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Transnational CLOUD for Interconnection of Demonstration Facilities for Smart GRID Lab Research & Development (CloudGrid)

CloudGrid
STRI - ZHAW - NTNU - CHALMERS - IPE

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of Applied Sciences

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IEFE Institute of Energy Systems and Fluid Engineering

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Summary

Energy policies are pushing towards a more sustainable energy production, which are resulting in deployment of considerable amounts of renewable energy sources. As consequence, these new assets in the electrical network are introducing more complexity and operating the power system in real time is becoming more challenging. For these reasons, projects like Cloudgrid have been developed so its possible to provide some answers to questions related on how these new technologies will impact the traditional operation of power systems at different levels. The project aims to answer the following questions: 1) How the dynamic stability of the future European Grid will be affected, where is envisaged less nuclear power and a higher shares of RES? 2) What will be the role of energy management and ancillary services in these future grid? and 3) How can we guarantee interoperability between converters in a European hybrid AC/DC Grid? The main results of this project, in relation to question 1), are formulated in the form of a list of recommendations to maintain the stability of the future power grid.

Résumé

Les politiques énergétiques poussent vers une production d'énergie plus durable, ce qui entraîne le déploiement de quantités considérables de sources d'énergie renouvelables. En conséquence, ces nouveaux actifs du réseau électrique introduisent une complexité accrue et l'exploitation du système d'alimentation en temps réel devient de plus en plus difficile. Pour ces raisons, des projets tels que Cloudgrid ont été développés, de sorte qu'il est possible de fournir des réponses aux questions relatives à l'impact de ces nouvelles technologies sur le fonctionnement traditionnel des systèmes d'alimentation à différents niveaux. Le projet vise à répondre aux questions suivantes: 1) Comment la stabilité dynamique du futur réseau européen sera-t-elle affectée, où envisage-t-on moins d'énergie nucléaire et des parts plus importantes de SER? 2) Quel sera le rôle de la gestion de l'énergie et des services auxiliaires dans ces futurs réseaux? et 3) Comment pouvons-nous garantir l'interopérabilité entre les convertisseurs d'un réseau hybride européen AC / DC? Les principaux résultats de ce projet, en relation avec la question 1), sont formulés sous la forme d’une liste de recommandations visant à maintenir la stabilité du futur réseau électrique.

Zusammenfassung

Die Energiepolitik drängt auf eine nachhaltigere Energieerzeugung, die zur Bereitstellung erheblicher Mengen erneuerbarer Energiequellen führt. Infolgedessen führen diese neuen Assets im elektrischen Netz zu mehr Komplexität und der Betrieb des Energiesystems in Echtzeit wird immer schwieriger. Aus diesen Gründen wurden Projekte wie Cloudgrid entwickelt, um einige Fragen zu beantworten, die sich auf die Auswirkungen dieser neuen Technologien auf den traditionellen Betrieb von Energiesystemen auf verschiedenen Ebenen beziehen. Das Projekt soll folgende Fragen beantworten: 1) Wie wird die dynamische Stabilität des zukünftigen europäischen Stromnetzes beeinflusst, wo ist weniger Atomkraft und ein höherer Anteil an erneuerbaren Energieträgern vorgesehen? 2) Welche Rolle spielen Energiemanagement und Nebendienstleistungen in diesem zukünftigen Netz? und 3) Wie können wir die Interoperabilität zwischen Umrichtern in einem europäischen Hybrid-AC / DC-Netz gewährleisten? Die Hauptergebnisse dieses Projekts in Bezug auf Frage 1) werden in Form einer Liste von Empfehlungen formuliert, um die Stabilität des zukünftigen Stromnetzes zu gewährleisten.

Contents

List of abbreviations

ZHAW	Zurich University of Applied Sciences
NTNU	Norwegian University of Sciences and Technology
IPE	Institute of Physical Energetics
PMU	Phasor Measurement Unit
TSO	Transmission System Operator
RES	Renewable Energy Sources
SCCER	Swiss Competence Centre of Energy Research
UCTE	Union for the Coordination of the Transmission of Electricity
ENTSO-E	European Network of Transmission System Operators for Electricity
HVDC	High Voltage Direct Current
RoCoF	Rate of Change of Frequency

1 Introduction

Energy policies are pushing towards a more sustainable energy production, which are resulting in deployment of considerable amounts of renewable energy sources. As consequence, these new assets in the electrical network are introducing more complexity and operating the power system in real time is becoming more challenging. For these reasons, projects like Cloudgrid have been developed so its possible to provide some answers to questions related on how these new technologies will impact the traditional operation of power systems. In this regard, recommendations on how to safely operate the system are some of the main outcomes of this project, which are described in this document.

2 Goal of Project

The goal of the project is to assess some of the challenges of the future European power grid from the perspective of i) Grid System Stability, ii) Ancillary Services & Energy Management Systems and iii) Converter interoperability. Specifically, the project aims to answer the following questions: 1) How can stability be reached in the future European Grid containing less nuclear power and a higher share of RES? 2) What will be the role of energy management and ancillary services in the future European grid? 3). How can we guarantee interoperability between converters in a European hybrid AC/DC Grid? These questions will be answered while at the same time providing recommendations, market design, control strategies as well as publication of research results. Through utilization of the proposed “Transnational Smart Grid Cloud”, the project will also lead to increased inter-lab validation and transnational co-operation between members of the consortium. To reach the stated goal, a number of objectives will be accomplished such as: A) Provide recommendations and actions to maintain stability in the future European power system, with a higher share of RES. B) Market as well as technical evaluation and mapping of ancillary services provided by distributed energy resources (DER) in the future European power system. C) Provide recommendations on energy management strategies in order to allow optimal operation of the distribution grid, as well as providing market design for integration of renewable energy in the European power system. D) Identify parameters and requirements critical to guarantee inter-operability of converters of different types and suppliers in European hybrid AC/DC grids. E) Connect leading European Smart Grid labs from the consortium members in order to validate findings in a transnational setting.

3 Summary of work achieved

Cloudgrid project was formed by six different working packages as depicted on Figure 1. ZHAW lead the grid system stability working group, where cooperated with ABB, Sweden and the power system group at NTNU in Norway. In the last part of the project, in order to profit from the results of common activities from the converter interoperability working group, we team up with the group lead by the power electronics group in NTNU to create an intra-work package collaboration and provide an interesting joint-result. Additionally, ZHAW was an active member and contributor of other general working packages devoted to dissemination and project management.

Although the Cloudgrid project covered a wide range of objectives depicted on Section 2, a summary of the main results in which ZHAW contributed are listed below, where more detail about each point is provided in the subsequent sections:

- Create a transnational smart grid database of PMU measurement exchange
- Set-up a common dynamic model of continental Europe for stability assessment
- Development of algorithms to cope with future stability challenges

- Analysis of HVDC effects on transmission systems with high penetration of RES
- Define a set of recommendations for system operators in order to maintain the system stability

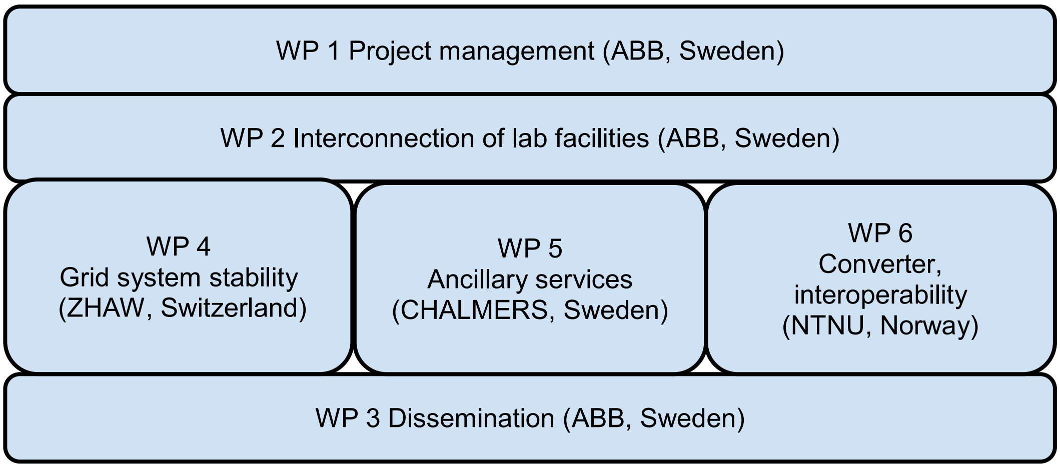


Figure 1 Cloudgrid Consortium

4 Interconnection of Lab Facilities

One of the main goals of the international consortium was to interconnect the different labs involved. During the first two years, there were a lot of efforts to make this happen. An initial attempt was to exchange excel sheets of measurements data sets such as photovoltaic irradiations, however, since not all of the labs had the same infrastructure, the acquired data was published on the project website available for partners and other interconnection options were investigated. Later in the project was found that exchange of PMU measurement was the most feasible solution to achieve the interconnection. To reach this goal, ZHAW profited from the know-how of some partners such as NTNU (Norway) and IPE (Latvia), who had previous experiences with these devices. The interconnection was also achieve with more international research institutions and the interconnection was extended beyond European borders. The final interconnection was not straightforward, there were several technical challenges that were faced in order to overcome and succeed with the lab interconnections. As result of this activitiy, ZHAW has now an important database of frequency measurements (see Figure 2 and 3) that is continuously growing in terms of research institutions and historical data.

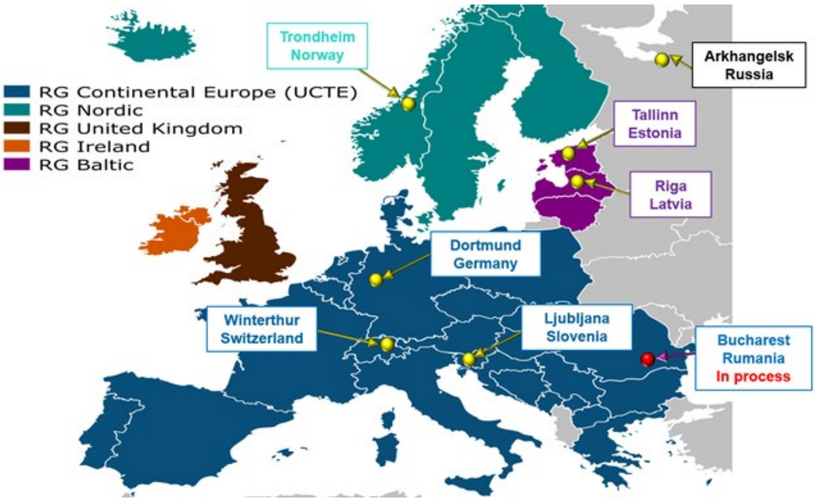


Figure 2 Interconnection of Labs in Europe

Figure 3 Snapshot of Frequency Measurements

With these data set, ZHAW is now able to observe and analyze frequency problems as in the control room of Swissgrid. With the historical data we can investigate recorded events in the Swiss power system in the same way as the transmission system opertator (TSO) does. As example, Figure 4 depicts an important frequency droop recorded in January 10th 2019, using the ZHAW PMU system.

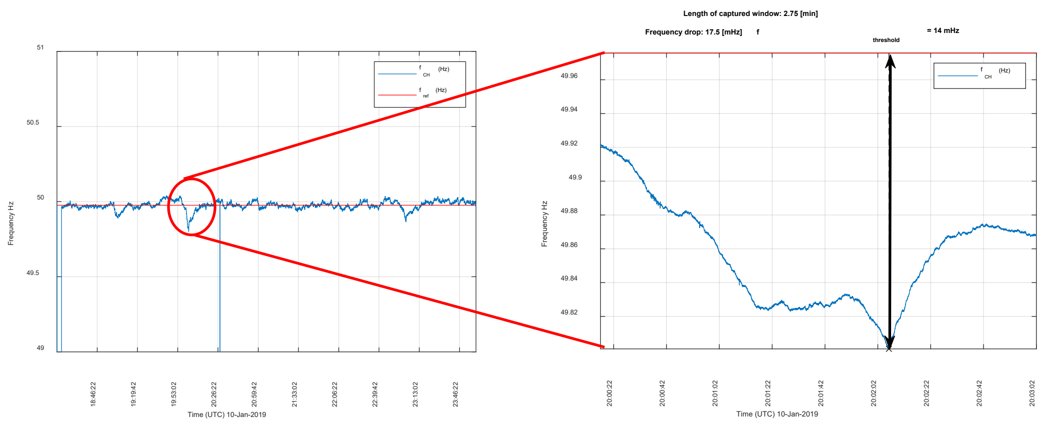


Figure 4 Frequency droop of more than 14 mHz in Switzerland recorder with PMU in ZHAW on 10.01.2019

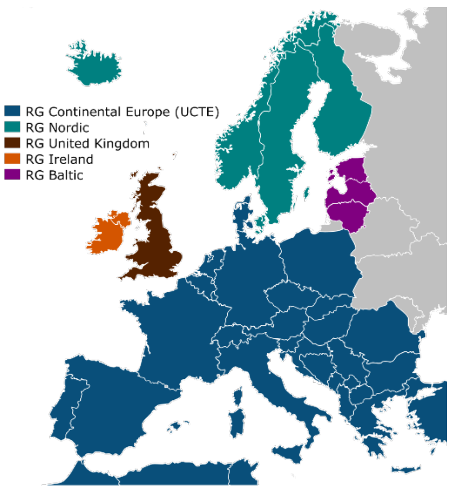
5 Grid System Stability

The Swiss energy strategy 2050 considers the increase of renewables and encourage carbon-free energy production. One of the key plans to achieve on this scheme is decommissioning the existing nuclear facilities within the Swiss borders long before reach their expected life time [BFE_2014]. Catastrophic failures in nuclear plants and the environmental issues linked to this technology have encouraged politicians on taking this decision. However, sudden removal of nuclear energy is not simple or straightforward, especially when 39% (up to 45% in winter) of Swiss energy is produced by four nuclear power plants and the enforced energy strategy aims for carbon free technologies [BFE_2015]. Based on this panorama, the development of the future generation portfolio is an open question which brings research opportunities to provide new energy-economic models and technical solutions. Given that a lot of effort is devoted to analyse how renewables will replace the contribution of the current nuclear production very little has been proposed on how this intermittent green technologies will affect the stability and dynamic of the system in a national and European level [Weigt_2014]. The objective of this study was to answer some of these questions by analysing the impact of the increase of renewables at different levels. In this section we present a summary of the activities within the project, were ZHAW participate. It is worth mentioning that all task and milestones were successfully achieved before the end of the project.

5.1 Dynamic model set-up

The European Network of Transmission Systems Operators (ENTSO-E) made available for research purposes the initial dynamic model of Continental Europe. This model mimics the dynamic behaviour of the interconnected network in Europe and provide the possibility to study the electric grid according to expected topology changes as illustrated in the smart grid road map in Switzerland and the energy strategies of most of Europe. The model was developed to be used as a playground to analyse the current conditions of the system and simulate future scenarios such as: (a) change the topology of the system adding new HVDC links, (b) representing decommissioning of nuclear power plants and (c) increase PV and wind generation, just to mention some. Developing a dynamic model for a large area such as Continental Europe represents a demanding challenge on its own, for this reason the ENTSO-E model was selected for the analysis done in this work.

The model is the most comprehensive representation of the power system synchronous area UCTE (blue zone in map). The model is complex and challenging comprising 26 countries more than 21,000 buses and 10,000 generators (see Table on Figure 5). It can be seen that France, Germany, Italy, Greece and Spain are the more detailed countries of the system as suggested by the larger number of elements within.



Code	Country	Lines	Buses	Loads	Generators
AL	Albania	193	339	110	77
AT	Austria	123	104	40	31
BA	Bosnia & Herz.	312	294	164	37
BE	Belgium	178	140	36	52
BG	Bulgaria	787	798	419	77
CH	Switzerland	244	193	82	88
CZ	Check Rep	106	288	76	113
DE	Germany	3378	3939	859	898
DK	Denmark	250	397	66	71
ES	Spain	1338	1385	646	496
FR	France	2599	2665	991	1564
GR	Greece	1133	1312	367	128
HR	Croatia	334	329	171	73
HU	Hungary	94	120	37	28
IT	Italy	817	1264	341	458
LU	Luxembourg	41	38	11	12
ME	Montenegro	80	94	35	18
MK	Macedonia	146	163	85	25
NL	Netherlands	905	1031	244	178
PL	Poland	988	648	199	140
PT	Portugal	365	506	87	158
RO	Romania	1194	1171	654	185
RS	Serbia	619	553	303	62
SI	Slovenia	111	230	65	73
SK	Slovakia	52	48	18	82
TR	Turkey	1943	4888	1245	1022
EU*	Europe*	9	316	26	1
	Total	18339	23253	7377	6147

* Elements not labeled for a particular country.

Figure 5 Synchronous power systems in Europe and number of elements in the dynamic model.

5.2 Definition of different case studies

With the objective of analysing the impact of future conditions on the power system, we developed two variations of the system in addition to the original base case, which make in total three different case studies (CS) as depicted on Figure 6. The case study one (CS1) is the model as it was provided by manufacturer (ENTSO-E) and it represents today's conditions. In CS1 the synchronous machines generate a total of 466 GW and the model consumes 458 GW. Case study two (CS2) was developed to force the system to increase the power flowing from North to South. This represents a future scenario where Denmark increments its wind production in almost 80%, 600 MW more than in CS1. To compensate the surplus generation in the north, loads are also incremented respectively in the south, particularly in Italy. Finally, the objective of case study three (CS3) was to induce the power flowing from East to West representing a future scenario where Turkey increments its current production and the Iberian Peninsula has more load demand. To achieve this goal, the production in Turkey grew 800 MW and the demand on the Iberian peninsula was respectively increased. Figure 6, depicts an overview of the three different case studies.

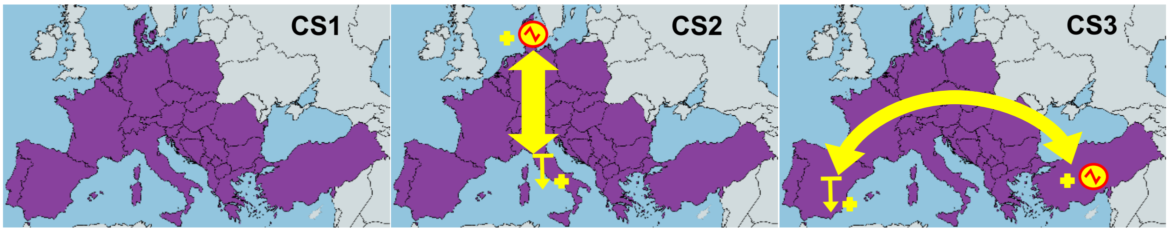


Figure 6 Definition of initial case studies.

Please note that due to the international nature of this project and due to complexity level of the European dynamic model, in the context of this project we did not create specific scenarios related to the Swiss Energy Strategy 2050 (SES2050) but concentrate more on European perspective. Thanks to the know-how collected after the evaluation this project, the ZHAW group has built the tools to made more punctual analysis in future projects, such as the representation of future scenarios as described on SES2050.

5.3 Analysis of the European power system

After the model was acquired and the scenarios were defined, the Cloudgrid team perform several analysis to test the robustness, weaknesses and strengths of the model.

The first test was the evaluation of the model under variation of different parameters under different scenarios (CS1, CS2 and CS3). Various simulations were performed to compare the model response against the variations in the form of simulations, the simulations included the following parameter variations: Saturation of synchronous machines, Variation of governor droop, Deactivation of PSS, Variation of AVR proportional gains and Variation of inertia

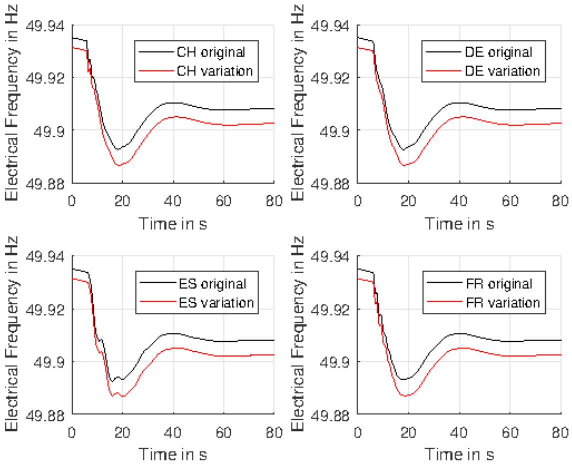


Figure 7 Frequency droop after change of inertia in the system

The results indicate that moderated variations in the original parameters produce small fluctuations on the time domain simulations. From the amount of elements that constitute the model, the high complexity of the model is evident. Nevertheless, the system is robust and suitable to perform transient analysis.

A second objective was to investigate the impact of decreased conventional generation and the corresponding introduction of renewable production in CS2 and CS3. The primary study focused on the impact of the changed contribution to system inertia and the frequency regulation by renewables. In the study, inertia constants and the droop of turbine governors was altered in Switzerland and Germany (totally 10 GW) using a perturbation in the system by means of loss of two large synchronous units in France to investigate the response. Frequency on nodes in different countries and phase angle response was analysed as well as cross country power flows. The results showed that frequency decay is not equal through the system nor is it monotonous. The linear analysis has confirmed known inter-area modes such as an east-west mode of 0.13 Hz which is also clearly observable in the time domain bus phase angles.

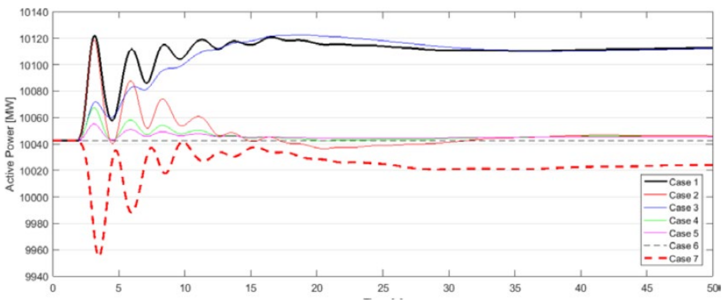


Figure 8 Active power in altered generators

5.4 Stability and control of the future grid

In this section, we present the role of HVDC technology in the future power grids (5.4.1), new tools to provide an indication of how much the integration of renewable sources could affect the stability and the performance of power grids (5.4.2 and 5.4.3). Finally, new control concepts to overcome the challenges resulting from inter-area oscillation problems (section 5.4.4). Please note that due to the complexity of the European model, the role of HVDC technology is not analysed directly on any of the aforementioned scenarios (SC1, SC2 or SC3) but the concept is evaluated on a reduced and simplified power system from the literature. However, to demonstrate the effectiveness of the proposed metrics presented on 5.4.2 are applied to the model and its variations described on Section 5.2.

5.4.1 Analysis and Control of HVDC Links in future power grids

Renewable energy sources are located close the natural source, for instance in the roof of households in the case of photovoltaic panels to receive solar irradiation and in the seaside or high mountains where the wind blows in the case of windmills. In the case of wind production, I has been proved that offshore areas in the North Sea have the major potential of energy production for this renewable source. As result, physical connections (cables) to bring this wind energy from offshore sea into mainland are required [PROM_2016]. Here is where HVDC links play an important role to make feasible the availability of significant amounts of energy from wind into the traditional power system operation.

For this reason, the aim of this task was to analyse the impact of HVDC technology in the dynamic response of traditional power systems. To achieve this, we use a simple dynamic model consisting of four synchronous machines representing two electrical areas that provide energy to two loads in the middle if the small system. This is known in the literature as the 4-machines 2-areas system and is depicted on Figure 9. To profit from the results of the converter and interoperability group (WP6) of NTNU within cloudgrid project. NTNU provide us with a comprehensive model of an HVDC link based on modular multilevel converters as highlighted on Figure 9. Our task was to integrate the HVDC model into the power system and to compare the dynamic response under different conditions.

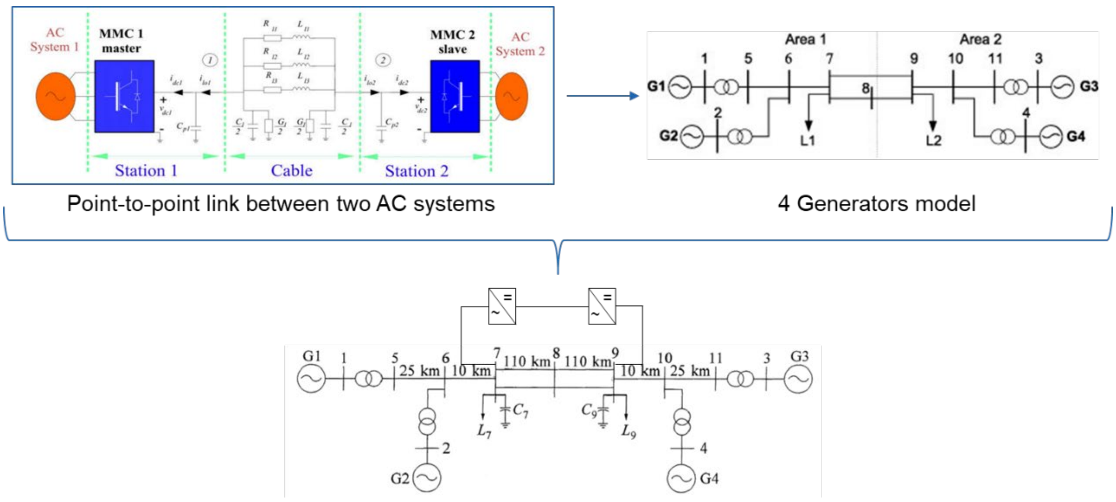


Figure 9 Integration of detailed HVDC-link in the academic 4-machine's 2-areas power system

To test the dynamic effects of the new element in the power system, we apply a 3-phase short circuit fault in the transmission line between bus 7 and bus 8 (see Figure 9). To create a realistic scenario, the fault was cleared after 100 msec as it would occur in a real power system as result of the operation of the line protection system. Then, to assess the influence of the HVDC link in the system, different levels of power flowing through the HVDC were considered from 0%, representing no connection of the new element in the system and from 10% to 50% representing a gradual increasing participation of the HVDC link. The results are displayed on Figure 10 and it can be observed the impact of the fault for the different levels power flowing through the HVDC link.

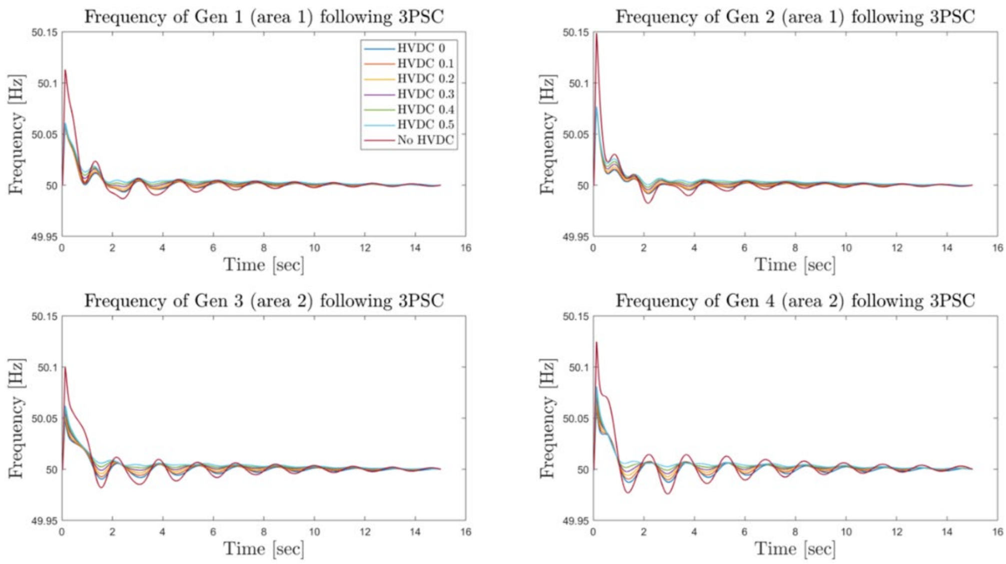


Figure 10 Impact of 3-phase short circuit in the system, for different levels of power flowing through the HVDC link

The take away message from this experiment is that the HVDC has a positively influence on the stability of the system even without any special control action from the device. This indicated that in a future power system with significant amount of RES, HVDC links could be used not just to access renewable sources from remote locations but also to improve the dynamic stability of the power system. Finally, Figure 11 summarize the ex-treme cases of the experiment (no HVDC and 50% power flowing through the HVDC) to highlight the effect of the new element, respect to the oscillations caused by the 3-phase fault in the system.

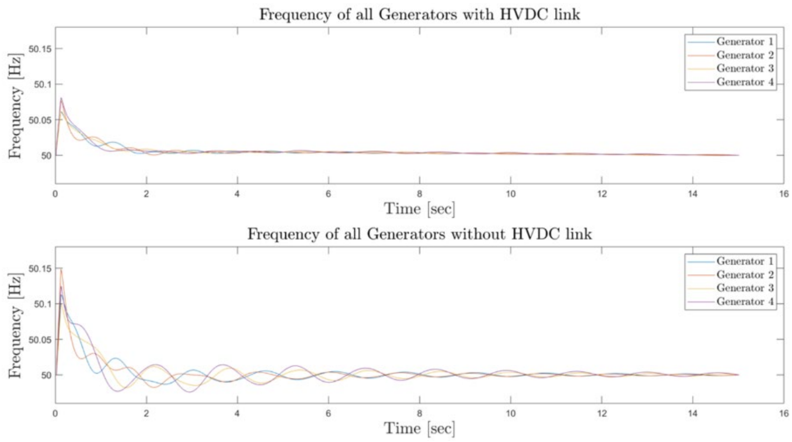


Figure 11 HVDC link in the system have positive damping effect in the system's response

5.4.2 Stability Impact assessment with high RES penetration

Significant amounts of RES in the future power systems represent not just significant amounts of stochastic energy sources but also the introduction of significant amounts of assets based on power electronic components such as inverters and HVDC links. These new components will introduce new challenges in the operation of the system but also can potentially be used in pro of the stability of the system if correctly used [Migrate_2016], as demonstrated in Task 3.1. In either case, new and more sophisticated tools to monitor the security of the system need to be developed. For this reason, we have propose the use of security metrics such as the Lyapunov exponent, to assess the stability response of the system following disturbances. If a severe deviation from the set point is identified following disruptions in the system, the proposed metric will rise an alarm so the system operator can perform a corrective action. Figure 12 illustrate the general idea investigated in the framework of this project. We used the initial dynamic model of ENTSO-E (SC1, SC2 and SC3), which was exhaustively studied within the first part of this project. Several line outages of 100 msec each, were simulated at different geographical locations in the system (one at the time) with the idea of generating one fault per country. Then, frequency measurements were collected all over the system and afterwards, the so called Lyapunov exponent was applied to each of the frequency measurement. A global measure to indicate a level of severity for the applied fault was tagged for each simulation and at the end it was possible to generate a ranking of severity impact for a given set of faults.

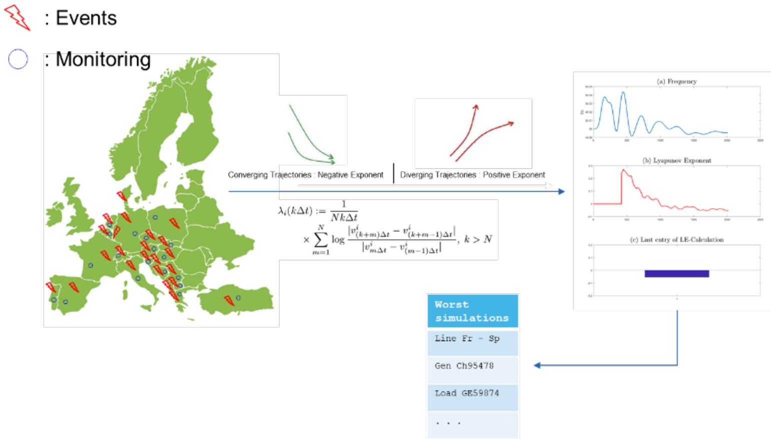


Figure 12 Ilustration of the Lyapunov exponent to assess security of the European System

The Lypunov exponent works in the following form: (a) A dynamic simulation, which include a disturbance in the system, is performed. (b) Frequency measurements are stored from all over the system. (c) The algorithm computes the first swing or oscillation within the time series. (d) A moving window of variable length, compares the time series with the initial swing and determine if the consecutive oscillations are ascending or descending using the logarithm of the difference between the moving window and the initial swing. (e) A negative Lyapunov exponent represent a descending oscillation which can be ex-pressed as mild disturbance in the system that is not treating the security of the system. On the other hand, a positive exponent is an ascending oscillation caused by a severe disturbance that is affecting the stability of the system and is in fact making the system unstable. Simulation results in the initial dynamic model of continental Europe, demonstrate the effectiveness of the proposed approach.

$$\lambda_i(k\Delta t) := \frac{1}{Nk\Delta t} \times \sum_{m=1}^{N} log \frac{\left|v^i_{(k+m)\Delta t} - v^i_{(k+m-1)\Delta t}\right|}{\left|v^i_{m\Delta t} - v^i_{(m-1)\Delta t}\right|}, \quad k > N \qquad (1)$$

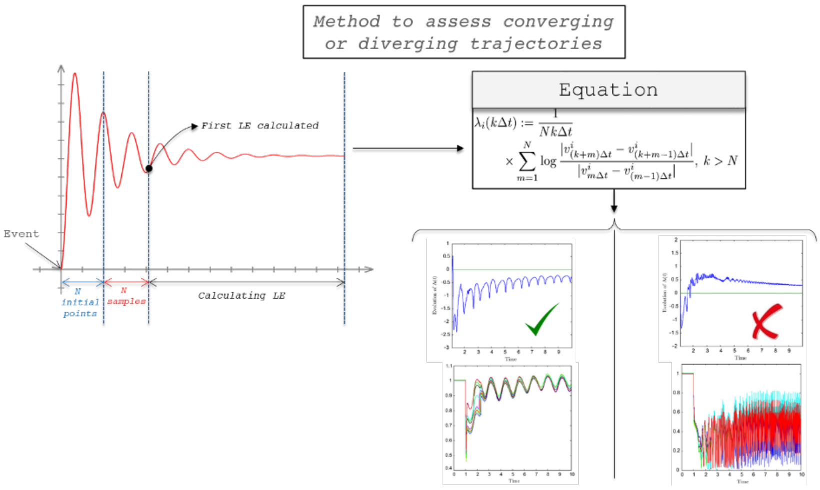


Figure 13 Illustration of Lyapunov exponent for stable and unstable case

5.4.3 Contingency Ranking for Dynamic Security Analysis Using a Trigonometric Based Index

A novel and simple measure to quantify how severe a contingency affects the dynamic of power systems, which is referred as the longest distance measure (LDM) was developed. The metric is important to assess how stable a power system is following disturbances, which is important for future systems where high penetration of renewables is expected.

The proposed metric works as follows: first, the general stability condition of the power system is examined (stable/unstable) and then the severity of the contingency is ranked as safe, mild or severe for stable cases. The proposed metric is the result of combining different and simple trigonometric concepts to offline time series. Considering that the proposed metric does not require significant computational effort, it can be used to assess large set of simulations that represent different scenarios. To demonstrate the effectiveness and reliability of the proposed approach, three different case studies using the ENTSO-E network are presented. Finally, the results of the proposed metric are compared with results from an under/over voltage index to reinforce the observations and findings.

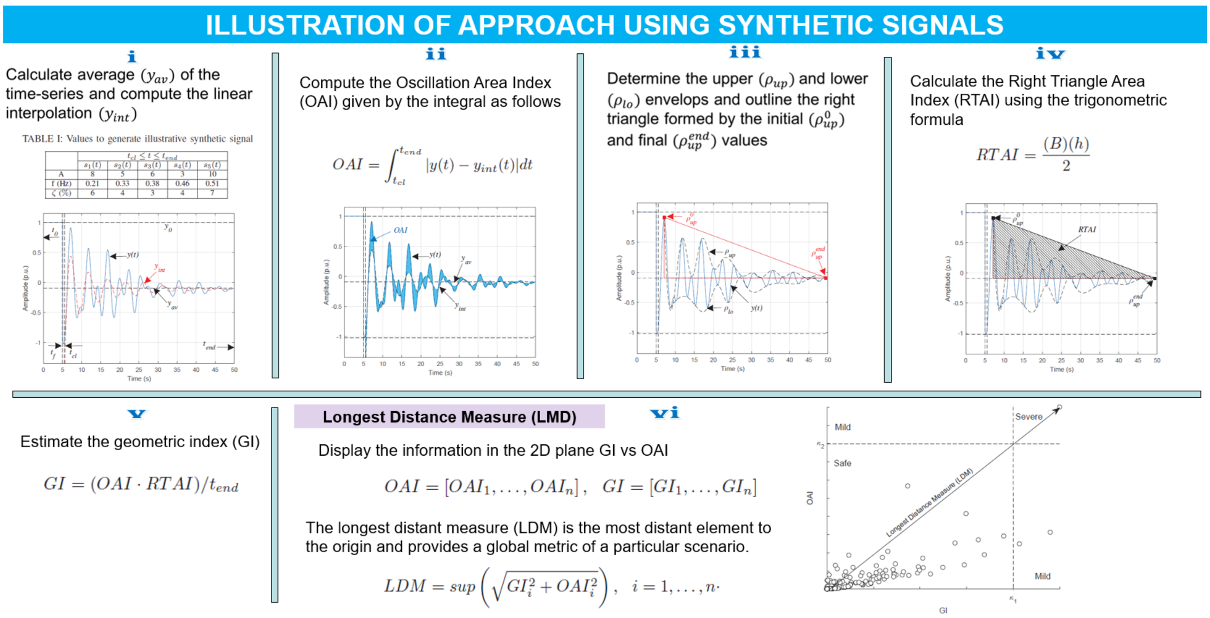


Figure 14 Overview of the proposed LMD approach.

5.4.4 Inter-area Oscillation Control Based on Eigensystem Realization Approach

The continuous growth and development of society have a direct correlation to the amount of energy required to satisfy its demand. As consequence, more interconnections of existing electrical networks are required, increasing the complexity on its operation. Thus, larger power systems are prone to experience inter-area oscillations, which are triggered by generators oscillating against each other from different geographic locations. Whether these so called inter-area oscillations are undamped, they could eventually lead to a system collapse. Base on this, a Linear Quadratic Gaussian (LQG) control approach to damp inter-area oscillations, which is coupled with a dynamic eigensystem realization algorithm (ERA) was proposed. Although these two concepts are well documented on the literature, the novelty presented here is its combination resulting on a fast and effective damping controller. The proposed architecture is implemented as a digital Power System Stabilizer (PSS) using the combination of the professional softwares DigSilent PowerFactory and Matlab. The presented controller is initially validated trough dynamic system simulations (CS1).

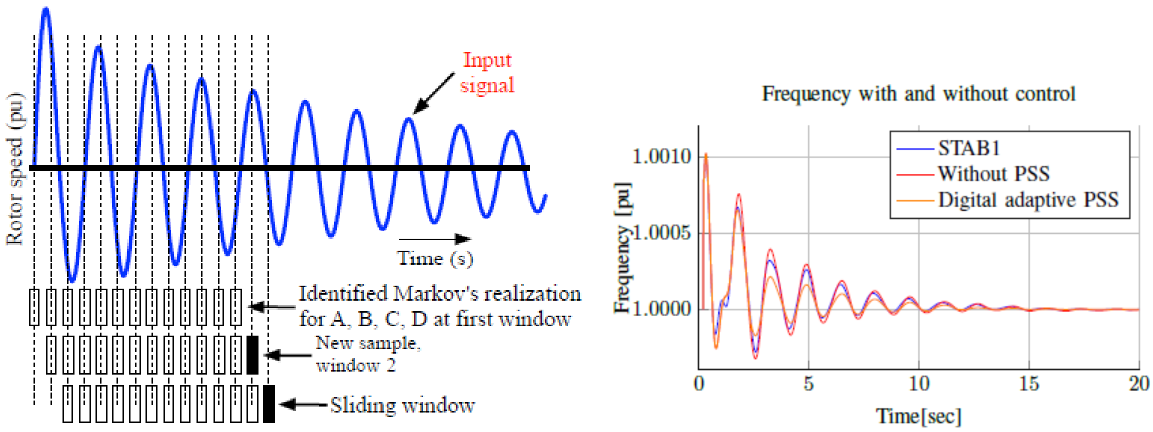


Figure 15 Sliding window for application of proposed method (left). Simulations result with PSS, without PSS and with digital PSS (right).

6 Dissemination activities

The success of the project was also possible thanks to two consecutive international workshops organized in the framework of this project and several scientific publications in international peer reviewed conferences.

The organization of two international events in 2017 and 2018, respectively, provided significant added value to the Cloudgrid project. In Switzerland, the visibility of the project grow exponentially, particularly because the content of the project was promoted and aligned with the national largest research energy program, the so called Swiss Competence Centre for Energy Research (SCCER). At European level, the project was also promoted with participation of renowned scientist in the field who contribute with oral presentations in both events. In summary, the two workshops attracted around 100 experts from more than 8 different countries. It is worth mentioning that attendees to the workshops were not only from academia but also from industry e.g. transmission system operators and also politicians. Figure 16 show some pictures from the aforementioned events.

Figure 16 International Workshops 2017 (left) and 2018 (right)

ZHAW has received as legacy of the Cloudgrid project an international workshop, which will continuing taking place in Winterthur during autumn every year and as example the 2019 edition is already under development [DynPOW_2019].

7 Recommendations

The main recommendations are presented in the form of a list and are aligned to the vision of the national transmission system operator in Switzerland (Swissgrid):

1) ***Challenge:*** Decommissioning of nuclear power plants has been simulated in the form of reducing the system inertia (Section 5). Simulation results in the initial dynamic model of continental Europe, indicate that lack of inertia in the system leads to lower frequency nadir values. Where frequency nadir is the point where the system reaches its mini-mum value during a transient event.

   Recommendation: In order to support lower frequency droops or lower nadir values, the future power systems can be receive synthetic inertia from power electronic components and it can to be use as part of the ancillary services to support frequency. However, this new ancillary service represent additional efforts for the trans-mission system operator, which will generate additional costs (deployment) that will have to be covered by the end user.

2) ***Challenge:*** Higher rates of change of frequency (RoCoF, i.e. how fast the system frequency reaches its nadir) have also been observed in simulated power systems with significant amounts of power electronic devices and decommissioned nuclear power plants, as result of large integration of renewable energy sources. A consequence is that traditional under frequency load shedding (UFLS) protections could fail to protect power systems under future conditions.

   Recommendation: UFLS protection schemes are a considerable concern. Potential future solutions could consider adaptive schemes that required more observability of the system in the sense of support from wide-area measurements to estimate the generation-load imbalance, which could be corrupted with telecommunication delays. However, the main challenge for transmission system operators become to have fast generation control. For renewable energy sources coupled to power electronic devices is possible to provide fast generation control, however for classical energy sources this might not be the case leading to problems implementing new schemes leading to time problems for opening medium voltage circuit breakers at appropriate time.

3) ***Challenge:*** European energy transitions prognosticate future power system with up to 70% of RES, where cross border exchange will play a crucial role in order to full fill the demand and thus

depend even more on power system interconnections. For this reason, the risk of blackouts will be higher on future power systems that will rely on cross border exchanges.

Recommendation: A potential solution is that transmission system operators collaborate on having plans for controlled islanding schemes in order to avoid propagation of cascade faults, to prevent massive blackouts and thus, the system collapse. This idea also suggests participation of Switzerland in the European energy market. Nevertheless, the technical, political and regulatory challenges behind this protective scheme imply to be an unfeasible direction to implement this option.

4) ***Challenge:*** The existing comprehensive and complex dynamic model of continental Europe (Section 5), which has been extensively investigated in this project, gives the possibility to analyse different dynamic stability phenomena. However, one limitation of this model is related to its order and complexity, which demand high computational time to perform different simulation case studies.

   Recommendation: There is a need of a simplified benchmark model of Continental Europe to speed up simulation time and evaluate more number of simulations with less time and efforts. This model could be developed in a joint collaboration between transmission system operators and academia within a project.

5) ***Challenge:*** Traditional studies for analysis of electromagnetic phenomena of power systems are in the range of milliseconds and minutes, which is known as mid/long-term transients. Therefore, RMS simulations have always been used to conduct dynamic analysis. Introduction of significant amounts of RES are also integrating significant amounts of power electronic components, which also introduce faster electro-magnetic phenomena.

   Recommendation: Future analysis of power systems need to be reinforced with electromagnetic transient (EMT) simulations in order to widen the simulation resolution time and observe the short-term electromagnetic transients caused by the new devices. This could be done modelling a power system area with high detail and simplifying the modelling of surrounding areas that do not play a key role in the analysis.

6) ***Challenge:*** EMT simulations require higher detail in modelling of components.

   Recommendation: Simplified dynamic models that maintain the actual dynamic behaviour of the real systems, are required in order to integrate the power electronic components in more detail (reinforcement of point 5). There should be a compromise between how detailed is the modelling vs complexity of the system under investigation.

7) ***Challenge:*** Extra high voltage networks or transmission systems are also moving towards a more digital era, where communication infrastructure is changing from copper wire to Ethernet connections and more smart measurement devices are also been installed. As consequence, more data is available for monitoring and control-ling the system in real time.

   Recommendation: Big data and data analytic tools that where not part of the traditional power systems analysis but rather for computational science need to be applied to develop new tools to face digitalization challenges in the future power grids.

8 Publications

A total of 5 publications in top international conferences and one poster, summarize the main findings of this work package within Cloudgrid project and are listed below.

ZHAW_2016 Mutule, Anna; Tedeschi, Elisabetta; Ehnberg, Jimmy; Oleinikova, Irina; **Segundo Se-villa, Felix Rafael; Korba, Petr**; Uhlen, Kjetil; Djurström, Jan; Hillberg, Emil, 2016. “CloudGrid : the development of a transnational smart grid lab cooperation”. In: 21 Annual International Conference on Innovation Baltic Dynamics 2016, Riga, Latvia, 15–16 September 2016.

ZHAW_2017_1 Hillberg, Emil; Pinares, G.**; Segundo Sevilla, Felix Rafael; Korba, Petr**; Uhlen, Kjetil; Sattinger, Walter. “Frequency stability assessment of decreased conventional production in the Continental European power system”. In: CIGRÉ Symposium Dublin, CIGRE Dublin, Dublin, Ireland, 29 May–2 June 2017.

ZHAW_2017_2 **Segundo Sevilla Felix Rafael;** Sattinger Walter; **Korba Petr;** Uhlen, Kjetil; Hillberg, Emil. “Evaluation of the ENTSO-E initial dynamic model of continental Europe subject to parameter variations”. In: Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2017 IEEE. IEEE ISGT North America, Washington DC, USA, April 23-26 2017. IEEE. Available from: https://doi.org/10.1109ISGT.2017.8085986

ZHAW_2017_3 **F. R. Segundo**, E. Hillberg, G. Lindahl, K. Uhlen, **P Korba** and W. Sattinger, “Robustness Assessment of the Continental Europe Power System Dynamic Model”, Elkraft 2017, May 17 - 18, Gothenburg, Sweden

ZHAW_2018 **Segundo Sevilla Felix Rafael**; **Korba Petr**; Barocio Emilio. “Contingency ranking for dynamic security analysis using a trigonometric based index”. In: 2018 IEEE PES Trans-mission & Distribution Conference and Exhibition - Latin America (T&D-LA). IEEE PES T&D Latin America, Lima, 18.-21. September 2018. Available from: https://doi.org/10.1109/TDC-LA.2018.8511662

ZHAW_2019 **Segundo Sevilla Felix Rafael; Korba Petr;** Barocio Emilio. “Data Analytic Tool for Clustering Identification based on Dimensionality Reduction of Frequency Measurements”. In: 2019 IEEE PES SGSMA, College Station, 20.-23. May 2019. [In Proceedings]

9 References

DynPOW_2019 https://www.zhaw.ch/de/engineering/institute-zentren/iefe/international-workshop-dynpower/

BFE_2012 SFOE (BFE), “Erläuternder Bericht zur Energiestrategie 2050,” 2012

BFE_2015 SFOE (BFE), “Nuclear Energy”, http://www.bfe.admin.ch/themen/00511/index.html?lang=en,

Weigt_2014 I. Schlecht, H. Weigt, “Swissmod - A Model of the Swiss Electricity Market“,(June 6, 2014). Available at SSRN: https://ssrn.com/abstract=2446807

Migrate_2016 https://www.h2020-migrate.eu/

PROM_2016 https://www.promotion-offshore.net/