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

Chair of Power Electronics

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Motivation

The attainment of a more sustainable, clean, and carbon-neutral energy supply is one of the great challenges of the 21st century. The German government has planned a long-term roadmap up to the year 2050 for the progressive transition from fossil- and nuclear-based power plants to an environmentally sound renewable energy generation. This energy transition process, denominated *Energiewende*, requires significant investments and the collaboration of political institutions, industries, and academic research institutes.

In geographic areas such as Schleswig-Holstein, the potential of wind energy generation is highly appealing. The increasing penetration of wind energy in the grid changes the concept of power generation from centralized to distributed: this change of paradigm brings new challenges for the grid stability, which requires novel power system modeling techniques to be investigated.

Besides the modeling, which allows to have a deeper insight in the grid dynamics and stability problems, stabilization strategies have to be investigated in order to address the detected problems. Wind energy resources are interfaced with the grid through power electronics-based converters. The power converters have the feature to be highly flexible in the control of the power injected into the electric grid; that makes them suitable to offer, in addition to the fundamental current injection, also ancillary services to the grid which contribute to address the power system stability and enhance the power quality. Among them, active damping has been investigated in the context of this project.

Active damping is the capability of the power converter to damp the power system oscillations due to small disturbances. Several incidences have been reported were resonances in power electronics units caused the disruption of the power supply. Active damping exploits the high flexibility of control of power converters, and modifies the control loops in order to mitigate the grid resonances and enhance the stability.

Wind turbines are usually interfaced to the grid through power electronics converters, and active damping solutions for them have been investigated in the context of this project. However, active damping strategies can be potentially implemented not only on wind turbines, but in each device based on power electronics energy conversion. Nowadays, power electronics devices are progressively becoming the main actors in the modern electric grids. The Smart Transformer, investigated in the context of this project, is a power electronics-based transformer which presents a wide number of advantages with respect to the traditional transformer, among which the possibility to implement active damping strategies. In this case, the damping action can be applied directly in the Point of Common Coupling, which represent a great advantage of using the Smart Transformer respect to the traditional transformer. The damping potential of the Smart Transformer has also been investigated in the context of this project.

Obtained Results

This section elaborates on the results obtained in this project in the context of power system modeling and power converter active damping. Afterwards, an application of active damping technique in the Smart Transformer is discussed.

Power System Modeling

The main challenge in power system modeling is the high number of dynamics involved in the power converter and the fact that they are coupled. The interaction among the synchronization unit, such as the phase-locked loop (PLL), the ac voltage control and the dc voltage control in weak grid conditions is very prominent and can be responsible of instability phenomena [1]. A modeling approach of a power converter with its control system based on differential equations have been proposed in [1]. This model has been used to study the control loops interaction to have a deeper insight in the instability phenomena. In Fig. 1, the eigenvalue analysis has been used to study how the converter dynamics changes when the ac and dc voltage control gains change. The main result is that both the control gains are able to move the eigenvalue, but on different directions. By changing the ac voltage proportional gain, the eigenvalue moves along the blue arrow, while by changing the dc voltage it moves along the green arrow. Therefore, the position of the eigenvalue depends on the combination of both the dc voltage control gain and the ac voltage control gain, not only one of the two, highlighting the coupling mechanism.

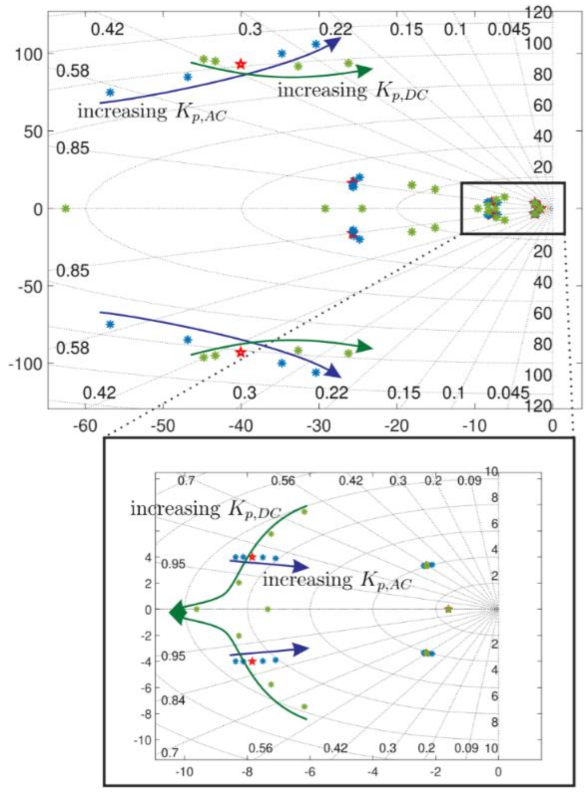

Figure 1: The interaction between ac voltage control and dc voltage control, studied through eigenvalue analysis

The accuracy of the proposed model has been demonstrated by experiments in the lab, as shown in Fig. 2. The waveforms obtained in simulation show a good faithfulness with the ones obtained in the lab.

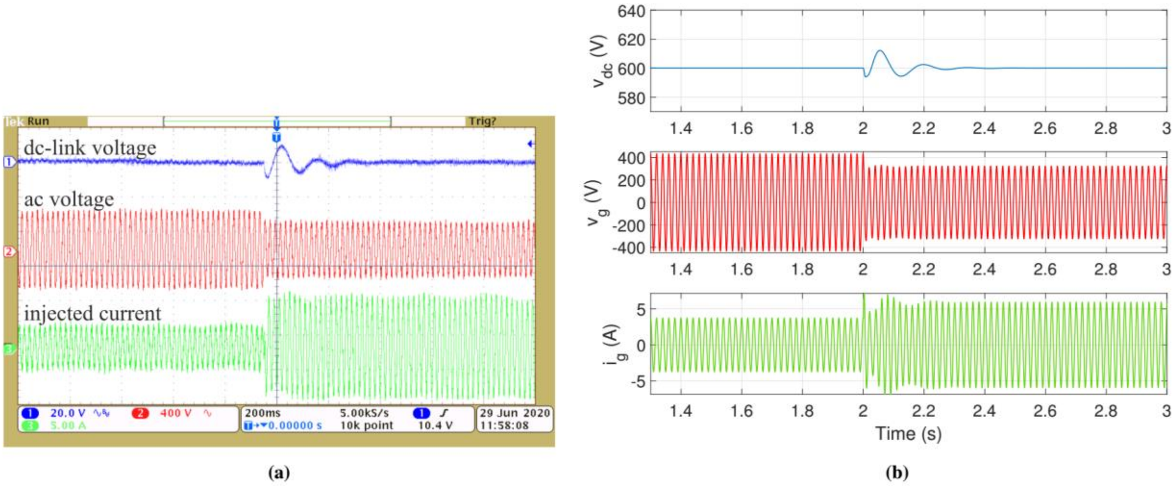

Figure 2: The proposed model validation under a voltage sag. (a) The experimental model built in the lab. (b) The proposed model in simulation

Power Converter Active Damping

In the term active damping, the word *active* refers to the fact that the damping action is realized through software, thus through appropriate control algorithms, in contrast with passive damping techniques where dissipation elements, such as resistors, are added to the circuit to damp the oscillations. The proposed control strategy for the active damping is highlighted in orange in Fig. 3. A feedback from several variables of the converter is applied as current reference of the converter current control. The application of this feedback is able to damp the system oscillation in the low frequency.

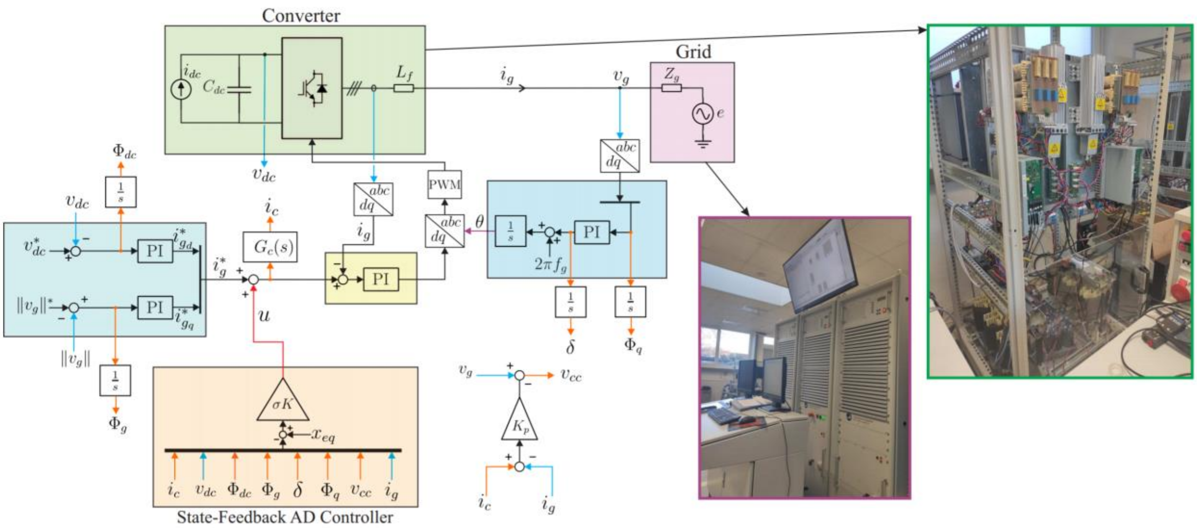

Figure 3: The proposed active damping control strategy and its implementation in the experimental setup.

The parameter σ is used in the control law to regulate the damping strength. The performances of the proposed active damping are evaluated in the experimental results shown in Fig. 4. It is clear from the results that with increasing damping strength, the oscillation of the dc voltage decreases in the amplitude. However, when the damping strength is too high, the converter output current increases very fast.

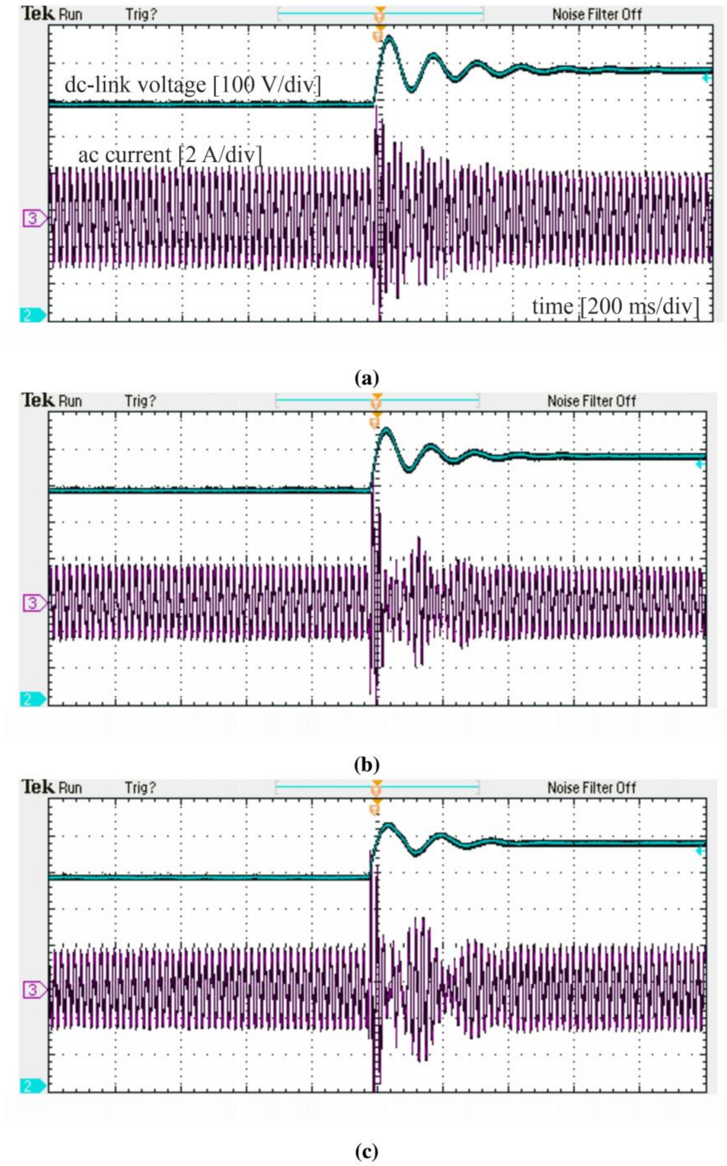

Figure 4: The experimental results of the proposed active damping with a step in the dc voltage. (a) Without active damping, (b) with active damping with modest strength, (c) with active damping with high strength.

Smart Transformer Modeling and Active Damping

The Smart Transformer is a power electronics-based transformer which can control the power flow from medium voltage to low voltage [3]. It is classified in Fig. 5 as grid forming converter, since it can form and control the grid voltage and frequency, differently from grid feeding converters, which synchronize with the main grid and inject power into that. Being the Smart Transformer based on power electronics converters, it can implement all the ancillary services discussed before, such as active damping. In this project, a proposed control strategy for active damping is implemented in the Smart Transformer in order to damp oscillations dangerous for the stability.

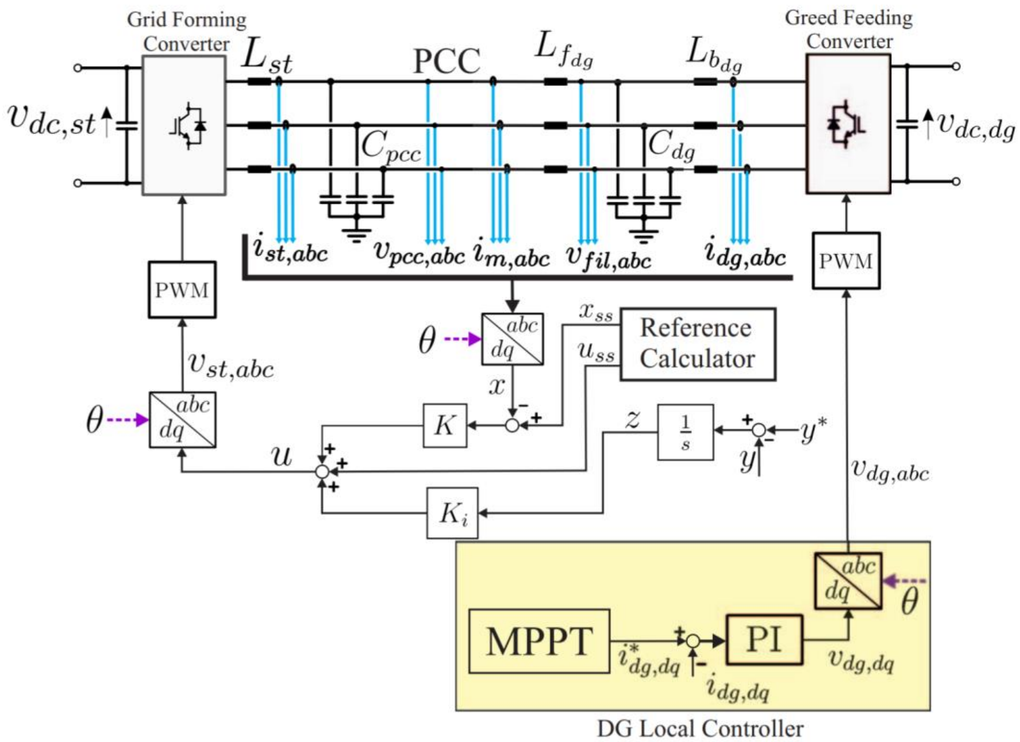

Figure 5: State-feedback based active damping of a Smart Transformer-based distribution grid

The results from the proposed control can be seen in Fig. 6. In presence of converters with high current control bandwidth, a voltage step in the Smart Transformer can result in instability, as shown in Fig. 6(a). However, the use of active damping in the Smart Transformer can eliminate the oscillations, resulting in a smooth voltage and current profile.

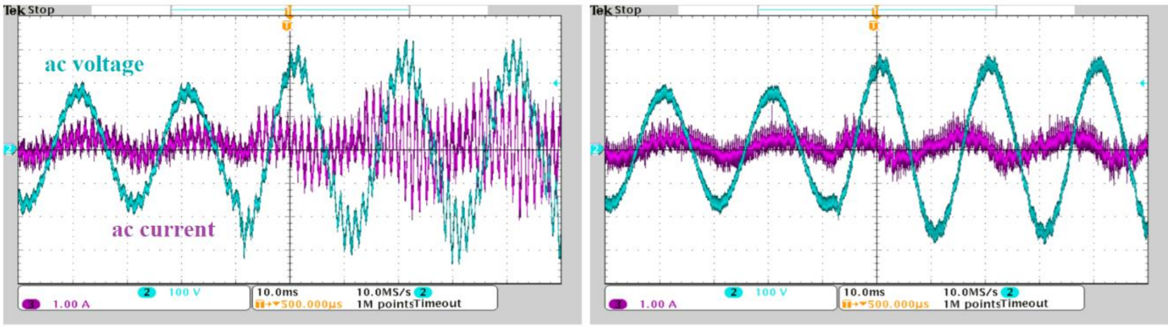

Figure 6: Experiments of a Smart Transformer voltage step. (a) Without active damping, (b) with active damping.

Collaborations with other Institutions

During the three years of the scholarship, a strict collaboration with the Department of Energy Technology of Aalborg University has been established. Aalborg University is an important research centre in the field of renewable energy, which host every year researchers from different universities around the world. It is a good place to present his own project and research topic to make it known and receive feedback from the international scientific community.

In the summer of 2018, in the first months of the scholarship, the project was presented in Kiel University to two professors of Aalborg University, Prof. Xiongfei Wang and Prof. Frede Blaabjerg, who agreed to collaborate in this project. The partnership with Aalborg university was carried on by doing periodical online meetings for the whole period of the scholarship. On September 2020, I was hosted by Aalborg University for a period of six months, in order to strengthen the professional relationship, and continue the research using also the laboratory equipment of the Department of Energy Technology.

Conclusions

In the context of this project, dynamic modeling techniques and control strategies for power converters to enhance the stability have been investigated. At first, a modular modeling methodology for a renewable energy-based grid has been developed. The obtained model allows to study the stability and the dynamics behaviour of the power grid. Afterwards, an active damping control strategy to mitigate the low frequency oscillations in the grid has been proposed and tested in an experimental setup. The developed modeling techniques have been used to study the dynamic behaviour of the proposed active damping control, and to highlight its benefit for the system stability. The modeling and control of the Smart

Transformer have also been investigated, proposing active damping solution implemented in the low voltage side converter.

The research done in this project focussed on finding new methodologies for the power systems modeling and control. The investigated methodologies have been applied to a limited number of cases, with the aim of assessing their validity. However, these strategies can be easily extended to other interesting cases, so far not considered in this research. As an example, the proposed modelling methodology can be also used to model electric vehicles charging stations, and analyse their impact on the electric grid stability and their interactions with other renewable energy sources connected to the grid, such as wind turbines. Moreover, the proposed active damping solutions for wind power converters can be easily extended to Photovoltaic systems, electric vehicles charging stations and flexible alternating current transmission systems.

This project brought at the actual state three published conference papers, and other two conference papers which have been accepted but still not published, therefore they are not mentioned in this document. The published conference papers are going to be submitted soon to scientific journals. The work about power system modelling have already been extended and submitted to a journal, and it is under review. The work about power converter active damping has been extended with stronger theoretical background, and more experimental results with the use of a Hardware-In-the-Loop system; its submission to journal is planned for September 2021. After the submission of these journals, the PhD thesis will be written, and its defence will be presumably held in 2022.

I would like to thank very much the Gesellschaft für Energie und Klimaschutz Schleswig-Holstein GmbH (EKSH) for supporting this project on emerging as well as important topics in the field of renewable energies. Furthermore, I would like to thank the whole staff of EKSH for creating a friendly, cosy and engaging environment among all the researchers.

Publications

[1] F. Cecati, R. Zhu, M. Langwasser, M. Liserre and X. Wang, "Scalable State-Space Model of Voltage Source Converter for Low-Frequency Stability Analysis," 2020 IEEE Energy Conversion Congress and Exposition (ECCE), 2020, pp. 6144-6149, doi: 10.1109/ECCE44975.2020.9236020.

[2] F. Cecati, R. Zhu, M. Liserre and X. Wang, "State-feedback-based Low-Frequency Active Damping for VSC Operating in Weak-Grid Conditions," 2020 IEEE Energy Conversion Congress and Exposition (ECCE), 2020, pp. 4762-4767, doi: 10.1109/ECCE44975.2020.9235338.

[3] F. Cecati, M. Andresen, R. Zhu, Z. Zou and M. Liserre, "Robustness Analysis of Voltage Control Strategies of Smart Transformer," IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society, 2018, pp. 5566-5573, doi: 10.1109/IECON.2018.8591116.