Stability Analysis and Control of a Distribution Grid with High Penetration of Wind Energy

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Preface

In the last years, the legacy power grids, which are dynamically dominated by centralized power plants, are progressively evolving into power electronic based power systems, driven by the large-scale adoption of electronic power converters. This evolution paves the way towards a huge improvement on sustainability and flexibility, but the **hosting capacity** of the grid for renewable energy is limited by the grid infrastructure. Moreover, the continuous increase of renewable energy sources in the grid poses new challenges, such as the stability of the grid without the centralized power plants.
More precisely, for distribution grids dominated by renewable energy sources, the problem of **Harmonic Instability** can arise and needs to be considered. Harmonic Instability is a variety of small-signal instability that induces a waveform distortion in different frequency ranges and can result in the instability of the system. Voltage oscillations affected by these phenomena may even **destroy** loads connected to the grid. Systems like photovoltaic and wind farms (low SCR) are more prone to this problem, that for this reason must be addressed with high priority to allow the development of modern renewable energy grids.
Northern Germany, in particular Schleswig-Holstein, as a land between the seas is continuously increasing the extension of wind energy, whereby in 2016 onshore wind energy is already accounted for covering nearly 76,1% of the Schleswig-Holstein energy consumption.

For enabling a further increase of the hosting capacity for renewable energies without excessive and expensive grid extension, the **Smart Transformer** (ST) [1]**,** which is a power electronic based transformer with control and communication capability, is a potential solution. The ST provides the opportunity to control the voltage in the distribution grid and to obtain intelligent nodes. Moreover, it enables to act on the problem of harmonic stability and to use the control of the ST for preventing several kinds of harmonic instability. Following this, the control of the ST is used to stabilize the system and therefore increase the hosting capacity for renewable energy sources in the grid.

Motivation

The increasing power injected into the electrical distribution grid, mostly generated by power electronics based distributed energy resources, is leading to the requirement of extending the grid infrastructure in Germany. Thereby, the **hosting capacity** of the distribution grid is limited, and adding several renewable energy sources becomes a risk for the grid stability and therefore the supply reliability of the customers. To increase the hosting capacity, while ensuring the stability of the grid without excessive new lines, the introduction of the **Smart Transformer** in the distribution grid is a potential solution. It can serve as an intelligent node in the grid, providing services and controlling the voltage in the distribution grid [1]. Particularly, the capability to control the voltage is an **economic benefit**, enabling the optimization of the voltage along the feeder and therefore minimize losses and reduce conduction losses in the grid.
Apart from the advantage of controlling the voltage, it is **mandatory** to take into account the stability of the system. Recently, several incidents in different situations were reported, where harmonics and resonances in power electronics units occurring at different frequency ranges caused disruption of the power supply. An example of destructive Harmonic Instability, obtained from a simulation, can be observed in Figure 1.

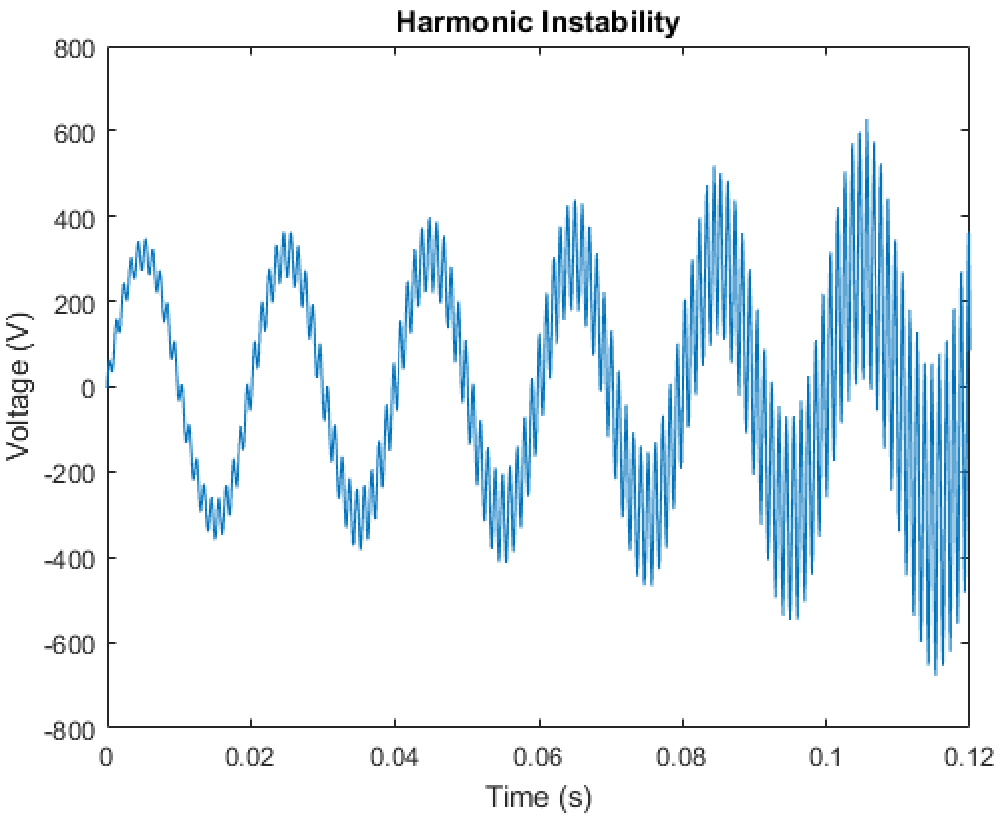
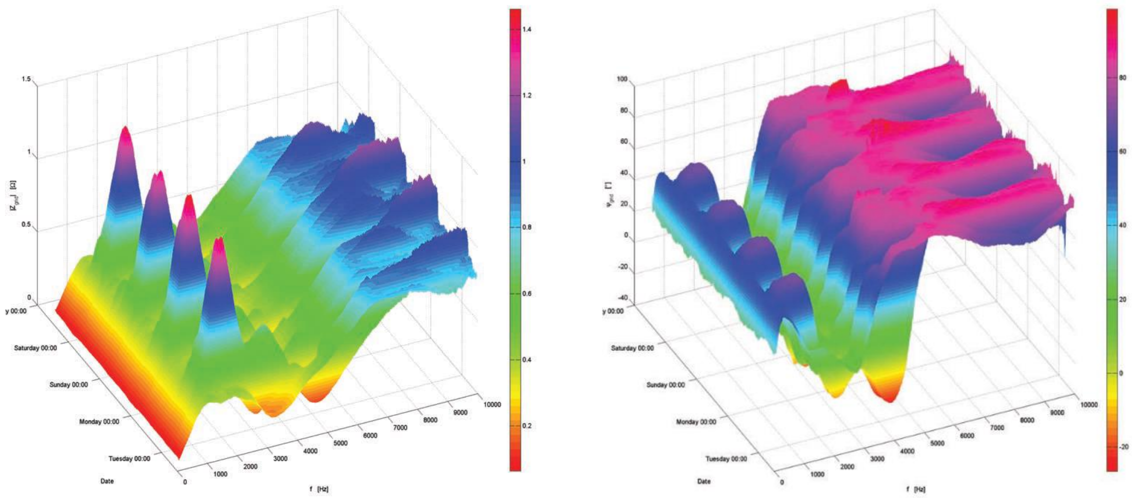


Figure 1: The phenomenon of Harmonic Instability

To avoid Harmonic Instability and consequently the power system breakdown, it is necessary to analyse the causes for this phenomena and study how to act directly on them through the controller, in order to ensure global stability and safety. Harmonic stability is a large topic and several factors have been demonstrated to be responsible of this phenomena, in particular **interaction problems**, **computational and transmission delays, frequency-coupling** [2], [3]. For a detailed analysis of harmonic stability and for its solution a model that included all the responsible factors is necessary. Yet deriving an appropriate model is quite challenging because it **cannot be done through traditional techniques** which neglect all these responsible factors. Indeed, with traditional method.

- It is usual to apply a moving average operator over each switching period to avoid the switching nature of converters. For harmonic stability analysis this approach is not appropriate because it neglect **frequency-coupling** terms occurring with the higher harmonics or when the system become unbalanced.
- **computational and transmission delays** are usually neglected but in this case they cannot, because they are included among the main causes of harmonic instability.
- harmonic instability is often caused by **interaction problems** between different power electronic units, so a separate modelling of each unit which neglect their reciprocal influence is not appropriate
- Variations of the grid impedance over a wide frequency range pose a challenge for the grid stability as well as shown in figure 2.



(a) (b)

Figure *2*: The time varying grid impedance seen from a point in a low voltage distribution grid over a high frequency range: (a) magnitude, (b) phase.

Remarkably, in all these cases, the Harmonic Stability is **strictly related to the control design of the converters**, and for this reason it can be addressed by acting on the control system. This is a great advantage, because modifying the control can be done via software and is cheaper and easier than acting on the hardware. Therefore, many different control strategies can be implemented to evaluate their performances and make comparisons.
Similar to the stability analysis in the AC grid, the study can be extended for the DC grid, which are getting relevant in the context of electric vehicle charging stations or high voltage direct current lines (HVDC). As a capability of the ST, it can feed DC grids represents an enabling technology. As a consequence, the interaction between AC stability and DC stability needs to be analysed.

State of the art

The traditional power system was based on centralized power plants and transformers for the distribution of the energy. The voltage control capability is thereby only available on the high voltage level, whereas all lower voltage levels do not offer any flexibility to control the voltage.
The need of more efficient and cleaner energy sources pushed the researchers to a new concept of energy generation and distribution based on renewable sources, that is the **MicroGrid**. A MicroGrid is a group of interconnected loads and distributed energy resources that acts as a single controllable entity with respect to the grid. A MicroGrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode. Behind all the advantages of MicroGrids and renewable and distributed generators it arises a huge number of challenges that are object of many researches and are progressively overcame through modern and advanced techniques. Harmonic Stability, that is one of those, is quite a recent topic, but it gained the attention of an increasing number of researchers. They have analysed it and proposed new techniques especially for the stability analysis, the modelling and the control.

Starting from the stability analysis, the most frequently used criteria for a power systems are the *impedance based model analysis* and the *eigenvalue based analysis* [4].
The first one has its strength in the simplicity, because it bases the stability condition on a ratio of impedances [5]. Thus it is not important to know the internal structure of the DER, but only its output impedance. Based on this stability condition, several control approaches provide an active damping to suppress the resonance, reshaping the grid impedance through a control action realized by the Smart Transformer in order to satisfy the stability condition [6]. The main advantage of impedance-based approach is the “black-box” modelling of converters, but it gives only a partial information about the stability, confined only to an interconnection point, and it is not easy to extend it to multi-inverter systems.

The other method is the eigenvalue based approach, that is based on the state-space modelling that requires a knowledge of the internal structure of the power system **to derive a model of the whole system**, but allows a more detailed stability and performance analysis [4]. For example, with this method it is possible to establish how much each component or subsystem is responsible for the behaviour of the whole system and to monitor the internal dynamics of the grid as well.
Anyhow, modelling power electronic based power systems is very challenging because they are very complex systems. From a technical point of view they can be classified as *nonlinear*, *time-varying* and *hybrid* systems. Nevertheless, power systems are composed by the interconnection of several low order subsystems, and they are often subjected to parameters or model uncertainties, stochastic disturbances and transmission and computation delays. To overcome all these modelling challenges and obtain a model that is aware of all the undesired behaviours, which can bring to Harmonic Instability many techniques have been developed.

To face the **frequency coupling problems**, multi-frequency modelling approaches allow to analyse the interaction between not only the fundamental frequencies, but also the harmonics generated by the power converters, that represent a real threat for the stability and the integrity of the grid. The two most commonly used techniques for this purpose are the dynamic phasors technique [7] and the Harmonic State Space technique (HSS) [8].
For the computation and modulation **delays**, it is normal to consider a certain delay, approximated through a proper transfer function [6]. Moreover, also time delay system theory can be exploited for this sake, modelling also transmission delays [9].
Overall, for overcoming the **interaction problems** between different units, the *Component Connection Method* has been developed to realize a global model of the system with a systematic and modular procedure in order to be able to add a new distributed energy resource to the model without changing all the rest of it [10].

On the control side, the **Smart Transformer** has been proposed to interconnect low voltage grids with the medium voltage grid and thereby control the grid voltage. This grid voltage control enables to form the grid through, which is hosting loads and renewable energy sources. Remarkably, this affects an interaction with the local controllers, commonly used in the renewable energy sources. For overcoming the related stability problems, not only the structure of the grid, as it is commonly done in literature needs to be considered, but also the capability for the grid voltage controller. Therefore, advanced control strategies in combination with communication are potential solutions.

The aim of the project

The increasing injection of power generated by renewable energy sources raises the problem of the best utilization of the available grid infrastructure. With a proper control, it is possible not only to avoid Harmonic Instability, but also to increase the hosting capability of the grid. That lays the foundation for the realization of a modern and efficient energy generation system based on renewable energy. This research is focussed on the control of a Smart Transformer fed MicroGrid in order to ensure Harmonic Stability. The Smart Transformer must provide voltage control and coordination among several distributed energy resources to ensure the grid stability and safety. However, before developing the control system, a preliminary and accurate modelling of the system is necessary.
Modelling and control are two aspects that are certainly distinct but strictly related. It is important to remark that all the modelling techniques that have been indicated in the previous section to deal with **interaction** problems, **frequency coupling** problems and **time delays** are important also in the control design. In fact, by including all the causes of each undesired oscillatory behaviour in the model it is possible to predict it before it occurs in the real system, and to act directly on it through the control, avoiding the occurrence of a destabilizing phenomenon.
To reach this target, a state space approach is more appropriate, because it allows an easier Multi Input Multi Output (MIMO) modelling, useful to deal with interaction problems and frequency couplings. Moreover, it enables a more detailed analysis of the system stability and more degrees of freedom in the control project. With this kind of model, the eigenvalue based stability criterion is more suitable respect to impedance based one.
To deal with **interaction problems**, Component Connection Method (CCM), that has been presented in the previous section, will be applied to easily model the whole power system composed of several subsystems. Thus the resulting controller takes into account the **interaction** between DERs and avoid instability phenomena.
Frequency coupling terms, which represent a problem for the stability, will be studied through their inclusion in the model, with techniques like Dynamic Phasors and HSS, that will be both used in this research, comparing their performances.

Therefore, the derived model provides a global vision of the system in all its parts, and each undesired behaviour can be predicted and studied through eigenvalue-based analysis.
With the availability of the global model, **dynamic output feedback** techniques that are able to exploit the knowledge of the internal model to improve the performances, are more appropriate. Thus the eigenvalue based method is not only a stability analysis tool, but is directly involved in the control design. The **Smart Transformer** will be used as a central control unit, which from the knowledge of the global model and from the information received from the various subsystems, is able to elaborate the proper control inputs to control and optimize the whole system in all its parts, thanks to the communication infrastructures.

The main advantage of **dynamic output feedback** is enabling to act on each single destabilizing dynamic without affecting the other ones. With the impedance based stability criterion instead, the control provides to reshape the grid impedance. However, with traditional controllers the eigenvalues can be replaced only in some specific configurations, whereas dynamic output feedback enables to choose the desired configuration. Therefore, it is possible to impose a desired dynamic behaviour of the global system with a higher level of independence. When the stability depends on a wide quantity of causes, like in this case, employing a control strategy that is able to ensure a sort of decoupling between all these different causes represents a huge advantage for the achievement of stability. Moreover, this kind of techniques ensure better scalability, because when a new renewable energy source is added to the grid, the control system upgrade is simple, further increasing the hosting capability of the distribution grid.

To apply dynamic output feedback control, it is often necessary to have the knowledge of the internal state of the system that will be reconstructed through an **observer**, which is able to estimate it with good precision from the knowledge of the model of the system and the available measurement. It works properly also in presence of noise, parameter variation and, using some advanced techniques, it is also able to estimate unknown parameters [11].

Furthermore, state-space control is a very wide field. A huge community of researchers steadily works on it, developing more and more performant and robust techniques. Linear state feedback control, one of the most developed field in control theory, is a good starting point for the research for its simplicity and flexibility. It includes a wide variety of techniques, expressly studied to deal with different challenges. In the following, methodologies to be applied in for the ST are described and explained.

- **Time delay control and distributed control** are used to deal with computational delays or transmission delays. Indeed in the case of power systems, they can not be neglected and are crucial for the stability. Time delay control theory allows projecting a controller that takes into account all the various delays present in each part of the system and incorporates all of them in the controller. In this way, the system is stable with good performances despite the delays [9].
- **Optimal control** techniques allow stabilizing the system **minimizing the power consumption** and maximizing the performance.
- **Robust control** techniques allow stabilizing the system despite unexpected perturbation or parameter uncertainties. The importance of this field arises when it is quite challenging to include some specific dynamic in the model of the system, because its behaviour is not completely known. In this case a robust control ensures the stability also without modelling the destabilizing dynamic [12],[13].

Besides linear control, there is **Nonlinear Control** that is able to stabilize the system globally and not only close to the operating point. It is a very wide field that includes several control strategies potentially able to overcome many barriers of linear control. Its application will bring very high improvements on Power System stability including faster response, better dynamic performance, more robustness respect to perturbations or parameter variation and the possibility to impose saturation on the inputs [14],[15]. Besides the advantages for the stability, nonlinear control present advantages also for the **power consumption**, because linear controllers use constant gains that in general must be set relatively high in order to face all the unmodelled nonlinearities. That is not the case of nonlinear control that take them into account and uses the proper gain for each case.

Own preliminary work

In my university studies I focussed for five years on the study of advanced and modern control techniques and their application on different kind of systems, including electrical ones. I gained a solid mathematical background and a knowledge of a wide variety of control problems often involved in real systems, and their solution. In my master thesis with title "Modeling and nonlinear closed-loop gait control of humanoid robots" I dealt with robotics. This work was very important for my education, because the humanoid robot model is highly nonlinear and complex, therefore it is not possible to control it through linear or frequency domain techniques. The use of nonlinear control techniques was very educational for me and represented an opportunity to study solutions for several control challenges.
During my university studies, I dealt also with *Analog Electronics, Digital Electronics, Embedded Systems, Optimization theory, Signal Theory and Modulation theory applied to Telecommunications, Digital Signal Processing, Stochastic Processes, and Information and Communication Technology* (ICT), *Electrical Drives and Power Electronics*.
After graduating with my master degree, I decided to apply my skills to electrical power systems, because in my opinion it is a field on which advanced and powerful control techniques find their breeding ground. With the integration of renewable energies and Power Electronic units, Power Systems become very large-scaled and complex system and they present a wide variety of control challenges. However I think that electrical power systems contains all the topics that I have dealt during my university studies, so it is a suitable field to apply the skills I have gained.
From January 2018 to June 2018 I'm involved in the HEART project at the University of Kiel, Chair of Power Electronics. This experience gives me a deeper knowledge of Power Electronics and Power Systems, also thanks to the strict collaboration with several researchers working in this field for many years. During my period in Kiel, besides learning much about electrical systems, I realized that my skills in control engineering could be very useful in the field of power system and power electronics. Moreover, often the skills are complementary to the skills of electrical engineers and for this reason through a strict collaboration, it is possible to give innovation thanks to the fusion of different skills and points of view.

Cooperation and knowledge pool

It is planned to stay for the major time of the work at CAU Kiel and for a period of six month at Aalborg University (AAU). In the following the competences and the expected benefits are described.

<u>Hosting institute CAU Kiel, Chair of Power Electronics, Prof. Marco Liserre</u>

From more than 15 years Prof. Marco Liserre, now head of the chair of power electronic at the Christian-Albrecht-University, is dealing with power systems and renewable energy generation systems, especially wind energy and photovoltaic energy. He has published more than 400 papers and collected more than 23.000 citations.

One of the most prestigious projects of the chair is the European consolidator grant for research on the "*Highly Efficient And Reliable smart Transformer*" (HEART), a new heart for the Electric Distribution System". It investigates the concept of the Smart Transformer for the distribution grid, designed to manage and control the LV grid and to provide services.
In the BMWi (Bundesministerium für Wirtschaft und Energie) funded project "*Analysis of the electrical characteristics of medium-voltage grids regarding the optimization during high energy input from wind energy systems*", the team of the PE chair is analysing the behaviour of the medium-voltage grid. A measurement system is designed and implemented to analyse grid impedance and also harmonics. This characterization is closely related to the varying grid conditions and potentially occurring harmonic instability. Local companies involved in this work are the Senvion SE, Moeller Operating Engineering, WSTECH, GL Garrad Hassan Deutschland and the EON Hanse AG.
In the "Add on" project, the chair is continuing the BMWi project described before with controller design targeted at active filtering of harmonics in the grid. This project carried out in cooperation with the local companies WSTECH.
The projects described before are closely related to the topic of this application and continues the work in the aspect of harmonic instability. The chair of power electronic with a team of about 20 researchers is highly reputed in the community and a tight cooperation is arranged to ensure the project success.

<u>Hosting institute AAU, Institute for Energy Technology, Prof. Frede Blaabjerg</u>

With almost 2000 publications and more than 70.000 citations, Prof. Frede Blaabjerg is the most recognized researcher in power electronics worldwide. He is leading one of the worldwide most recognized institutes in power electronics and he received several awards for his work.
One of the most prestigious projects at his institute is the Harmony project, which deals with harmonic stability in the electrical grid. The goal is to obtain "Harmony" between renewable energy sources, the power system and the loads in order to keep stability in all aspects seen from a harmonic point of view, which is an urgent need due to the fast growth of power electronic based generators, and loads. z

Milestones and Project Plan

Research Step	Duration months
(a) Theoretical fundaments and literature research	**5**
○ (1)Review of power converters modelling and control strategies	2
○ (2)Review of MicroGrid modelling and control strategies	1
○ (3)Review of robust control and output regulation methods	1
○ (4)Review of time delay system control theory	1
(b) Modelling and Linear Control of AC MicroGrid	**15**
○ (1)Modelling of converters interactions	1
○ (2)Modelling of frequency coupling	2
○ (3)Modelling of computational and transmission delays	1
○ (4)Linear state-space control with observer	4
○ (5)Construction of an experimental set-up and validation	4
○ (6)Implementation and tuning of the linear control system	3
(c) MicroGrid expansion and advancer control design	**15**
○ (1)Inclusion and modelling of DC resources in the MicroGrid	2
○ (2)Optimal and robust linear control for parameter variations	2
○ (3)Application of time-delay control theory	2
○ (4)NonLinear control: Feedback Linearization and Sliding Mode	4
○ (5)Nonlinear observer design for parameter estimation in presence of noise	2
○ (6)Implementation and tuning of nonlinear methods	3
(d) Comparison between traditional, linear and nonlinear methods	**1**

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