This paper was presented at the 20th Wind Integration Workshop and published in the workshop's proceedings

Grid Forming Converters in Interconnected Systems - Final Results from the Joint Research Project VerbundnetzStabil

Soenke Rogalla
Fraunhofer ISE
Freiburg, Germany
soenke.rogalla@ise.fraunhofer.de

Andreas Greulich
KACO new energy
Neckarsulm, Germany
andreas.greulich@kaco-newenergy.de

Joachim Lehner
TransnetBW
Stuttgart, Germany
J.Lehner@transnetbw.de

Hendrik Lens
IFK, University of Stuttgart
Stuttgart, Germany
hendrik.lens@ifk.uni-stuttgart.de

Philipp Ernst
Fraunhofer ISE
Freiburg, Germany
philipp.ernst@ise.fraunhofer.de

Thomas Schaupp
TransnetBW
Stuttgart, Germany
T.Schaupp@transnetbw.de

Roland Singer
Fraunhofer ISE
Freiburg, Germany
roland.singer@ise.fraunhofer.de

Jakob Ungerland
Fraunhofer ISE
Freiburg, Germany
jakob.ungerland@ise.fraunhofer.de

Christian Schöll
*IFK, University of Stuttgar*t
Stuttgart, Germany
christian.schoell@ifk.uni-stuttgart.de

Rebekka Denninger
Fraunhofer ISE
Freiburg, Germany
rebekka.denninger@ise.fraunhofer.de

Ammar Salman
Fraunhofer ISE
Freiburg, Germany
ammar.salman@ise.fraunhofer.de

***Abstract*— When integrating grid forming converters (GFC) into the power system, it is not just a matter of replacing the converter's current controller with a voltage controller; all aspects of power system dynamics have to be considered in order to design a suitable behavior of GFC. This is necessary in order to fully replace the grid forming and grid stabilizing properties of synchronous generators with converters. Within the joint research project *VerbundnetzStabil* the partners KACO new energy, TransnetBW, University of Stuttgart and Fraunhofer ISE investigated the stability of interconnected power systems with a high penetration of converters over the past four years. This paper summarizes the work of the project team and their major findings.** **Keywords— grid forming converters; converter control; power system stability; converter based generation**

I. INTRODUCTION

From a system perspective, it was already known at the beginning of the *VerbundnetzStabil* project that converters would play a decisive role in the stability of future power grids. In addition, extensive experience with voltage-controlling converter concepts for converter-based microgrids was already available. The project partners formed a one-of-a-kind consortium combining both profound know-how in dynamic grid control and in-depth knowledge in power electronics. With this starting point, the partners combined their expertise and began their work of defining and evaluating suitable converter control concepts that can ensure reliable and stable grid operation at all times without relying on the presence of synchronous generators. Years of collaboration have resulted in a deep understanding of the interaction between converter control and the dynamic behavior of interconnected power systems as well as of what is commonly known as grid forming converter today.

The project's major findings are presented in this paper according to the following structure: Section II summarizes the principal requirements for GFC from a grid perspective. Section III describes the converter demonstrator and grid forming control that was developed within the scope of the project. Section IV provides an insight in the testing activities that were performed to evaluate GFC behavior in different grid scenarios on a megawatt scale. Section V addresses the challenge of reducing detailed distribution network models containing GFC for the purpose of power system stability studies. Finally, section VI discusses the influence of GFC on power system stability and its analysis.

It should be mentioned that this paper can only give a rough overview of the project results. More detailed information can be found in the final project report, which will be published in early 2022.

II. PRINCIPAL REQUIREMENTS FOR GFC FROM AN INTERCONNECTED GRID PERSPECTIVE

In order to ensure stable system behavior in future interconnected power systems with very high penetration of converter-based generation, the grid forming contribution of synchronous machines has to be substituted. The most promising path to supersede synchronous machines (SM) is the partial replacement of today's state-of-the-art current controlled concepts of converter-based generation, storage devices, and load with grid forming control concepts. While several of such concepts have been successfully applied in the context of microgrids, their application in large interconnected power systems requires:

- specification of the conditions under which a converter is considered to be „grid forming“,

---

The work presented here was supported by the German Ministry for Economic Affairs and Energy (project VerbundnetzStabil - FKZ 0350015A-D).

- specification of the behavior of GFC under emergency conditions (e.g., over-current limitation) and related boundary conditions for dimensioning GFC,
- evaluation of the system needs, i.e. which share of GFC is required,
- quantitative and verifiable criteria that express the grid forming contribution (e.g., inertia time constant).

In general, GFC have to fulfill the following fundamental requirements: In the first instance they have to act as a stiff AC voltage source behind an impedance. In a second step, the angle, frequency and amplitude of the fundamental component of that voltage are allowed to change, but with a slow dynamic response. The requirements related to this transition phase between the instantaneous response and the steady-state behavior have to be well defined based on RMS-values, both with respect to active and to reactive power.

Similar as for SM, this property has the consequence that GFC provide an instantaneous reaction of their current (and subsequently of active and reactive power) following any event in the power system, such as voltage faults, phase jumps or active power imbalances. However, different from SM, converters are not capable of providing currents significantly beyond their nominal current. Hence, GFC have to control their output voltage in such a way that the power electronics are protected from harmful over-currents. While limiting currents, the contribution of GFC to the fundamental requirements mentioned above is reduced or may even cease completely. Therefore, in case of grid faults leading the GFC to limit currents, it is of utmost importance that the control temporarily transfers the converter to a different operating point at which the converter is able to provide grid forming properties based on the requirements mentioned above again. However, the GFC should return to its original operating point as soon as the situation in the grid allows for it, i.e. as soon as it does not require current limiting anymore, for example after clearing a fault.

The implementation of the GFC determines the instantaneous reaction and its transition towards the steady-state behavior (based on set-points generated by top-level controllers such as voltage control, reactive power control, or load frequency control). It makes sense to differentiate the transition behavior by an active and a reactive part. The active power transition behavior covers the adjustment of the phase angle (and the frequency) of the converter voltage, being directly related to the specification of inertia (e.g. swing equation with inertia constant H). The reactive power transition behavior covers the adjustment of the amplitude of converter voltage (e.g. using a voltage droop).

It is the responsibility of transmission system operators (TSO) to identify the system needs for GFC. Within the interconnected power system of continental Europe, system splits were identified as the determining contingency for the minimum ratio between grid forming and grid-following controlled generation. Analysis of the four German TSOs yielded that a minimum share of synchronous machines or GFC is needed to cover relevant system split scenarios in the future [10].

III. GFC IMPLEMENTATION ON A REAL CONVERTER PLATFORM

One focus of the project *VerbundnetzStabil* was the development of a voltage control concept with an outer power control loop and an inner current limitation loop. The controller was then implemented on a 50kVA battery converter platform of the type *blueplanet gridsave 50.0 TL3-S* from KACO new energy.

The voltage control concept includes, in addition to the voltage controller, a virtual impedance. This is necessary to operate the converter even at strong grid connection points, as well as to influence the ohmic inductive ratio. The power control is based on droop control. However, a characteristic of the droop control concept is the provision of an active power response that is proportional to the change of frequency. However, in some cases this behavior may not be desired. Therefore, the developed controller was enhanced so that it does not exhibit a steady-state response to frequency deviations. Since the basic droop control concept has some drawbacks regarding the current limitation, additional functional features were added that prevent possible loss of grid synchronism even during severe grid faults and maintain the voltage source behavior in such cases.

The result is a grid forming control which contributes to system strength and power quality, provides inertia and remains stable under any grid disturbances with or without reaching the current limit.

IV. LAB-BASED GFC-TESTING ON A MEGAWATT SCALE

A. *Procedure for Testing General GFC Properties*

An essential step to validate GFC is to agree on an exact definition and specification of their electrical behavior as well as to define a suitable conformity assessment procedure. For converters that can be tested in a laboratory, a standardized testing guideline for GFC is needed to evaluate the relevant requirements. Thus, Fraunhofer ISE, KACO new energy and University of Stuttgart teamed up with partners from the British project *Battery VSM* to work on a first draft for a testing guideline. The tests are designed in a way that the converter is considered as a black box in order to avoid unwanted constraints regarding the control strategy used.

In addition to the fundamental requirements described in Section II, the testing guideline suggests clustering the testing of GFC into four groups (Fig. 1): voltage source properties, power quality, inertial response and overload behavior [4].

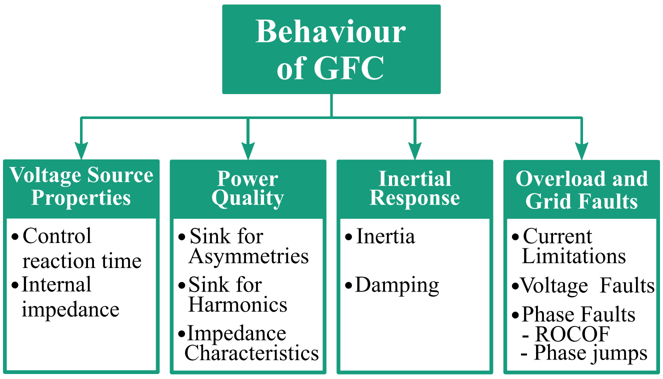

Fig. 1 Structure of the guideline for testing GFC

The test for the voltage source property determines the dynamics of the voltage control as well as the internal impedance. These characteristics are important as the GFC is considered as a voltage source behind an impedance.

The power quality requirement can be derived directly from the voltage source behavior since it is considered as a sink for harmonics and asymmetries. Thus, in case of an asymmetric voltage, it must be verified that the GFC provides a current counteracting these asymmetries. In addition, it must be tested within which frequency range the converter can provide harmonic current to counteract harmonic voltage distortions [5].

As the first two properties are primarily related to the instantaneous behavior of the voltage source, the inertial response focuses on the dynamic response of the voltage source based on RMS values. Thus, the ability of a GFC to provide inertial response and damping has to be demonstrated. As the GFC behavior does not rely on physical properties there is a possibility that inertial response can differ regarding different grid events (e.g. phase jumps, RoCoF). Therefore, multiple tests must be carried out [6], like a voltage phase jump or an islanding test.

The last part of the testing guideline deals with the limited over-current capability of the converter and the related issues such as loss of grid synchronism. The current shape during the current limitation as well as the overall dynamics have to be evaluated [7].

B. Emulation Grid Scenarios

Besides the testing of the fundamental properties of GFC, their behavior in parallel operation and its impact on the stability of the interconnected power system is of great interest. Therefore, in the project typical grid events were scaled down to a megawatt scale in order to perform according tests in the lab.

During the test campaign, twelve converters from KACO new energy with either grid forming or grid following control were used. Two different MV transformers were used for the connection to the grid, each connecting a cluster of six converters. For the test of the interaction between converters and synchronous generators (SG), a diesel genset with a nominal power of 100 kVA was used. The genset was connected to the grid via its own transformer. The load of the system was represented by an ohmic-inductive load bank with a nominal power of 1.85 MVA at a power factor of 0.8. The load was connected to the grid via a fourth MV transformer. Furthermore, two separate fault ride through (FRT) test facilities at medium voltage were available for the tests. These were used to test the FRT behavior of GFC devices as well as combinations of GFC, SG, grid following converters and the load. Moreover, the grid side impedances of the FRT test facilities were used to emulate the line impedance in various grid scenarios. In Fig. 2 the test setup is shown. As one can see, up to two grid nodes on MV side could be realized in this setup, by separating them using the impedances of the FRT facilities. The four transformers could be connected to either of these nodes in order to realize different grid operation scenarios.

For the tests, the following relevant grid scenarios were selected, considering normal operation of GFC as well as fault situations

- active and reactive load changes in grid-connected configuration
- active and reactive load changes in island grid configuration
- over- and under-voltage events
- phase jump events
- system split event

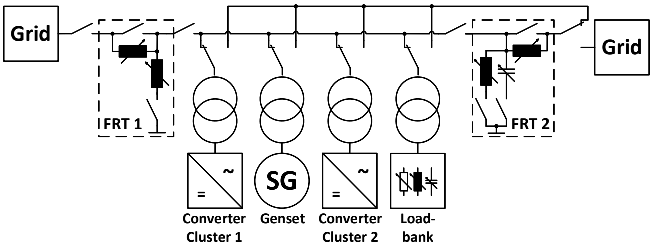

Fig. 2 Test setup during the measurement campaign.

During the tests, the ratio between converter-based and SG-based generation was changed by connecting further converters to the grid. The share of grid forming to grid following converters was varied by changing the control software of the converters.

For downscaling the grid scenarios, not only voltage and power were modified accordingly but also the impedances were chosen such that the phase angle differences over lines are comparable to those observed in typical operation scenarios of transmission grids.

Fig. 4 shows an exemplary measurement result of a phase jump test in a two-node setup. The phase jump was induced by connecting a load at the first node (cf. Fig. 3). In each cluster only one converter (GFC) was in operation, both with an active and reactive power set point of zero. The load step resulted in a phase jump of -0.1° for node 2 and -0.5° for node 1. Both converters react with an active power counteracting the phase jump (cf. Fig. 4). The reaction is similar to a synchronous generator.

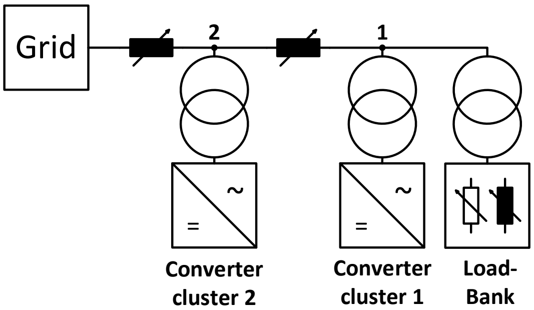

Fig. 3 Exemplary test setup for the described phase jump test case.

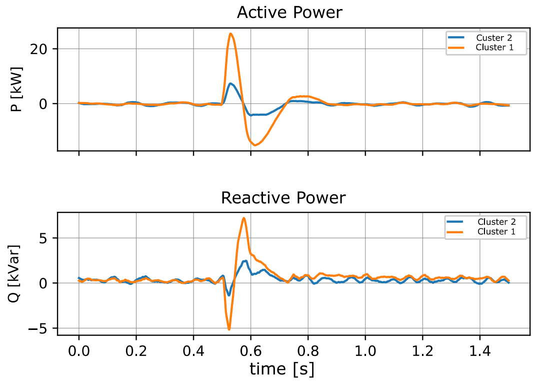

Fig. 4 Active and reactive power of two converters connected to different nodes during a phase jump event.

V. GFC Consideration in Equivalent Distribution Network Models

The increasing importance of generation in distribution systems necessitates a proper representation of distribution networks in grid models for stability analysis. However, generally the distribution system is not of particular interest for the study. For this reason and because of a high computational effort and insufficient data availability, detailed distribution network models may be substituted with an equivalent model. Stability analysis focuses on the transmission system in which the relevant faults occur. Therefore, the transmission system is modeled in detail. Previous work [1] elaborated the suitability of gray-box parameter identification methods for capturing the dynamic response of converter dominated networks in corresponding dynamic equivalents. However, with the introduction of GFC, new challenges arise for the compiling equivalent dynamic models [2].

The dynamic behavior of GFC is highly dependent on the electrical grid's strength at the GFC's point of common coupling (PCC) and the electrical distance to the fault location. Voltage sensitivities at the PCC of the GFC in the detailed network are a suitable measure for considering these factors in an equivalent network model. The proposed method for obtaining an equivalent network model considering GFC can be sketched as follows: First, the nodes of the detailed network are clustered by voltage level, generation technology, and control strategy. The loads and grid following converter-based generators then are aggregated according to the clusters and connected to one equivalent node, which is coupled to the system of interest by an equivalent transformer and the boundary bus. Finally, each GFC of the detailed model is represented by an individual GFC connected to the equivalent node with an impedance. The parameters of these impedances are tuned to achieve the same voltage sensitivities at the PCC of the equivalent GFC compared to the detailed network. Moreover, an additional slack load is used so that the static power flow at the boundary bus of the equivalent model matches the one in the detailed model.

The performance of the proposed method is illustrated by simulation results in the following. As a test network model, a 10 kV radial distribution network of the open-source tool DINGO [3] is used. The total load is 40 MW and 10 Mvar. 99 % of the load is covered by converter-based generation and 60 % is generated by six distributed GFC. The external grid is modeled as a voltage source connected to the distribution network with a transmission line of 50 km length. The voltage source induces a voltage angle step of 10 degrees, representing a fault at t = 0 s. In Fig. 5 the active power flows at the boundary buses both of the detailed and equivalent network model are shown. As the figure shows, the response of the equivalent model is very close to the one of the detailed model, while the equivalent model consists of only 7 nodes (detailed model: 195 nodes). Additionally, simulation time of the equivalent model was reduced by 97.3 % compared to the detailed simulation. This exemplary simulation can be conducted for other faults, e.g., frequency changes or short-circuit faults, with similar results. Hence, the proposed method appears to be very well suited to create equivalent network models capable of capturing the detailed network's dynamic behavior.

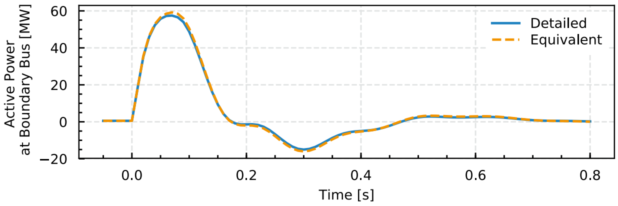

Fig. 5 Active power at boundary bus of detailed and equivalent network model after a 10 degree phase angle step

VI. Influence of GFC on Power System Stability

Even though GFC are controlled in such a way that they mimic essential properties of SM, they are fundamentally different from a hardware perspective. Instead of a voltage source that is based on the induction by a rotating magnetic field, the AC voltage is created by fast switching of power electronic devices at frequencies of several kHz, depending on the type of power electronics used and on the configuration of the converter. In order to analyze the behavior of single GFC, detailed models have been created in the research project *VerbundnetzStabil*. They are able to reflect the real behavior of the GFC implementation used in the project with a very high level of detail.

However, the complexity of such models prohibits their use in the context of power system studies. Hence, the question arises how GFC should be modeled in this context. Simplifications are required in order to obtain models that can be used as sub-models of large power system models. However, these simplifications need to be adequate in the sense that they should not lead to different conclusions.

Two common simplifications are a) the use of an average value model (AVM), meaning that the output voltage of the converter is a continuous value, ignoring high frequency switching of the power electronics and b) the assumption that the DC voltage is constant, corresponding to the simplification that an infinite, or at least appropriately dimensioned, energy storage capacity is available for each GFC. Both are considered as reasonable assumptions in the context of power system stability studies.

A further simplification commonly used for such studies is the representation of voltages as phasors in a suitable rotating coordinate system (usually Park coordinates). This representation usually is denoted as “RMS”. A key advantage of RMS-models is that the phasor variables (angle relative to the reference coordinate system and amplitude) change much slower than the physical values. Hence, the simulation of the model can be performed with significant less computational effort. Phasor based modeling is justified if all system voltages are nearly sinusoidal, i.e. for SM, grid following converters in strong grids and GFC that are operating in grid forming mode.

However, this is not true for the case of GFC with active current limiting, as the voltage provided may not be sinusoidal anymore and is not represented adequately by a phasor. However, the effect of current limits on system stability may be significant, as shown in [4, 5]. The same is true for grid following converters in weak grids, where instability may arise from interactions between controls and grid voltage at frequencies other than the fundamental frequency. For this reason, EMT (electromagnetic transient) models, which do not represent voltages and currents as phasors but rather use their instantaneous physical values over time, of a power system of limited complexity were developed in the project in order to validate simulation results obtained with RMS models and to further evaluate the effects of dynamics that are not adequately modeled in RMS simulations.

The transmission system simulations in the research project were performed using a benchmark network model of the transmission system of the German federal state of Baden-Württemberg. The simulations consider islanding of the benchmark network model while having an export surplus of 30 %, which leads to a strong increase of the system frequency.

The maximum RoCoF that occurred in the simulations are shown in Fig. 6. The share of SM, GFC and grid-following inverters were varied in 10 % steps. On the basis of the maximum RoCoF, the minimum share of SM or GFC is derived by means of a maximum permissible RoCoF of 2 Hz/s. For this purpose, the RoCoF was determined over a moving 500 ms window. The results show that, unlike SM and GFC, grid-following converters do not contribute to power system inertia. Therefore, higher shares of grid-following converters with today's control concepts led to greater RoCoF. In conclusion, the simulation-based investigations to determine the necessary minimum share of grid-forming contributions, i.e. either by means of SM or GFC, suggest a minimum percentage of 40-50 % based on the evaluation criterion mentioned above.

Depending on the specific grid situation, especially in the case of a weak grid connection of grid following converters, oscillatory instabilities may occur even with a higher proportion of grid forming contributions. Therefore, this result should only be interpreted as an approximate guideline and is no substitute for an assessment of individual grid situations.

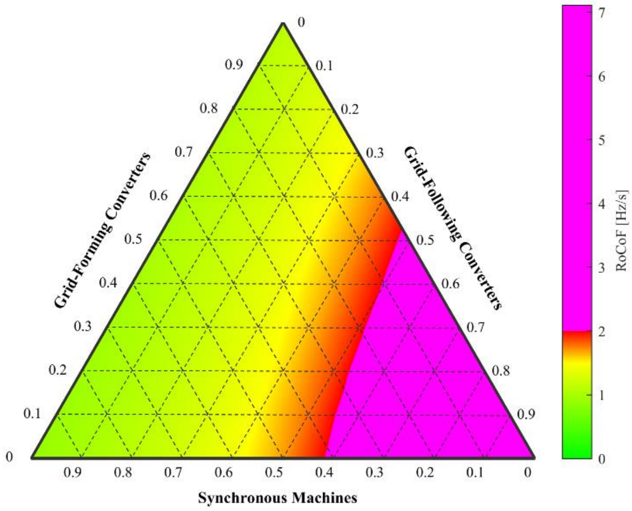

Fig. 6 Ternary diagram with maximum RoCoF for different shares of synchronous generator-, grid-following- and grid-forming-based generation after a 30 % export loss.

VII. SUMMARY AND OUTLOOK

Strong expertise in grid control and deep knowledge on power electronics enabled the partners of the *VerbundnetzStabil* project to elaborate principal requirements for GFC from a system perspective and based on given converter capabilities. Relevant aspects were addressed, such as the instantaneous current response on sudden grid events including overload performance as well as well-defined behavior during transition phase towards a new quasi-stationary operational point of the GFC. These findings formed the basis for the development and implementation of a new GFC control algorithm on a KACO converter platform. The proper behavior of this GFC prototype was demonstrated by intensive lab tests on a megawatt-scale. For this purpose, specific test scenarios were defined that allow to assess the adequacy of the behavior of GFC in normal and emergency grid situations. Finally, the consortium developed simulation strategies to investigate power system stability issues under the consideration of GFC integrated in transmission and distribution grids.

In conclusion, it can be summarized that the *VerbundnetzStabil* project contributed to a much better understanding of power system stability with very high share of converter-based generation over the past four years. Thus, the fundamentals of interactions between the grid and converters, which are relevant for a stable grid operation, are well understood. For the future, more field testing of GFC in the networks is recommended to gain more experience in parallel operation with the grid.

REFERENCES

[1] M. F. Valois-Rodriguez and J. Ungerland: Evaluation of Grid Reduction Techniques for Distribution Networks with a High Penetration of Inverter-based Generation. In *2020 IEEE PES ISGT-Europe*, pages 824-828, 2020.

[2] J. Ungerland and P. Pant: Challenges of Modelling Equivalent Active Distribution Grids under Consideration of Grid Forming Inverters. In *Conference Proceedings of the 19th Wind Integration Workshop*, 2020.

[3] J. Amme, G. Pleßmann, J. Bühler, L. Hülk, E. Kötter, and P. Schwaegerl: The eGo grid model: An open-source and open-data based synthetic medium-voltage grid model for distribution power supply systems. In *Journal of Physics: Conference Series*, volume 977, 2018.

[4] M. Kersic, T. Müller, R. Denninger, P. Ernst, S. Reichert, R. Singer, A. Dýsko, A. Egea Alvarez, Q. Hong, E. Lewis, A. Roscoe, H. Lens, C

Schöll, T. Schaupp, and K. Jalili: Testing characteristics of grid forming converters part I: Specification and definition of Behavior. In *Conference Proceedings of the 19th Wind Integration Workshop*, 2020.

[5] R. Denninger, S. Reichert, S. Rogalla, and K. Jalili: Testing characteristics of grid forming converters part II: Voltage Source Properties and Contribution to Power Quality. In *Conference Proceedings of the 19th Wind Integration Workshop*, 2020.

[6] A. Dýsko, A. Egea Alvarez, Q. Hong,A. Khan, P. Ernst, R. Singer, and A. Roscoe: Testing characteristics of grid forming converters part III: inertial Behavior. In *Conference Proceedings of the 19th Wind Integration Workshop*, 2020.

[7] R. Singer, P. Ernst, R. Denninger, and K. Jalili: Testing characteristics of grid forming converters part IV: Overload Behavior and Response to Grid Faults. In *Conference Proceedings of the 19th Wind Integration Workshop*, 2020.

[8] C. Schöll and H. Lens: Instability Phenomena in Interconnected Power Systems Caused by Current Limitation of Grid-Forming Converters. In *Conference Proceedings of the 19th Wind Integration Workshop*, 2020.

[9] C. Schöll and H. Lens: Impact of Current Limitation of Grid-forming Voltage Source Converters on Power System Stability. In *IFAC-PapersOnLine* 53.2 (2020): 13520-13524, 2020.

[10] T. Hennig, J. Lehner, J. Weidner, and G. Deiml: Einfluss leistungselektronischer Betriebsmittel auf die Frequenzstabilität bei Teilnetzbildung. In *ETG Fachtagung Netzregelung und Systemführung*, 2019.