distributed generation, fault detection, fault isolation, smart grids, power systems

I. INTRODUCTION

This project addresses the issue of fault detection and isolation methods on renewable energy sources, mainly on photovoltaics and wind farms, connected to the grid. The main objective is to develop fault detection and isolation algorithms for the various modes of connection of power plants in order to ensure high level availability of renewable power plants and reduce the impact of outages.

Electricity interruptions have huge economic and social impact. For example, production loss, restart costs, equipment damage and raw materials spoilage can be very costly. At the same time, uncomfortable temperatures at work or home, loss of leisure time and risk to health and safety (e.g. interrupting hospital service or industrial operations) are some of the aspects of electricity interruption's social impact [1].

For the aforementioned reasons, a fault should be detected, located and isolated as quickly as possible. A restoration plan should then be implemented aiming to minimize the number of interrupted customers with a minimum number of switching operations [2]. Fault detection, isolation and restoration are key elements of a self-healing smart grid.

II. FAULT DETECTION APPROACHES

Self-healing is defined as the ability of a distribution system to reconfigure itself, after being subjected to a fault, through a series of automatic and intelligent actions, in order to return to the best possible state [3]. The system should then be able to operate with safety and without violating any

constraints. Self-healing perceives fault detection, isolation and service restoration as one unified procedure [2].

Fault location detection and isolation approaches according to [2],[4] and [5], include the following steps:

- Detecting the fault through threshold crossing detection.
- Localizing the fault thanks to the apparent impedance-based method (most commonly used method), three phase circuit analysis, integrating artificial intelligence and the travelling wave based method.
- Isolating the fault by sending a crew to localize the fault and fix the problem.

III. FAULT TYPES

Faults can be divided in two major categories depending on their location: a) faults in the distributed generators and b) faults in the grid.

A. Faults in distributed generators

A categorization of faults on the DC part of the photovoltaics is proposed in [6], where faults are classified by the type of the component where they appear as follows:

- Faults in the photovoltaic generator (shading, dirt accumulation, etc.).
- Faults in the junction box.
- Cable and connection faults.
- Protection system faults.
- Faults inside the inverter.
- Faults in the data acquisition system.

Among the numerous possible faults in a PV array, ground fault, line-to-line fault, and arc fault are the most probable to damage a PV array and even cause electrical fires [7]. Ground faults and line-to-line faults may remain undetected for a long time and thus cause severe damage to the PV array as well as to the surrounding environment [7]. Moreover, in wind farms, faults appear mostly in the electrical machine and the converter. Potential causes of these faults are described in [8]:

- Short circuits in the stator or the rotor of the machine.
- Mechanical faults (roller bearing and gearbox).
- Overheating resulting in the ageing of components.
- Insulation breakdown which leads to short-circuits.

Faults of this category may have a serious impact on the grid, depending on the grid size and short-circuit power. For example, a fault inside a photovoltaic panel in a micro grid will have greater impact on the grid than if it was part of a hyper grid.

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B. Faults in the grid

Faults may also appear in distribution networks and they can affect the distributed generators. Weather conditions (hurricane, lightning, etc.), component wearing and accidents are the most occurring causes of such faults. A smart self-healing grid should be capable of fault ride through [2]; although faults in the distribution network may affect the distributed generators, certain distributed generators will remain connected to the grid during a fault in order to support its voltage level. For example, a method is proposed in [9] where a wind turbine with a double fed induction generator can continue to operate under severe grid faults and at the same time manage to maintain a constant output voltage, irrespective of the fluctuating wind.

IV. CONCLUSION

In this project the first category of faults (i.e. faults in distributed generators) is selected for further investigation. Finally, the aim is to study and analyze the impact of these faults to the grid.

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Review of Methods plus New Approaches for Distribution System State Estimation

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I. INTRODUCTION

The problem of State Estimation (SE) consists on estimating the state of a power system represented by the voltages at the system's buses. Typically the length and type of the lines are known, so that it is possible to determine the admittance matrix of the system and thus the non-linear function relating measurements to state variables. Then, taking several currents, voltages and loads (active and reactive) measurements, it is possible to compute the best approximation of the state variables. This problem has been widely analyzed for transmission networks, where many measurements are available, in most cases solving a Weighted Least Squares problem using an iterative solution like Newton-Raphson, see [1], [2], [3], [4]. Due to the lack of measurements till now, this problem has not yet been studied enough in distribution networks. With real-time measurements from Phasor Measurement Units and Smart Meters becoming available, it's possible to develop methods to include this information ([5], [6]). This work is a summary and comparison of current methods. We extend some of them to generally big, 3-phase distribution systems and enable them to respect given constraint. Moreover, a new method is developed that takes advantage not only of the real-time measurements, but also their evolution, while respecting the constraints of the system.

II. DISTRIBUTION SYSTEM MODEL

The power flow equations are defined using the admittance matrix Y , that depends on the connections, the length and characteristics of the lines. State voltages are $V_{buses} = [V_{source}^T, V^T]^T$, where $V_{source} \in \mathbb{C}^3$ are the known voltages at the source bus, and $V \in \mathbb{C}^N$ the voltages in the grid that need to be estimated. This way the Power Flow equations to determine currents I and loads S at all buses can be expressed as:

$$\begin{bmatrix} I_{source} \\ I \end{bmatrix} = \begin{bmatrix} Y_{0,0} & Y_{0,1} \\ Y_{1,0} & Y_{1,1} \end{bmatrix} \begin{bmatrix} V_{source} \\ V \end{bmatrix}$$

$$S = V \cdot I^* \quad \text{where } \cdot \text{ denotes element-wise product and } (*) \text{ the conjugate-transpose.} \quad (1)$$

So that V can be expressed as:

$$V = Y_{1,1}^{-1} \frac{S^*}{V^*} - Y_{1,1}^{-1} Y_{1,0} V_{source}$$

where $\frac{1}{\cdot}$ is the element-wise division (2)

And the voltages under no load ($I_{grid} = 0$) are:

$$V_0 = -Y_{1,1}^{-1} Y_{1,0} V_{source} \quad (3)$$

In a power network, SE consists on estimating the state of the network, represented for example by the voltages V .

III. SOURCES OF INFORMATION

Several different sources of information are available to solve the SE problem:

- 1) Load pseudo-measurements S_{pseudo} for every hour, based on predictions and known installed load capacity at every bus. Therefore, they have a noise with large standard deviation ($\sigma_{pseudo} \approx 50\%$);
- 2) Real-time voltages and currents measurements, respectively V_{meas} and I_{meas} , from PMU and SM. They have a noise with low standard deviation ($\sigma_{meas} \approx 1\%$). With C_{meas} mapping state voltages to measurements:

$$\begin{bmatrix} V_{meas} \\ I_{meas} \end{bmatrix} = C_{meas} V + noise \quad (4)$$

- 3) Buses without loads, acting only as a connection. If $\varepsilon = \{i, \dots, j\}$ is the group of their indexes, then the constraints can be written as:

$$\begin{aligned} V &\in \{V \mid (Y_{1,1})_{\varepsilon} V + (Y_{1,0})_{\varepsilon} V_{source} = 0\} \\ &= \{V \mid V = Fx + V_0, x \in \mathbb{C}^{N-|\varepsilon|}, F = \ker((Y_{1,1})_{\varepsilon})\} \end{aligned} \quad (5)$$

IV. METHODS FOR STATE ESTIMATION

A. Static Power Flow Solution with Pseudo-Measurements

The basic method uses the pseudo-measurements S_{pseudo} , the power flow problem is solved iterating over (2) to obtain an estimate of the state of the system. This algorithm is called POWERFLOW and the solution is V_{pseudo} .

B. Static Solution of Weighted Least Squares

This is a well-known methodology largely used for SE problems. It uses S_{pseudo} , and V_{meas} and I_{meas} . The solution V_{WLS} is computed by minimizing the Weighted Least Squares (WLS) cost function $J(V)$. With $h(\cdot)$ being the nonlinear function mapping voltages states at all buses V to measurements and weights W^{-1} the inverse of the variance of the measurement noises, the cost function is the following:

$$J(V) = (z - h(V))^T W^{-1} (z - h(V)) \quad (6)$$

However, we solve the system in a subspace to take the constraints into account:

$$V_{WLS} = \operatorname{argmin}_x J(Fx + V_0) \quad (7)$$

Equation (7) is then solved using a Newton-Raphson iterative method.

C. Static Power Flow Solution plus optimal constrained linear update

This method uses the Power Flow solution as a prior $V_{pseudo} = V_{prior}$, which is updated using the real-time measures V_{meas} and I_{meas} to get a posterior estimate V_{post} :

$$V_{post} = V_{prior} + K \left(\begin{bmatrix} V_{meas} \\ I_{meas} \end{bmatrix} - C_{meas} V_{prior} \right) \quad (8)$$

As in [5], the optimal gain K is computed minimizing the expected error $E[(V_{post}-V)^*(V_{post}-V) | V_{prior}, V_{meas}, I_{meas}]$. To obtain a feasible solution, we have imposed K to have the form $K = F\tilde{K}$, then the optimization problem becomes:

$$\begin{aligned} \tilde{K} &= \operatorname{argmin}_{\tilde{K}} \operatorname{tr}(\Sigma_{post}) \\ &= F^* \Sigma_{prior} C_{meas}^* (C_{meas} \Sigma_{prior} C_{meas}^* + \Sigma_{meas})^{-1} \\ \Sigma_{post} &= \Sigma_{prior} + F\tilde{K}(\Sigma_{meas})\tilde{K}^* F^* \\ &\quad + F\tilde{K}(C_{meas} \Sigma_{pseudo} C_{meas}^*)\tilde{K}^* F^* \\ &\quad - F\tilde{K} C_{meas} \Sigma_{prior} - \Sigma_{prior} C_{meas}^* \tilde{K}^* F^* \\ \Sigma_{meas} &= \sigma_{meas}^2 \operatorname{diag}(C_{meas} V) \operatorname{diag}(C_{meas} V)^* \\ \Sigma_{prior} &\approx \sigma_{pseudo}^2 Y_{1,1}^{-1} \operatorname{diag}\left(\frac{S_{pseudo}}{V_0}\right) (Y_{1,1}^{-1} \operatorname{diag}\left(\frac{S_{pseudo}}{V_0}\right))^* \end{aligned} \quad (9)$$

The approximation in Σ_{prior} corresponds to one iteration of the power flow equation 2 with S_{pseudo} and V_0 as initial value, but it is close enough to the exact solution.

D. Forecasting Aided Solution with Kalman Filter

Similar to the previous method, but now dynamics are introduced to the load. At the transition $k \rightarrow k+1$ the load estimations from previous step $S_{k|k}$ are used to predict future load and voltages:

$$\begin{aligned} S_{k+1|k} &= S_{k|k} + t_k, \text{ where } t_k \text{ is a time depending tendency} \\ V_{k+1|k} &= \text{POWERFLOW}(S_{k+1|k}, V_{source}, Y, \delta, N_{it}) \end{aligned} \quad (10)$$

Which are then updated using the measurements at time step $k+1$:

$$\begin{aligned} V_{k+1|k+1} &= V_{k+1|k} + K_{k+1} \left(\begin{bmatrix} V_{meas} \\ I_{meas} \end{bmatrix} - C_{meas} V_{k+1|k} \right) \\ S_{k+1|k+1} &= V_{k+1|k+1} \cdot (Y V_{k+1|k+1})^* \end{aligned} \quad (11)$$

Where K_{k+1} is computed as in the previous section. The solution is defined as $V_{dynamic}$.

V. SIMULATION

These methods will be tested in a simulation using a distribution system like the 123-bus test feeder available online in [7]. This test feeder is chosen, since it is unbalanced enough and bigger than the examples in most of the literature, so that it is a challenge for the methods. Some measurement will be placed, see Fig. 1 for an example with voltage measures (red) placed at buses 97, 18, 13, 60, current measurements (green) at 48, 76, 65, and branch current (blue) measurements at $97 \rightarrow 197$, $18 \rightarrow 135$, $13 \rightarrow 152$, $60 \rightarrow 160$. Historical data from a German local utility will be scaled and adapted to the system to create daily 15 minutes load profiles for each load.

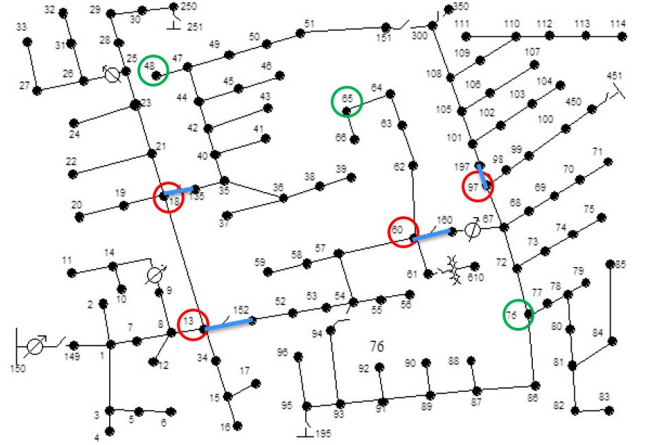


Fig. 1. 123-bus test feeder

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Advanced functionalities for the future Smart Secondary Substation*

Konstantinos Kotsalos, Nuno Silva

Abstract— This paper aims to provide an overview of planned developments of ESR 4.4 framework -part of INCITE project-, as well as to describe the technical challenges of future distribution networks to be addressed within the scope of this work. The project entails the implementation of consistent solutions that contribute for an effective Smart Grid implementation, focusing on the further integration of Distributed Energy Resources (DER) by facilitating advanced functionalities at the Secondary Substation. An overview of the basic Low Voltage (LV) technical architecture and a brief introduction of the aspired control strategies is given.

I. INTRODUCTION

Countries over the world are promoting remarkable integration of energy share from renewable sources. The main drivers are global awareness of environmental pollution, the depletion of natural sources as well as the significant global energy demand growth.

The ever-increasing presence of Distributed Energy Resources (DER) takes place predominantly in Distribution Networks (DN) possibly leading to technical challenges. The integration of distributed generation (DG) is progressively facing limits intrinsic to current power systems, which have a top down structure based on centrally generated power. The continuous growth of DERs integration pose challenges to current DN operation since they distort basic assumptions in distribution network planning [1]. The electric power system is evolving from a large, central generating stations interconnected with customers through grids of transmission and distribution lines into a system that includes substantial DER. The connection of DERs along the DN creates bidirectional power flow, with the possibility of occurring constraints such as branch congestion and voltage unbalances among downstream feeders.

In order to allow the further integration of DG units, multiple grid reinforcements may need to be planned. Nevertheless, this could be surpassed if a smoothly integration of these decentralized sources into the electricity system is promoted. This is only feasible by evolving networks with more intelligence, paving the way of the so-called smart grids. More than a significant technical challenge, it is an evolutionary opportunity to progress towards the Smart grid concept integrating smart metering,

advanced Information and Communication Infrastructures (ICT), Intelligent Electronic Devices (IED) and smart inverters in addition to distribution automation to ensure a proper interface between DGs and the electric utilities.

Concurrently, the distribution automation and secondary Substation Automation (SAU) have already revolutionized the way utilities manage their networks. Since substation compose the linchpin of power systems comprising important functions of the utility, it is plausible to stress that a major breakthrough in substation technology and active management of LV networks is seen as one of the foremost aspects of the smart grid revolution.

Among the LV grid, the proportion of monitoring and SAU is typically considerably lower than in MV. More specifically, the measurements rely on aggregated information from substations and are only available with a significant time lag. Nevertheless, in the last few years, there is a continuous reinforcement of LV monitoring by installing smart meters, Phase Measurement Units (PMUs) and advanced Remote Terminal Units (RTU), enhancing its observability level.

These significant technological advances contribute essentially in enabling of DERs participation on network operation. That new feature triggers the transition to the Active Distribution Networks (ADN), where the efficient management of DER's flexibility tackle largely the technical issues aforementioned. Accordingly, the main targets of the ADN is to substantially reinforce network's reliability, ensuring security of supply and power quality, by managing DER's flexibility -i.e. Active Network Management (ANM).

The ADN will introduce radical changes on the structure of the electricity market, as the continuous growth of DERs in addition to the potential for providing ancillary services to the network, induces intermediate supervision and operation stakeholders (i.e. Aggregators) [2]. The Aggregators are typically defined as service providers who cater mainly for contracting DERs and provide services to retailers, DSO or the market itself. The DERs integrated with smart inverters are capable to actively participate modifying their operational via an economic return (i.e. incentives).

This research project focuses particularly on designing novel control strategies and architectures capable to further release and decentralize functionalities amongst other smart grid features. Besides, these novel functionalities aim to enable a massive deployment and control in combination with ANM features. All these will follow along the research progress towards Smart Grid concept, thus to develop innovative controls facilitated on the Smart Secondary Substation based on the key drivers denoting scalability,

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modularity and interoperability [3]. Following are presented some guidelines as well as specific challenges and notions planned to be researched within this research project. The main research motivation is to contribute in the development of novel control strategies which possess either prevalingly decentralized or distributed features.

II. CONCEPTUAL DEPICTION OF RESEARCH PROJECT

The objective of this Individual Research Project is to develop advanced functionalities for the Smart Secondary Substation, based on managing commercial and technical functionalities as well as advanced market services.

The distribution automation approach adopted at the Secondary Substation level will pave toward a further step to decentralize the DN management by defining a novel substation architecture capable to monitor and manage the downstream LV feeders.

The main pillar of the proposed technical architecture referring to the LV network will be a controller installed at the secondary substation called Distribution Transformer Controller (DTC) [4-5]. The DTC (Fig. 1) constitutes a multi-functional controller which is capable to provide advanced RTU functionalities, while it is compliant to communication protocols (e.g. MODBUS, GPRS, ADSL, RF). In the frame of consumers smart metering devices will tender accurate tracing and recording of load and generation profiles. This controller will be responsible for the aggregation of measurements from the smart meters in order to monitor the current state of the downstream grid. The DTC provides adequate computational resources to cope with the efficient management of LV consumption and microgeneration as well as to provide surveillance services. In fact, as previously stressed, the multiple DG connected along the feeder inject active power in an intermittent way. Although, since DGs are connected to the network via smart inverters, appropriate set-points can be dispatched from DTC in order to tune their output according to network's operational point.

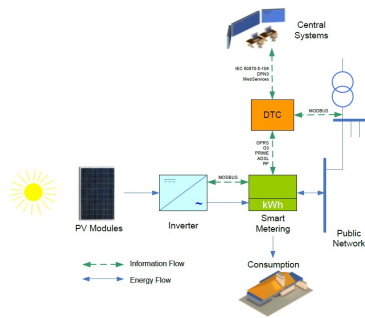


Fig. 1 Basic technical architecture for LV network [4]

The control algorithms that are planned to be developed will make particular use of the flexibility provided by DERs, in order to construct a multi-criteria optimization problem as to address the decision making of an efficient power flow delivery, even considering uncertainty on future behavior of loads and generation connected at LV level. Therefore, the control algorithm relies on managing methodologically the

available DG units, responsive loads, storage systems and Electrical Vehicles subject to optimize network's operation. The main features of the control schemes developed will follow demand side management, congestion management, losses minimization (technical and non-technical) and load balancing strategies.

Among the anticipated objectives of the control schemes will be the essential power delivery, the improvement of LV grid reliability and the optimization of the operation. The smart substation controller will interact with the downstream grid connected IEDs facilitating functionalities such as demand side management and local balancing to ensure that nodal voltages are within the permissible limits. This approach will assure an adequate control through embedded functionalities on the secondary transformer controller which will be able to respond to technical issues occurring at the LV grid level by interacting with several field controllable devices (DERs, smart meters, On-Load Tap Changing).

The DTC will be additionally assigned with the interrelation between LV and upstream network, acting as a gateway interface referring to the data driven to the Control Centre. The DTC may be seen as a cluster point of a flexible node for the upstream network (e.g. MV network), it needs to be available to inform concerning its flexibility and execute the respective orders (e.g. namely for dispatch set-points) [5].

III. CONCLUSION

Amid the emerging technical challenges on current LV distribution this research project targets on the development of consistent control strategies which are in line with the smart grid paradigm. More analytically, particular effort on the further transcendence of conventional functionalities will be given, in order to propel advanced features which are along with the massive deployment of ANM. The control will be leveraged with the various aspects of smart grid such as distribution automation, its technologies and levels of automation and the responsibilities of each level.

The primary challenge and focal point on this research project is the concerted approach to develop, implement and test pervasive control and intelligent strategies that contribute in the prosperous transition to the SG concept.

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The GREDOR project. Redesigning the decision chain for managing distribution networks.

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In Wallonia, the political willingness to increase the capacity of renewable generation, the evolution of the consumption pattern (for example electrical vehicles), and the changes in the electricity markets sector will raise several challenges in distribution systems in a near future. Without re-thinking the system, issues such as congestion, under and over voltage, and renewable power curtailment are likely to appear more often than today. In addition to investing in costly physical devices, one of the key aspects is to accommodate the variability of the renewable energy sources by some demand flexibility or by some storage, which are both currently almost inexistent. The GREDOR project will address these challenges. It is funded by the Public Service of Wallonia, Department of Energy and Sustainable Building, coordinated by the University of Lige (ULg) and encompasses academic partners and partners from the power systems industry. It is decomposed in 5 main work packages. GREDOR started on January 1, 2013.