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CloudGrid
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Final Project Report of Cloudgrid

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ERA-Net Smart Grids Plus | From local trials towards a European Knowledge Community

This project has received funding in the framework of the joint programming initiative ERA-Net Smart Grids support from the European Union's Horizon 2020 research and innovation programme.

Smart Grids Plus
ERA-Net

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Technical report 2019:1
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INTERNAL REFERENCE

- **Deliverable No.:** D 1.4
- **Deliverable Name:** Final Project Report
- **Lead Partner:** ABB
- **Work Package No.:** WP1
- **Task No. & Name:** Task 1.4
- **Document (File):** D1.4 Final project report - 20190331 - Final.docx
- **Issue (Save) Date:** 2019-03-31

DOCUMENT SENSITIVITY

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DOCUMENT STATUS

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DOCUMENT REVISION

Revision	Date	Comment
Rev 01	2017-05-13	First draft
Rev 02	2018-02-27	Second draft
Rev 03	2019-03-29	Third draft
Final	2019-03-31	Final

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About ERA-Net Smart Grids Plus

ERA-Net Smart Grids Plus is an initiative of 21 European countries and regions. The vision for Smart Grids in Europe is to create an electric power system that integrates renewable energies and enables flexible consumer and production technologies. This can help to shape an electricity grid with a high security of supply, coupled with low greenhouse gas emissions, at an affordable price. Our aim is to support the development of the technologies, market designs and customer adoptions that are necessary to reach this goal. The initiative is providing a hub for the collaboration of European member-states. It supports the coordination of funding partners, enabling joint funding of RDD projects. Beyond that ERA-Net SG+ builds up a knowledge community, involving key demo projects and experts from all over Europe, to organise the learning between projects and programs from the local level up to the European level.

www.eranet-smartgridsplus.eu

1 Introduction

The CloudGrid project is done in cooperation between NTNU, IPE, ZHAW, Chalmers and STRI/ABB. The work is split in six work packages where ABB/STRI, ZHAW, Chalmers and NTNU were package leaders. Besides the authors of this report, the following persons contributed to the project: I. Zikmanis (IPE), M. Calder (ABB), M. Javdani (ABB), A. Babak (Chalmers), A. Bahmani (Chalmers), P. Chen (Chalmers), C. Agathokleopus (Chalmers), O. Lennerhag (STRI/ABB), G. Pinares (STRI/ABB), A. Perez (STRI/ABB) and S. Sanchez (NTNU).

The cooperation between the parties is established on many levels. Laboratory facilities and field measurements were shared to a certain extent and data sharing through a cloud was accomplished. This has a high significance for future smart grids where data exchange is essential for stable operation as well as short term and long-term planning.

The scope of work covers of the work packages covers a broad range of topics, including stability of current and future power grids, ancillary services, energy management as well as multiterminal HVDC links and high power converter design and control.

2 Executive summaries of project reports

This section includes executive summaries of all technical reports prepared within the CloudGrid project. A list of the reports in presented below:

Report no and name	Work package	Lead institute	Report date	Reviewed & Summarised by
D 4.1 **Report 1: Challenges and situation of today's power system**	WP4	ZHAW	2017-05	J. Ehnberg Chalmers
D4.2 **Recommendations and future actions to maintain the stability of the future power**	WP4	ZHAW	2019-02	J. Ehnberg Chalmers
D5.2 **Report on potential of inertia support in Europe**	WP5	Chalmers	2019-02	R. Segundo ZHAW
M 5.2 **Basic Energy Management Strategies and system element description**	WP5	IPE	2017-05	J. Ehnberg Chalmers
M 5.3 **Report on Ancillary services identification and circumstances identified**	WP5	ABB	2017-06	E. Tedeschi NTNU
D 5.4 **Demand control program development and experimental validation**	WP5	IPE	2019-01	J. Ehnberg Chalmers
M 5.4 **General Ancillary Service Market Model developed**	WP5	Chalmers	2018-01	E. Hillberg STRI
D 5.5 **Report on the Energy management strategies development**	WP5	IPE	2019-02	J. Ehnberg Chalmers
D 6.1 **Report identifying common reference test cases**	WP6	NTNU	2017-03	R. Segundo ZHAW
D 6.2 **Study of the different structures, simulation models for the main relevant converter topologies, control strategies, static and dynamic behaviour/limits**	**WP6**	**NTNU**	**2017-06**	**R. Segundo ZHAW**
D6.3 Set of system level simulation models and accompanying documentation for converter interaction analyses in ACDC grids	WP6	NTNU	2019-02	A. Mutule IPE
D6.4 Report on design aspect of a MW size dc/dc-module as a function of efficiency. Efficiency versus switching frequency.	WP6	NTNU	2019-02	A. Mutule IPE

D6.5 Stability assessment of complex offshore HVDC systems and modelling of critical components in view of laboratory validation	WP6	NTNU		J. Ehnberg Chalmers
D6.7 Guidelines for the analysis and small-scale experimental validation of complex HVDC systems	WP6	NTNU		A. Mutule IPE

2.1. D4.1 Challenges and situation of today's power system

The deliverable consists of two major parts; an evaluation of the ENTSO-E initial dynamic model of continental Europe and a study on the frequency stability due to decrease of conventional electricity production in the continental European power system.

The ENTSO-E initial dynamic model of continental Europe was evaluated based on the variation of six standard grid operation parameters, saturation of synchronous machines, variation of governor droop, deactivation of power systems stabilizers and variation of the proportional gain of the automatic voltage regulators, variation of inertia and loads. The model behaved as expected due to the variations of the parameters which shows that model is robust and therefore well suited for transient studies.

The dynamic model then was used study the impact on the system when 10 GW conventional power production are replaced with renewables. As a case study was Germany chosen due to the ongoing phasing out of nuclear power. The difference in behaviour of the grid due to an ENSTO-E reference incident was examined. Active power flow response, cross border flow, frequency behaviour, small signal and rotor angle response were investigated. The results shows that cross border flow is only slightly affected but both neighbouring and more distant countries is clearly impacted of the replacement. It can be concluded that in a very large power system, as the Continental European network, the impact of substituting 10 GW of generation in Germany from traditional (synchronous based) to renewable does not significantly influence the frequency levels, frequency nadir, frequency derivative, or the system damping but it does influence.

2.2. D4.2 Recommendations and future actions to maintain the stability of the future power

There is more work needed to be done to secure the stability of future power grids. Several challenges are pointed out with recommendation on how to meet them. The challenges are addressing the need for cooperation and new models due to the expected paradigm shift in the power system with significantly higher levels of converter connected electricity production. The recommendation is that the industry together with academia develops new and, in some case, simplified models and, in some cases, more detailed models, all based on the new available data from e.g. PMUs. Other challenges are more action related where recommendations are suggested directly to increase stability of the transmission grid. Practical challenges related to security is also brought up for attention as well as the contribution of HVDC for stabilization purposes. The later shows a really good potential.

2.3. D5.2 Report on potential of inertia support in Europe

The authors provide answers to three important questions related to lack of inertia in the future power systems and present their results of an important analysis on this regard with strong emphasis in the role of wind energy to contribute with additional inertia. The authors use a simplified model representing the different synchronous power systems to perform several simulations that represent different future scenarios. The main results are divided in three different sections. In the first section, the authors analyse the projection of the different power systems in the future to compare with the current conditions. Then, the inertia from wind power generation units is analysed as main solution to the problem. Finally, alternative inertia sources such as flywheels and storage devices are also discussed. The results of this work is extended into a conference publication which has also been included along with the deliverable report.

2.4. M5.2 Basic Energy Management Strategies and system element description

During the reporting period, the deployment of the demand side management (DSM) was analysed. The analysis includes a definition of a common terminology and its usage, demand response management methods oriented towards DR implementation and appropriate system elements description.

The report consists of five sections. Introduction, where authors define terminology and used concepts. The second section is devoted to demand side management methods application analysis. An architecture is proposed for this analysis. Therefore, in scope of CloudGrid project and European energy system and market conditions we advise our vision for DSM architecture, where the difference is set in DR actions change. Considering the goals and capabilities of potential DSM participants, several DSM approaches have been highlighted: load and consumption analysis based approach. This approach is a passive DSM part, and can be useful in the early stages of the project; the feedback system, which consists in informing the consumer about the system constraints; the price-based approach, which requires behaviour change on the customer side triggered by price signals; the system capacity-based approach, which does not rely on the price sensitivity of customers but on other system forecasts. In this approach, the customers indicate their preferences to a third-party player (aggregator or system operator) and consent to let this player take the control of smart appliances. During the execution of tasks under the CloudGrid project, IPE focused on pricing and incentive approaches as a hybrid solution and final goal.

The third section is dedicated to energy efficiency measures were considered, but the focus was on office buildings and their possible benefits. In the fourth section, the DR classification is considered into two groups: the first one can trigger on energy market prices, while the second one is based on the reaction controlling system behaviour. The fifth part deals with energy management strategies and their components. Several key components of EMS were reviewed in more detail – functionality, reaction time, mathematical models and EM system with add-ons. A preliminary structure of the EMS was provided in the report. The presented concept refers to the previously proposed mechanism for setting strategies for the project. The sixth section provides a brief description of the system elements (agent based smart sockets), which was used for the project implementation.

2.5. M5.3 Report on Ancillary services identification and circumstances identified

This report reviews the main existing and likely future ancillary services, adopting the perspective of the system operator. Ancillary services related to frequency support, voltage support, system restoration and other services (e.g. power quality enhancement techniques) are categorized, their main characteristics are described and related market-aspects are analysed, with particular attention to the Nordic countries.

Different technologies and strategies, including conventional and converter-interfaced renewable generation, HVDC & FACTS, energy storage and demand side flexibility are systematically assessed in order to evaluate their capability to provide different ancillary services. The potential presence of techno-economical barriers preventing their applications for the various services is highlighted, and the results are compiled in table format.

2.6. D5.4 Demand control program development and experimental validation

The goal of the document is the implementation of a demand control program and its performance validation. As a first step, the report describes the structure and control of the smart sockets built by the IPE research group, as well as their technical improvement over time. It also presents their potential use to collect user consumption information and directly control connected appliances. Data gathered through the smart sockets are used as a basis for the design of a for Demand Side Management (DSM) strategy. Load appliances that can contribute to DSM in the form of flexible loads are integrated into a Building Energy Management Strategies (BEMS) model, resembling the consumption pattern of a commercial type building as IPE's one. The analysis showed that flexible loads coculd provide constant savings, but the amount saved is very dependent on user interaction. The report also explores the potential contribution of renewable energy integration (e.g. Photovoltaic installation) and energy storage deployment within the BEMS and it provides an indicative sizing of both components, in order to find the most suitable combination for the IPE building. A preliminary version of BEMS has also been validated experimentally through real time digital simulations.

2.7. M5.4 General Ancillary Service Market Model developed

Several new type of ancillary services are expected to be needed in the future, to support the stability and security of the power system.

This proposed method, *Any Service Benefit and Risk Analysis* (ASBRA), is a method to support intended providers and procurers in building up and participating at markets for ancillary services.

The method support inter-dependencies between different services supplied by the same asset, as well as penalties in not supplying a service when it is required.

An open use of this method could support establishing fair risk sharing between providers and purchasers at an ancillary service market.

2.8. D5.5 Report on the Energy management strategies development

The main goal of the report is to review, present and analyse different energy management strategies, which can be used by active customers/prosumers in order to reach a higher level of flexibility in the power supply and demand in electric networks. Different energy management strategies are developed and classified, in the form of an architectural model. Energy management strategies are then introduced and analysed based on three main criteria: 1) the trigger for the demand-response program implemented (e.g. Price-based vs. incentive based); 2) the type of equipment owned by the user (ranging from pure consumer to prosumers with variable number and types of add-ons); 3) the reaction time, referring to the type of data that are measured and collected as a basis for the energy management decisions. The application of user comfort level on the energy management strategies efficiency is considered. Several cases are analysed and compared, using as a demonstration object the building of the Institute of Physical Energetics (IPE) in Riga, capturing the main common features of energy management strategies that can be implemented there, complying with the local constraints. Based on both literature review and local assessment and analyses, the evaluation of the type of energy management strategies according to different criteria is performed and effectively summarized in two comprehensive tables, which use of a straightforward colour code.

2.9. D6.1 Report on identifying common reference test cases

The deliverable clearly introduces three test study systems that are expected to be used as the basis for the proof of concept during the duration of the project. Each of the proposed systems under investigation is gradually more complexity than the previous one. Before introducing the test systems, section 2 presents a brief introduction about general principles such as converters configuration, cables and transmission lines and different HVDC topologies. The study cases are based on a bench mark model from CIGRE. It has been indicated that deviations to the presented case studies could be expected during the course of the project, if required.

2.10. D6.2 Study of the different structures, simulation models for the main relevant converter topologies, control strategies, static and dynamic behaviour/limits

The deliverable clearly introduces three test study systems that are expected to be used as the basis for the proof of concept during the duration of the project. Each of the proposed systems under investigation is gradually more complexity than the previous one. Before introducing the test systems, section 2 presents a brief introduction about general principles such as converters configuration, cables and transmission lines and different HVDC topologies. The study cases are based on a bench mark model from CIGRE. It has been indicated that deviations to the presented case studies could be expected during the course of the project, if required.

2.11. D6.3 Set of system level simulation models and accompanying documentation for converter interaction analyses in ACDC grids

The main goal was to provide a supporting documentation for simulation models developed in Matlab/Simulink under task 6.3 and part of task 6.5 in WP6. Document describes the analysis applied to the main components of an HVDC system, the background modelling approaches used, as well as presents created model capabilities through sample examples. Used model equations and their respective parameters within MMC and cable model calculations are explained. The cable model uses the universal line model with added frequency dependency.

Three test cases chosen in previous deliverable had been examined – two terminal (point to point) HVDC grid, four terminal radial HVDC grid and four terminal mashed HVDC grid. Parameter values used within tested cases are collected in according data tables. Each HVDC grid test case performance was analysed by individual terminal activization time and activization impact on exchanged power through the converter. The stability of HVDC in each test case was examined by the two main terminal DC voltage fluctuation during additional terminal sequential activization.

2.12. D6.4 Report on design aspect of a MW size dc/dc-module as a function of efficiency. Efficiency versus switching frequency

The main goal of the report is to present and analyze the high-power bidirectional isolated DC-DC converter capabilities as potential component in future inter-connected DC grids with different voltage levels. Requirements of high-power DC-DC converters and several challenges that must be addressed are mentioned. Challenges are divided into two categories – semiconductor switches and high-frequency/medium-frequency power transformers. A down scaled medium-frequency power transformer prototype was designed for best operational capabilities and experimental verification. Designed transformer materials were carefully selected and calculated for optimal parameters, loss reduction and long lasting peak performance. Performance of series connected modular LV semiconductor switches are tested through hardware in the loop. Semiconductor switch test includes sudden small and a significant load change, the impact on switches power transfer is analyzed. HV semiconductor switch benefits over LV and three generation advancements are reviewed and analyzed. Three generation semiconductor switch improvements are compared based on switching losses by device voltage or current change. Analyzed data of transformer and semiconductor switch is depicted in several graphs and tables. Finally a graphical comparison of efficiency versus frequency of the designed DC-DC converter with prototype medium-frequency transformer and selected HV semiconductor.

2.13. D6.5 Stability assessment of complex offshore HVDC systems and modelling of critical components in view of laboratory validation

The deliverable deals with two parts, stability of complex offshore HVDC system and impact of a DC cable model in a two terminal HVDC systems. The stability analysis was based on the Lyapunov criteria of stability for two different cases, stiff and weak grid, to evaluate performance indices and supervision methodology, for respective case. The investigated system was a four-terminal meshed HVDC grid for the stiff grid and a converter connected to a weak grid was considered for the second case. Based on earlier developed test cases it was shown that fever events where found for the stiff then the weak grid. All events were considered well damped for the stiff grid but that was not the case for the weak grid which is highlighted. In the second part, was a new DC cable model evaluated. A real 400 kV cable was used for parametrization of the model. The evaluation showed that with the proposed cable model in a HVDC-system, more high frequency system dynamics can be investigated in the future.

2.14. D6.7 Guidelines for the analysis and small-scale experimental validation of complex HVDC systems

Document generalizes some of the approaches and lesson learned from the conducted analysis, methodology and results obtained while working under WP6. Document encompasses simulation tests performed in PSCAD and Simulink platforms. Multiple test cases involving modular multilevel converter had been examined with two different switch models used, created in both software platforms to compare, and multiple terminal setup tests with different interconnections had been simulated.

Examined model can provide stability analysis and oscillation monitoring, that can be used to support TSOs working with HVDC system and provide helpful guidelines for HVDC designers. Test results can be examined in graphical and flow-chart format for clarity with added reference for further details. Moreover, recommendations from the laboratory testing of HVDC grid are given. Highlighting precision of used model with created accurate cable models, which provides close values in comparison to real measurements performed.

3 Project conclusions, recommendations, and future work

3.1. Work Package 4

3. Conclusions

The introduction of renewable energy sources (RES) and lack of conventional generation such as nuclear power plants is certainly changing the topology and thus, the dynamic response of the meshed power systems. Monitoring devices such as phasor measurement units (PMUs) are playing a key factor to maintain the secure operation of these networks. Current protection schemes need to be revisited and improved in order to cope with the future changes related to massive integration of RES. More projects such as Cloudgrid need to be supported to generate ideas and solve the future challenges.

4. Recommendations

Several recommendations have been proposed to face the future challenges. Some of them include the improvement of the under-frequency load shedding (UFLS) protection. Calculation of a more accurate rate of change of Frequency (RoCoF). Generate a bench mark model of continental Europe and provide more tools for handling large volume of data considering the upcoming digitalization in power systems.

5. Future work

More algorithms need for real time implementation need to be provided. Concepts as control hardware in the loop (CHIL) and power hardware in the loop (PHIL) need to considered to validate algorithms in real time operation. Simulations with faster sampling time have to be also investigated in order to observe the fast phenomena introduced by power electronic components.

3.2. Work Package 5

6. Conclusions

There are is a great potential for many more providers of ancillary services. To provide more than one service are challenging when it comes to the current business models. The potential for wind power and battery energy storage systems form provision of emulated inertia is especially promising. They could be make significantly contribution to solve the expected challenges in the future, when conventional power production is replaced by converter based. IPE developed BEMS model can provide a versatile look of the potential flexible load, RES and electricity storage unit usage added benefit to modelled building in price-based DSM. The model setting can be easily modified for specific test scenarios and provide comparison between each tested outcome in search of optimal setup for modelled bounding situation.

7. Recommendations

With power being the biggest cost for both commercial and residential facilities, effective energy management is more important than ever before. A thorough understanding of energy and its use in buildings is essential – this way, you can understand your energy use per square meter and benchmark yourself with others. It is, in this regard, vital to create awareness in your building of energy utilization and the impact it has on the environment and cost.

Create other business models for ancillary service that would make it possible for more providers to participate in gird operation and thereby lower the overall system cost for grids.

Utilize more sources of inertia (emulated) in the system.

8. Future work

Full scale test of emulated inertia from wind turbines. Test of emulated inertia from small scale off-the-shelf battery energy systems. Development of new business models of all types of the ancillary services. The models should be developed in a way that make them comparable with business models outside the power industry to ease the introduction. Investigate risk management for grid operation to be bale to develop a model for sharing risks.

BEMS accuracy can be improved by adding more flexible load groups as well as regular non flexible loads, which also could be modified in their work patterns, testing optimal work patterns or load efficiency. Implementation of wind generation would increase RES diversity and forecasting feature for both RES and building load is needed. For IPE BEMS building model more PV panel and ES unit setup combinations will be tested, finalizing the most optimal setup combination possible. Adding more flexible loads are expected once appliance measurement operation will be allowed by other IPE residents.

3.3. Work Package 6

9. Conclusions

Offshore HVDC networks are systems of increasing complexity, whose correct operation relies of the interoperability of many different components, typically provided by multiple vendors and that are designed independently but required to function in a coordinated way. Availability of suitable tools to analyse the stability and proper operation of such systems, both prior to commissioning and during normal operating life, is pivotal. Suitable tools to facilitate such analyses have been investigated in detail and/or created within WP6.

10. Recommendations

The analyses implemented within WP6 demonstrated the importance of utilizing simulation models that, although simplified, are able to accurately describe the frequency dependent behaviours of components, such as cables, as they can significantly affect the results of stability analyses conducted on large offshore HVDC systems. Small-scale laboratory testing of such system should also rely on corresponding emulation of such components. When an HVDC grid is operated, the implementation of real-time algorithms for early detection of potentially critical power oscillations is also suggested.

11. Future work

Future work on the stability of large interconnected offshore systems will include the attempt to overcome the adoption of classical tools used for stability analysis of linear systems in order to perform large signal stability assessment.

Moreover, the availability of reliable simulation models for all the different components of the HVDC networks, possibly associated to the availability of suitable HVDC operational data provided by TSO, could enable the use of artificial intelligence to support new paradigms for digital energy management.

The use of FPGA-based simulation technologies will also be explored during experimental validation, to enhance the computational performance and allow co-simulation of systems whose dynamics involve coupled phenomena occurring on very different time-scales.

4 List of publications

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