Small-Signal Analysis of Grid-Supporting Droop-Based Converter Control for Wind-Power Applications

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***Abstract*—This paper investigates the stability of the grid-supporting converter of a wind energy plant, acting as a current source with superordinate droop control. The small-signal model of a grid-side converter was extended and the movement of eigenvalues investigated. Different approaches to droop-control were compared.**

***Index Terms*—converter control, droop control, small-signal analysis**

I. Introduction

The shutdown of conventional power plants results in a lack of inertia in the power grid. Therefore, converter-connected sources and converter-connected loads have to participate in grid stabilisation. Thereby, especially wind energy plants as the primary source of renewable energy are addressed.

At the moment, scientists hold a major debate if there is a need for grid-forming converters in the European grid. Grid-forming converters have a lot of distinct advantages. They can run in weak grid conditions and even in island mode because they can self-synchronise to the grid and no Phase-Locked Loop (PLL) is needed. Most concepts help to stabilise the grid with their additional grid-supporting behaviour. Like conventional power plants with rotating masses of synchronous generators, they are theoretically able to inject active and reactive power to the grid instantaneously. Unlike grid-feeding converters need at best $20\,\mathrm{ms}$ to measure and response to grid-frequency change.

Moreover, grid-forming converters have black-start capability. In [1], a simulation study of an offshore wind park showed that around one-quarter of the installed power fed in by grid-forming converters is enough to power up the whole park. The grid-forming control is based on the idea that the machine-side converter controls the converter dc-link. However, this implies that machine-side dc-link control has to be faster than changes in the power drain of the grid side to ensure a stable system. The required energy to provide transient power is a common drawback of all classical synchronous generator-emulating control structures, e.g. [2] - [5].

Additional problems, like the current limitation, how to share the power between parallel grid-forming converters, the risk of unintended islanding and the unclear consequences of changes in "mass"-distribution from transmission level (real synchronous generator) to distribution grid (grid-forming converter), are addressed in [6]. However, there is no doubt that the grid-supporting behaviour of most participants, loads and sources, will be essential to stabilise a grid with high converter penetration.

This paper investigates the stability of the grid-supporting converter of a wind energy plant, acting as a current source (controlled with classical Voltage Oriented Control (VOC)) with superordinate droop control. On the one hand, the stability of converter control is analysed with the state-space approach and eigenvalue analysis. With the help of the participation matrix, the relevant states for every oscillation modes can be identified, and the control parameters can be optimised. It is shown that the possible gain of the droop control depends on the way the dc-link is controlled (machine-side or grid-side dc-link control). Additionally, the influence of the PLL is investigated. Because the PLL needs some time to track changes in the grid angle, the dq-system of the control and the dq-system of the grid match each other only for steady-state. The dynamical misorientation of the PLL introduces new poles, which are especially relevant in weak grids (microgrids). The theoretical results are compared with time-domain simulations in MATLAB/Simulink.

Furthermore, the influence of the suggested converter control is shown based on a reduced model of the ENTSO-E grid.

II. THEORY

A. State-Space Model of Grid-Feeding Control

VOC is the most common control structure for grid-feeding converters. It consists of an outer loop to control the voltage of the dc-link capacitor and two parallel inner loops to control active and reactive current. Control is done in dq-coordinates, which are based on the synchronisation to the grid voltage. Therefore, VOC uses a PLL to measure the grid frequency and the grid angle.

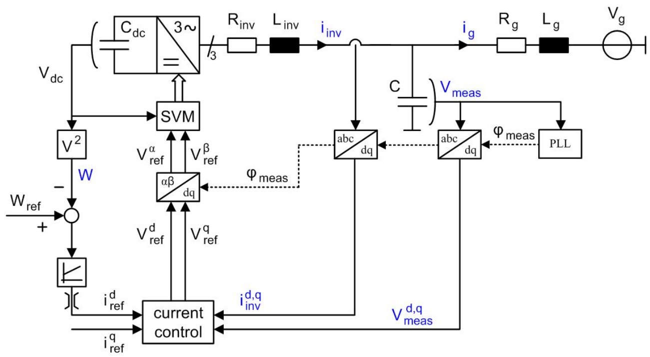

Fig. 1: block diagram of VOC

The whole system is shown in Fig. 1. The control parameters are designed by Internal Model Control [7]. In [8], a systematic derivation of the state-space model is given. The state space consists of 14 state variables: 5 of VOC, 2 of PLL, 6 of ac-side (LCL filter) and one of the dc-link. All equations are linearised around the operating point by Taylor series.

It was shown that the PLL has a massive impact on stability. The dynamic misorientation of the PLL describes the transient response of the output angle of the PLL to grid angle changes. Because the output angle of the PLL is essential for the coordinate transformation, an error can lead to small errors in converter output power or even to the instability of the control structure.

B. Droop Control of Active Power

An additional value $\Delta f \cdot k_{droop}$ is multiplied with the setpoint i^d_{ref} of the dc-link control to implement grid-supporting behaviour to the state of the art VOC. This is shown in Fig. 2 (green: additional droop control, blue: states). k_{droop} is the gain of the droop, whereas a $k_{droop} = 1$ means that $100\,\%$ of actual power is added for $1\,\text{Hz}$ deviation of setpoint frequency.

The state-space model of [8] was extended, and the stability of the system was investigated for increasing k_{droop}. Fig. 3 and Fig. 4 show the eigenvalue movement for a droop gain $0 \leq k_{droop} \leq 0.3$. Eigenvalues for $k_{droop} = 0$ are marked with a cross. They are equal to the eigenvalues without superordinate droop control.

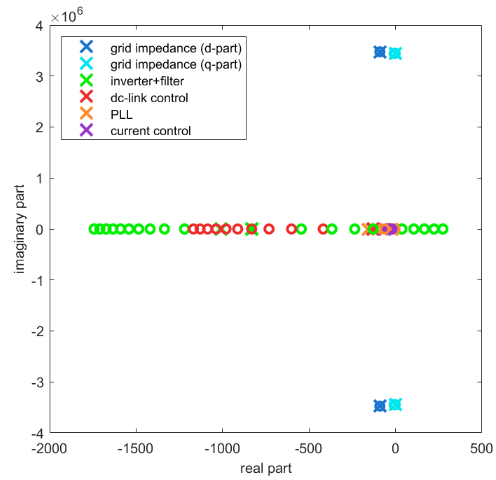

Fig. 3: whole plot of root locus for small-signal behaviour of VOC with increasing droop gain

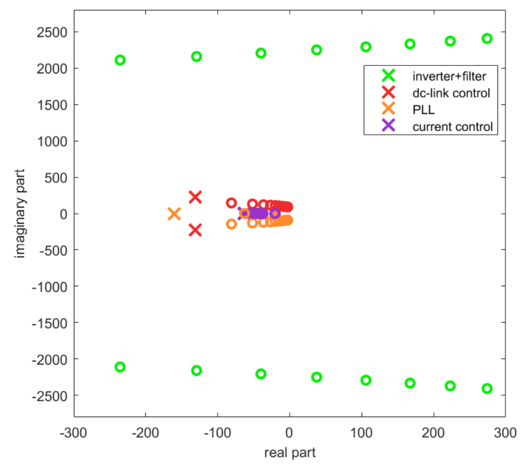

Fig. 4: zoom in of root locus for small-signal behaviour of VOC with increasing droop gain

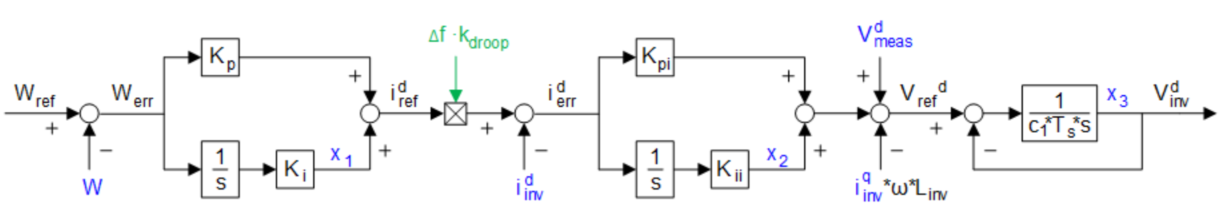

Fig. 2: states of dc-link and i^d_{inv} control with superordinate droop (green)

With the help of participation factors, the influence of the states on every single eigenvalue can be investigated. Unfortunately, at least two states participate in every eigenvalue. The colours in Fig. 3 and Fig. 4 mark the most participating states for $k_{droop} = 0$. Except for the eigenvalues depending on grid impedance (dark blue and turquoise), the influence of state x_2 increases with increasing droop gain. State x_2 is the state of the current control of the d-axis (1). The stability limit is reached for $k_{droop} = 0.165$.

$$\begin{aligned} \dot{x}_2 &= i^d_{err} \cdot K_{ii} \\ &= (i^d_{ref} \cdot (1 + \Delta f \cdot k_{droop}) - i^d_{inv}) \cdot K_{ii} \end{aligned} \tag{1}$$

C. Validation of Small-Signal Model

The theoretical results of the small-signal model were compared with time-domain simulations in MATLAB/Simulink. The setpoint for active power was 3 MW and for reactive power 0 var. Simulation was done without brake-chopper resistors because using them can hide instabilities. The droop gain k_{droop} was chosen to 0.3. Steps in grid frequency from 50 Hz to 49 Hz and back were applied at 3 s and respectively at 3.5 s. As another test signal, a phase-angle step of 30° was applied at 4 s. Fig. 5 shows the measured frequency of the PLL (blue) and the applied grid frequency (red). The PLL can track the grid frequency with PT_2 behaviour. As can be seen, a step in the grid angle causes a very high distortion in the PLL frequency.

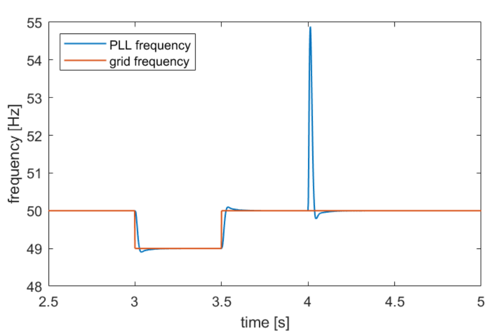

Fig. 5: grid frequency (red) and PLL frequency (blue)

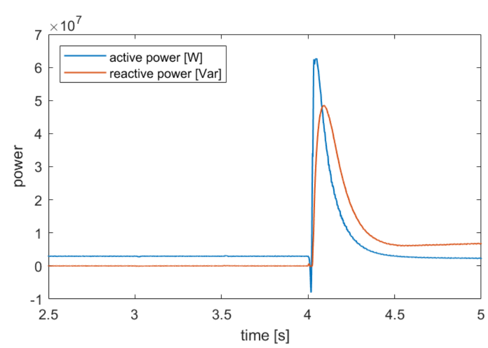

Fig. 6: output power of converter

Fig. 6 shows the output power of the converter. Converter control is stable for the applied changes in grid frequency but cannot react appropriately to grid-angle steps introduced distortions and becomes unstable. This fits the result from small-signal analysis. Control is stable as long as the dc-link control is faster than the superordinate droop control. From the control point of view, droop control on the grid side is a distortion which has to be compensated by outer loops. Therefore, even in the stable region, no grid-supporting behaviour of the output power can be seen (for 49 Hz active power is constant instead of increased).

D. Increased dc-link Capacitor

Additional energy is necessary to implement grid-supporting behaviour (for both grid-forming and grid-feeding control). Wind energy plants have three possible sources of energy storage:

- dc-link capacitor
- rotating masses (generator and blades)
- power reserve because of operating point

The dc-link can provide power very fast, but the stored energy is low. If the converter should be able to provide inertia as a first-step response, the dc-link capacitor has to be used. One idea is to increase the dc-link capacitor to store more energy. In [4], it is shown that the behaviour of a synchronous machine can be emulated with huge energy storage (battery or increased dc-link storage and dc-link control from machine side). The concept in [5] benefits from higher dc-link capacitance, too.

The small-signal analysis was done for VOC with increasing dc-link capacitance (from 0.01 F to 1 F) and a droop gain of $k_{droop} = 0.3$. The results are shown in Fig. 7. There is no significant movement of eigenvalues and control is still unstable. This result is confirmed by the time-domain simulation (Fig. 8). The test signals are the same as in Fig. 5.

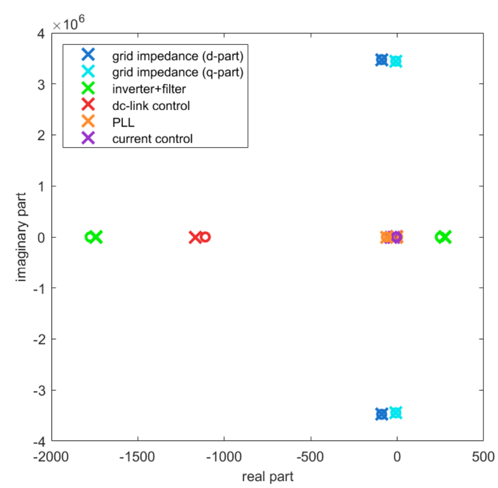

Fig. 7: root locus for small-signal behaviour of VOC with increasing dc-link capacitance

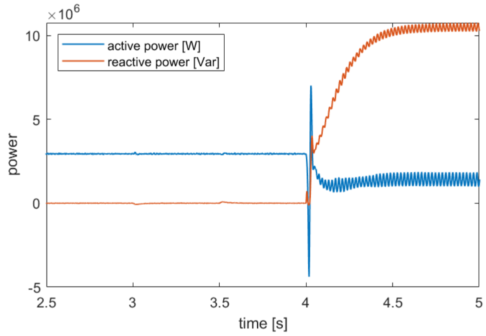

Fig. 8: output power of converter

Small-signal analysis and time-domain simulation showed: It is not possible to control dc-link with the grid-side converter and add a droop-control to the grid side even with an increased dc-link capacitor. Consequently, either dc-link control or droop control has to be implemented in machine-side control. Furthermore, another energy source has to be used.

Another possible energy source is the rotating masses of generator and blades. By breaking and accelerating energy can be provided and stored. The time-constant for this process is the time-constant of the mechanical torque control, which is in the range of about $120\,\mathrm{ms}$ (depending on machine parameters). Compared to the dc-link capacitor, much more energy is stored/storable. But it is still limited. Moreover, changes in torque lead to oscillations in the mechanical system. It is necessary to make sure that these oscillations are well-damped to avoid ageing and destruction of the mechanical parts.

Running the wind energy plant in an operating point which uses not the full power of the wind is also possible. This concept provides, e.g. $10\,\%$ more power for a long time (constant wind speed assumed). Also, of course, the output power can be ramped down entirely if it is necessary, too. However, this idea depends on pitch control, which is too slow to provide inertia. But it is useful to provide primary reserve.

E. Machine-Side Control

As mentioned before, it is not possible to implement dc-link control and droop control on the same side. Three time constants have to be taken into account:

PLL time constant to track the grid frequency $T_{PLL} \approx 20\,\mathrm{ms}$

grid-side dc-link control time constant $T_{dc}^{g} \approx 10\,\mathrm{ms}$

machine-side dc-link control time constant $T_{dc}^{m} \approx 120\,\mathrm{ms}$

To ensure a stable control, it is necessary that the dc-link control is faster than the droop control.

Case a) Droop control on the grid-side converter and dc-link control on the machine-side converter (This is the typical assumption for grid-forming control concepts): dc-link control has a time constant of $T_{dc}^{m} \approx 120\,\mathrm{ms}$ and droop control of around $T_{PLL} + T_{dc}^{g} \approx 30\,\mathrm{ms}$. This means that dc-link control is four times slower than droop control. An additional time constant is needed for droop control to ensure stability. The whole control has to be slower than $120\,\mathrm{ms} \cdot 5$ (stability margin).

Case b) Droop control on the machine-side converter and dc-link control on the grid-side converter: dc-link control has a time constant of $T_{dc}^{g} \approx 10\,\mathrm{ms}$ and droop control of around $T_{PLL} + T_{dc}^{m} \approx 140\,\mathrm{ms}$. That means dc-link control is faster than droop control. The system is stable.

Moreover, adding the droop control to the machine side offers the possibility to limit the permitted torque variation to prevent mechanical damage.

III. Simulation Results for ENTSO-E Grid Model

A model of the ENTSO-E grid [9] was used to show the stabilisation effect of grid-forming converters with superordinate droop control on the European grid. The rotational inertia is set to $H = 3$ (average penetration of converter-connected sources) and the self-regulation effect is given with $SB = 230\,\mathrm{GW}$. At $t = 100\,\mathrm{s}$ the ENTSO-E reference incident ($3\,\mathrm{GW}$) happened. Fig. 9 shows the caused frequency deviation and Fig. 10 the necessary ancillary services.

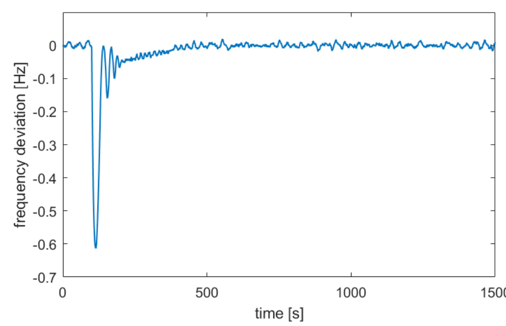

Fig. 9: frequency deviation

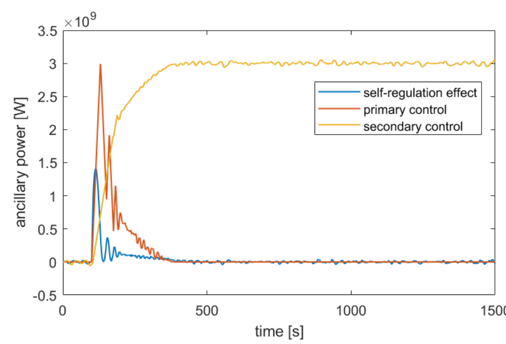

Fig. 10: ancillary services

Further on, it is assumed that $20\,\%$ of the overall produced energy ($300\,\mathrm{GW}$) is from wind energy plants which are equipped with a droop controller with $k_{droop} = 0.5$. Fig. 11 shows the additional active power from the wind energy plants.

Source for the additional power is the rotating masses. The droop control is added on the machine-side converter-control, and the dc-link control remains on the grid-side converter. Hence, a time constant of $T = 140\,\mathrm{ms}$ is used.

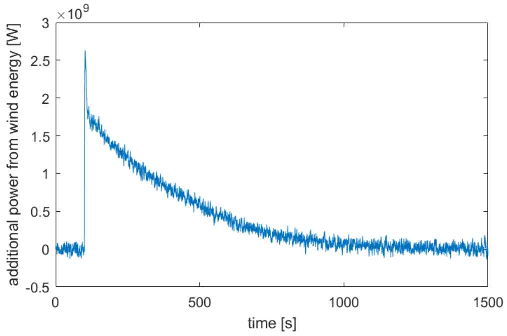

Fig. 11: additional power from droop control of wind energy plants

Fig. 12 shows the caused frequency deviation and Fig. 13 the necessary ancillary services.

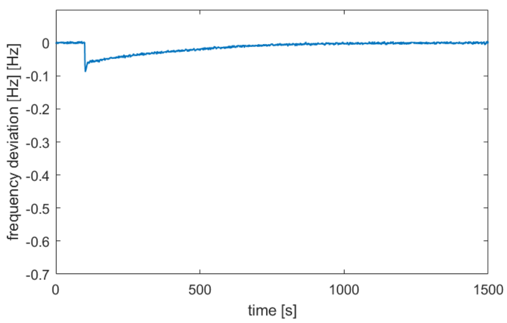

Fig. 12: frequency deviation

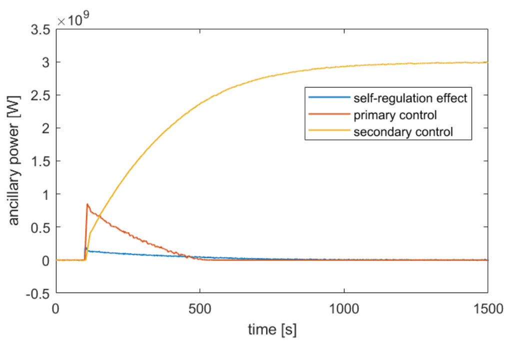

Fig. 13: ancillary services

The maximum frequency deviation decreases from 0.6 Hz to 0.1 Hz and the maximum needed primary control reserve decreases from 3 GW to 0.9 GW.

IV. Conclusion

It is possible to provide inertia respectively grid-supporting behaviour with grid-feeding converter control. In contrast to grid-forming control, it is a second-step inertia and not an inherent first-step inertia. Small-signal analysis and time-domain simulation proofed that it is necessary to split droop control and dc-link control to ensure stability. The fastest reaction to frequency deviation is achieved, if droop control is added on the machine-side converter.

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