Frequency Control by HVDC connected Offshore Wind Farms for Overfrequency Limitation

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***Abstract*—This paper discusses the utilization options of high voltage direct current (HVDC) connected offshore wind farms (WFs) to contribute to the fast frequency control during overfrequency events. A disturbance such as a sudden loss of load in a grid will cause the frequency to increase; the first seconds in the response are shaped mainly by the total inertia level in the grid. With increasing share of inertia-less wind generation in modern grids, a fast overfrequency limiting control should be provided by the wind farms. Power reduction by pitching is the most common and straightforward method. Kinetic energy control can additionally reduce the overfrequency. An alternative strategy utilizing the HVDC chopper to limit the frequency overshoot is introduced in this paper. A test grid is used to analyze the performance of the above mentioned strategies. Significant improvements in the frequency response are achieved through combined strategies.**

***Index Terms*—Offshore Wind Farms, Pitch Control, HVDC Chopper, Kinetic Energy Control.**

I. Introduction

Large offshore WFs are being installed in the region of the North Sea in Europe. High numbers of those concentrated offshore WFs will be connected to the onshore grid via VSC-HVDC transmission technology. In Germany, the offshore wind power generation in the north is planned to be transmitted through new corridors of HVDC lines to the large load centers in the south as illustrated in Fig. 1. This new grid configuration makes a scenario whereby a sudden loss of load such as disconnection of the northern part with concentrated generation from the southern part with main load centers possible. As a result a frequency rise will occur in the separated northern part due to the surplus energy coming from the offshore WFs. The rate of change of frequency (RoCoF) is higher in low-inertia grids with high wind share, thus wind farms should offer a fast contribution to the primary frequency response to improve the grid reliability.

Grid codes in several countries introduced new requirements regarding fast frequency support by wind turbines (WTs) [1][2]. This includes that the WT should be able to emulate the inertial response of conventional synchronous generators. This topic has been discussed in a number of works [3],[4],[5],[6]. The current German grid code define requirements [7] for overfrequency conditions without fast overfrequency limitation requirements. The increasing concern here is whether the WTs are able to reduce its output power fast enough to limit the frequency overshoot in the first seconds of the frequency excursion to support the overall inertial response of the grid and avoid consequently tripping large number of offshore WTs. This paper discusses the utilization options of offshore wind farms with HVDC connection to contribute to the overfrequency limiting control.

Frequency deviations are not detected inherently by modern WT systems as is the case for conventional generation with synchronous generators. Additionally, the HVDC connection provides a complete decoupling between the main grid frequency and the offshore WF frequency. If a robust communication channel is assumed, the measured grid frequency can be transmitted to the offshore WFs to be the input variable for a dedicated frequency control. The total time delay caused by the measurement and signal transmission is assumed to be 50 ms which has minimal effect on the frequency control performance. If the communication based method proved to be unreliable, a communication-less scheme [8] will be the preferable solution to replicate the onshore frequency at the offshore side. In the latter case, the frequency can be measured at the terminal of each offshore WT.

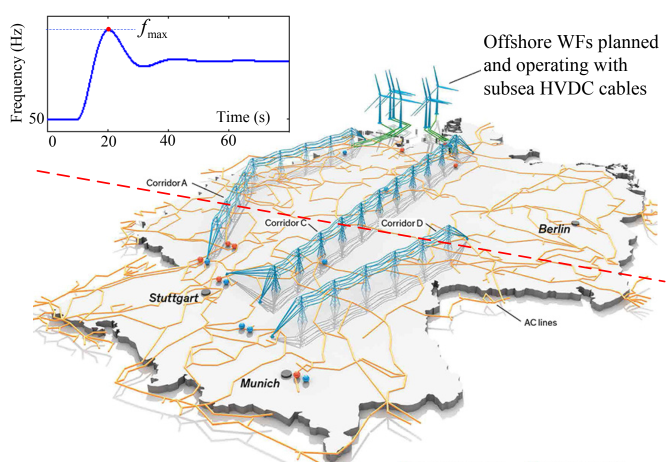

Fig. 1. The planned three corridors of HVDC lines for the transmission of large offshore wind power through Germany.
[*http://spectrum.ieee.org/energy/renewables/germany-takes-the-lead-in-hvdc*]

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The rate of power reduction by pitch control is constrained by the maximum pitching speed of the rotor blades. Moreover, the higher the RoCoF the faster the power reduction to limit effectively the frequency overshoot should be. Thus WTs may require alternative strategies to provide a fast frequency response.

Kinetic energy control (KEC) strategies in wind farms for emulating the inertial response were discussed in [3]. These concepts are utilized usually for the frequency drop event to support the inertial response of the primary frequency. In this paper the KEC strategies will be utilized for overfrequency events. Hereby KEC strategies target controlling the kinetic energy stored in the WT rotor to cause a temporal drop of the output power and thus limiting the frequency overshoot. Combinations of different control strategies are tested and compared to illustrate their enhanced effect on the frequency response.

In [9] a new method is proposed for utilizing the DC chopper in the HVDC for overfrequency limitation during the transient period of the primary frequency response. Anew control layout of this strategy is introduced and its performance is compared with other strategies considered in this paper. One important criterion that is highlighted in this paper is the maximum energy that can be absorbed by the DC chopper. Moreover, the same control strategy is applied to the DC chopper installed in full scale converter generator (FSCG) based WT (type 4). Simulation results are carried out for different scenarios and the results are compared.

II. Test Grid

A two-area, weakly-coupled grid based on [3] is used to study the frequency response in case of loss of load causing the overfrequency. The frequency response for different strategies of frequency control by wind farms is then compared to the case with no frequency control by wind farms. To test the frequency response of the grid, a small load L21 of (170 + j50) MVA is disconnected from the grid at the node shown in Fig. 2. This causes the frequency to rise to nearly 51 Hz. The total generated power of conventional plants adds up to 3.2 GW, in addition to the offshore wind power of approximately 800 MW. That means the wind power share of generation is around 20%.

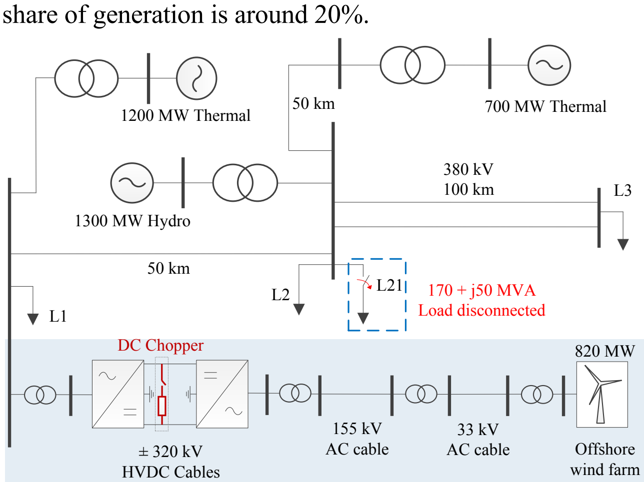

Fig. 2. Test grid applied for the frequency studies.

III. Frequency Support Strategies by WTs

A. Frequency Support by Pitch Control (FSPC)

This is a well-known method for reducing the WT generated power by increasing the pitch angle through pitch control. In both low and high wind speed conditions the pitch control can limit the generated power by a certain increase in the pitch angle. The WT power conversion model with pitch and speed control proposed in [3] for doubly-fed induction generator (DFIG) based WTs is adopted in this work. However, the control concepts in this paper apply also for FSCG based WTs.

Fig. 3 illustrates the FSPC strategy which is applicable for over and underfrequency events. Here $\Delta\beta_0$ represents the pitch angle offset that is added for a de-loaded WT operation. The de-loading provides a reserve power to be used in case of underfrequency events. In this paper the focus is on the overfrequency event and thus the power reduction strategy. When an overfrequency event occurs during low wind speeds the pitch angle offset $\Delta\beta_{FS}$ will be increased from zero to a specific value according to the frequency deviation level and the gain K_{FS}, speed control thru pitch is not active in this case. For the same overfrequency event at high wind speeds, the pitch controller will be active to limit the rotor speed and will work against the pitch angle offset $\Delta\beta_{FS}$ generated by FSPC. To avoid this control conflict and improve further the frequency response, an additional offset $\Delta\omega_{FS}$ in the rotor speed reference is introduced at the input of the pitch controller. In this manner the pitch angle increase is driven directly by the pitch controller. To limit the frequency support period the washout filter time constant can be adjusted accordingly.

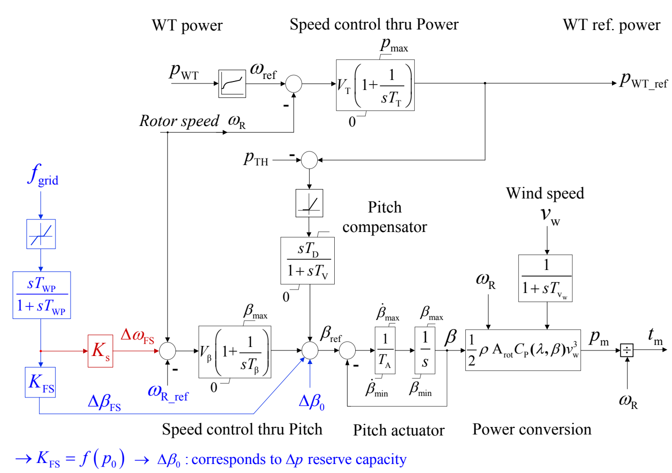

Fig. 3. WT power conversion model with pitch and speed control with FSPC scheme.

Fig. 4 shows the performance of FSPC during the overfrequency event described in the previous section. The steady-state overfrequency level is reduced here due to the high time constant (here 10 min) chosen for the washout filter which keeps the pitch angle and thus the power reduction for the defined duration of the frequency support. The pitch speed is limited by the WT manufacturer to avoid any mechanical stresses. Thus FSPC will not be able to limit significantly the transient frequency overshoot as the wind share increase in the grid.

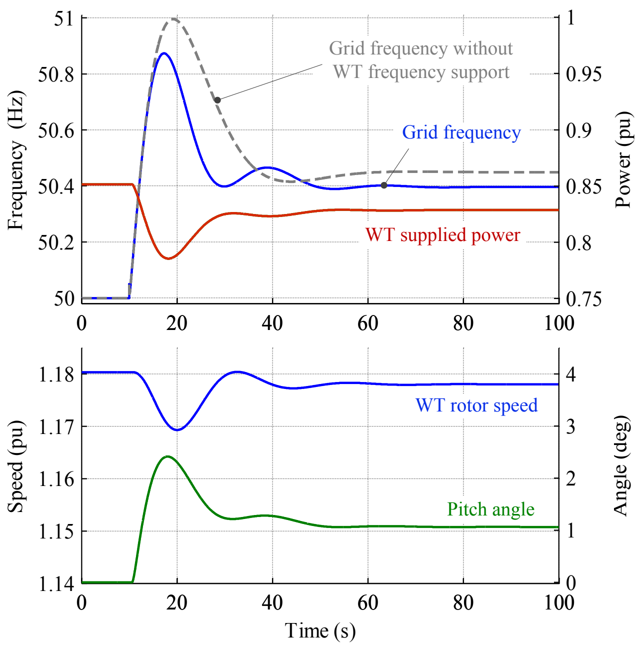

Fig. 4. Performance of FSPC strategy for an overfrequency event.

B. KEC for overfrequency limiting control

Fast frequency support by WTs which target inertial response support has been introduced in [3] and [4] for underfrequency events. Fig. 5 shows the additional power command generated by the KEC using the measured frequency as an input variable.

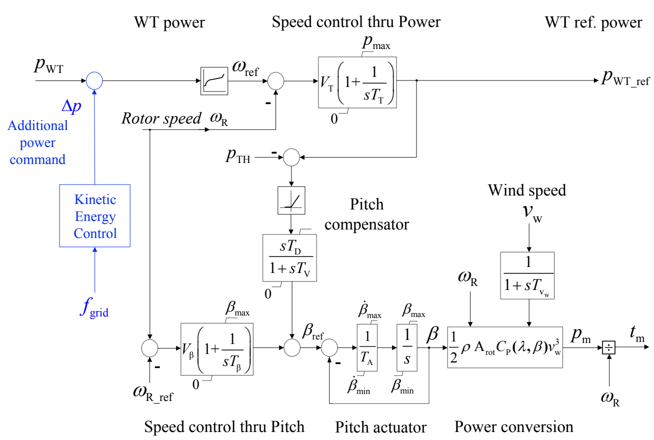

Fig. 5. WT power conversion model with pitch and speed control with KEC scheme.

Two KEC schemes were introduced in [3]: KEC I which is a common intuitive approach, while the second scheme KEC II is a less intuitive approach that showed a promising results for underfrequency events. Fig. 6 illustrates KEC I and KEC II schemes, where the only difference is the negative sign of the power command in KEC II and the different controller parameters. KEC II has the advantage of not requiring additional tuning or adjustments of the speed controller parameters as in the case of KEC I [4]. The application of these KEC schemes for overfrequency events is discussed in this section.

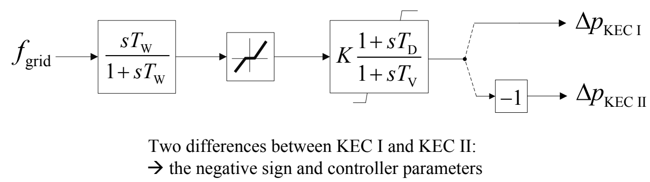

Fig. 6. KEC schemes as proposed in [3].

1) KEC I

By applying this scheme the rotor speed is accelerated initially to operate temporarily at a higher mechanical power setpoint. It follows that the rotor will absorb extra kinetic energy causing a temporal drop in the output power. This control action limits the frequency overshoot during the first seconds of the primary response. The rotor speed is afterwards restored which means the extra kinetic energy will be discharged causing thereby a temporal increase in the output power which can be characterized as the recovery phase. Fig. 7 illustrates the control phases of KECI strategy. The decelerating period becomes shorter as the rotor speed increases and nearly disappears during high wind speeds.

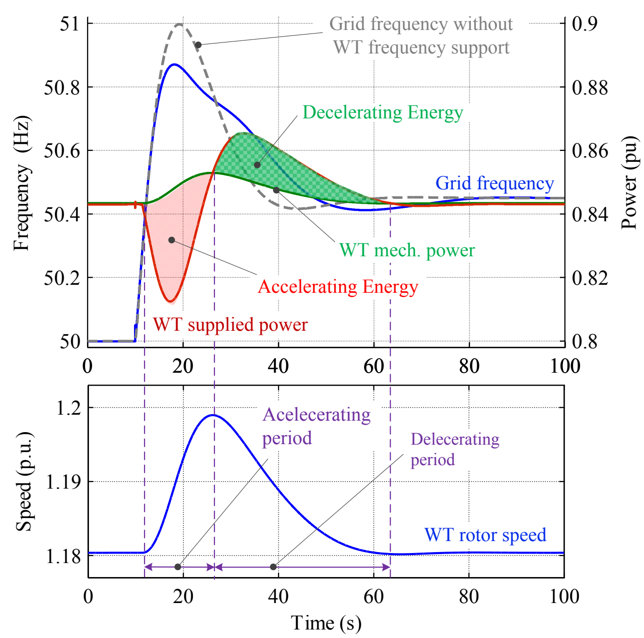

Fig. 7. Performance of KEC I for an overfrequency event.

2) KEC II

KEC II strategy is utilized for the limitation of the frequency overshoot as illustrated in Fig. 8. When the frequency rises above a defined threshold, KEC II will initially increase the output electrical power by dropping the rotor speed and releasing part of the stored kinetic energy. In the next phase the WT is controlled to deliver less electrical power by accelerating the rotor and charging it with kinetic energy limiting therefore the frequency overshoot. The WT is afterwards controlled to operate normally at the optimal speed.

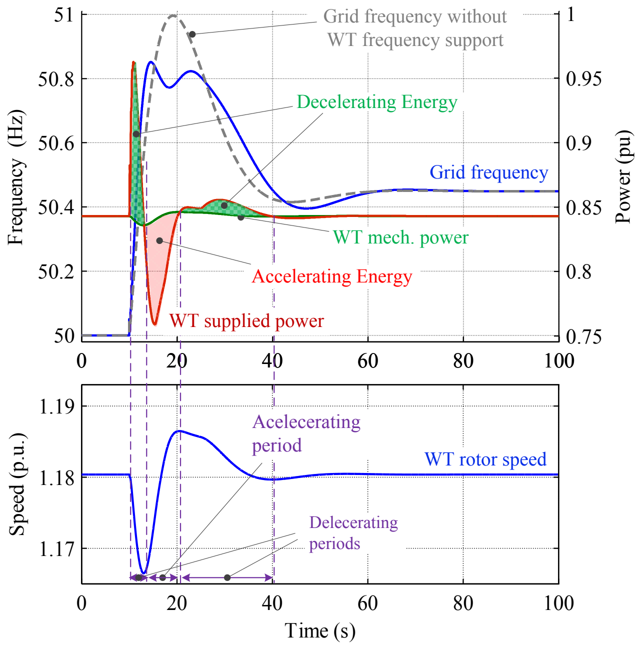

Fig. 8. Performance of KEC II for an overfrequency event.

In the results shown in Fig. 7 and Fig. 8 the controller parameters for KEC I and KEC II are tuned for a specific wind share level (20%) in the test grid and their performance cannot be reflected to all operating points.

The main drawbacks of the KEC strategies for underfrequency events which were addressed in [6], [10] and [11] apply to a certain extent for overfrequency events and can be summarized in the following points:

- KEC parameters are tuned for limited rotor speed range for best possible results.
- Close coordination with the speed and pitch control is of a high importance (especially for KEC I) to avoid a second incursion.
- The higher the wind share and therefore the RoCoF the harder is to tune parameters of the KEC controller.
- Large wind speed variations within the offshore wind farm could weaken the overall KEC performance if no coordination exists between the WTs.

C. Combined FSPC and KEC strategies.

1) FSPC and KEC I

The performance of the combined FSPC and KEC I strategies are compared to each single strategy in Fig. 9 for the same load switching event that causes the overfrequency. FSPC and KEC I delivers in this case comparable results regarding the limitation of the frequency overshoot. The combined strategy offers a considerable enhancement of the frequency response.

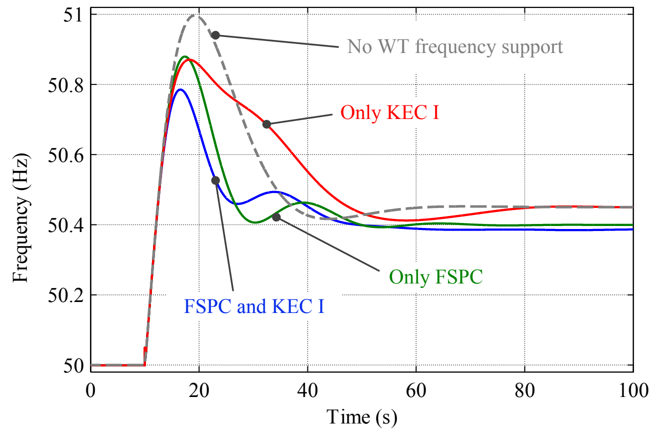

Fig. 9. Results of KEC I and FSPC strategies for an overfrequency event.

2) FSPC and KEC II

The combined control action of KEC II strategy and FSPC offers a considerable enhancement for the overfrequency limiting performance as shown in Fig. 10. The main drawback of method KEC II is the initial increase of RoCoF prior to the overfrequency limiting. However, the combination with FSPC mitigates this negative effect.

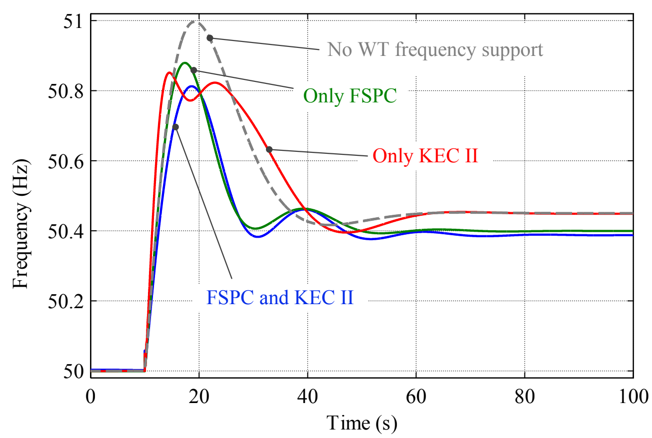

Fig. 10. Results of KEC II and FSPC strategies for an overfrequency event.

D. HVDC chopper control for overfrequency limitng

This method was recently introduced in [9]. The DC chopper is installed typically in the HVDC system to dissipate excess energy and therefore isolate the offshore WF from onshore grid faults (Fig. 11). The functionality of the DC chopper is extended to dissipate excess energy during overfrequency events in the main onshore grid to limit the frequency overshoot during the transient period of the primary response.

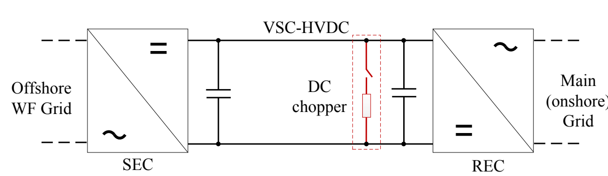

Fig. 11. Simplified chopper concept at HVDC for offshore WFs applications.

The proposed chopper control strategy introduced in [9] employs a separate frequency control which generates directly the switching signals of the chopper. In this paper, an alternative control strategy is introduced by adding an additional DC voltage reference Δv_{DC_f} to the DC voltage controller at the HVDC receiving end converter (REC) as shown in Fig. 12. Once the grid frequency exceeds a specific value (here 50.2 Hz) the DC voltage controller will increase the DC voltage level to activate the chopper protection function. The DC voltage rise and thus the chopper switching instances are controlled by a lead-lag compensator with a specific gain. The controller targets limiting the transient frequency overshoot during the primary frequency response.

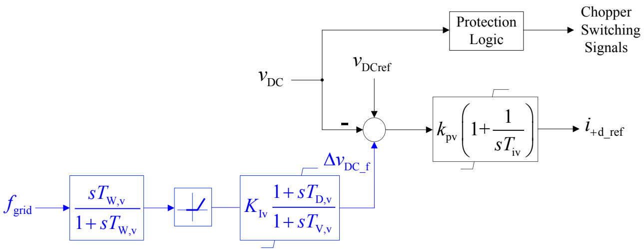

Fig. 12. DC voltage control at REC with overfrequency limiting control.

One important aspect that should be considered in the control design is the maximum energy that can be absorbed and dissipated by the DC chopper. Typically in WTs with FSCG the DC chopper is designed to be able to dissipate the rated power for a period of 3-5 s. This means that the chopper should be able to dissipate the full rated power (1 pu) for 3-5 s. Thus the maximum energy must be considered as a limiting factor for the overfrequency limiting control. In the following 1 pu energy is equal to 1 pu power absorbed in 1 s. Fig. 13 shows how the chopper absorbs a defined amount of energy limiting effectively as a result the frequency overshoot during the primary frequency response.

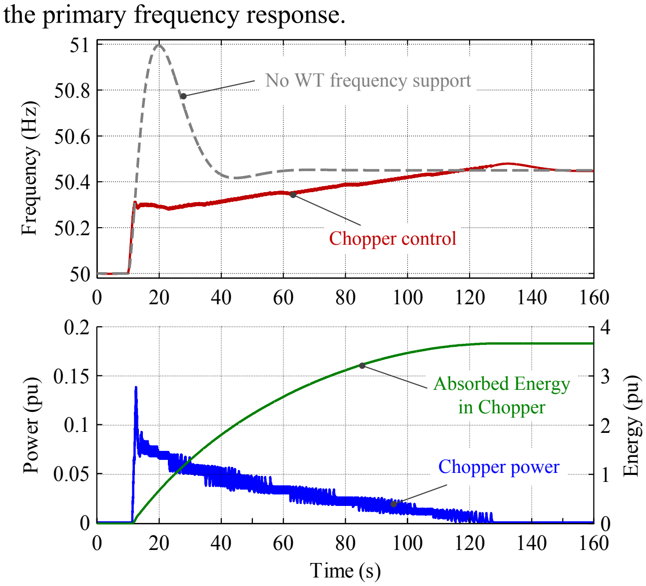

Fig. 13. Results of DC Chopper control for overfrequency limiting.

The combined strategy of the chopper control and FSPC offers several advantages. On one hand the DC chopper will have to absorb less energy while the wind turbines can reduce their output power more slowly to avoid possible oscillations or mechanical stresses. Fig. 14 shows that the energy absorption by the DC chopper decreases when the FSPC strategy is enabled. As a result unnecessary over-dimensioning of the DC chopper can be avoided.

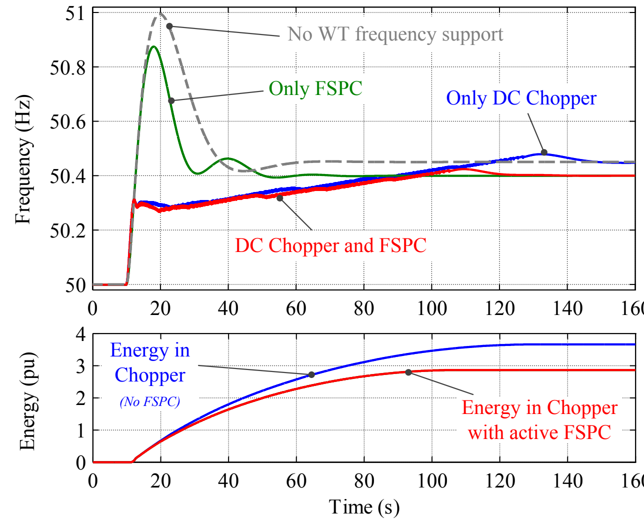

Fig. 14. Comparison results for HVDC chopper and FSPC strategies.

The same overfrequency limiting concept can be applied to the DC chopper installed in FSCG based WTs (type 4). Thus in an offshore wind farm consisting of FSCG based WTs, each WT that is equipped with a DC chopper can participate in the overfrequency limiting action by limiting locally its output power through its own chopper. A robust communication link that sends the frequency measurement to the offshore WTs is prerequisite for this strategy. Fig. 15 compares between two simulation cases. In case 1 only the overfrequency limiting control for the HVDC chopper is enabled. In case 2 each WT in the offshore WF receives the 'onshore' grid frequency measurements and activates its own chopper to participate in the overfrequency limiting control.

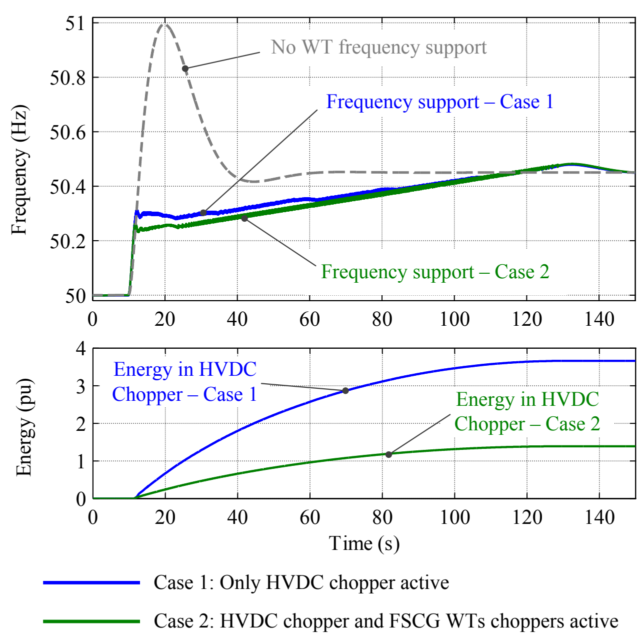

Fig. 15. Comparison results for HVDC chopper with additional local FSCG-WT chopper control strategies.

The results in Fig. 15 indicate that applying the chopper control strategy locally for each FSCG based WT enhances the transient part of the primary frequency response and reduces the total energy absorption by the HVDC chopper.

The chopper control strategy has the advantage of offering a defined amount of energy dissipation independent of the actual wind power prior to the overfrequency event. Furthermore, badly tuned chopper control leads only to less limitation of the overfrequency and will not adversely interact with the wind turbine controllers as the case with KEC strategies.

Fig. 16 summarizes the discussed control strategies for overfrequency limiting by the offshore WF with VSC-HVDC.

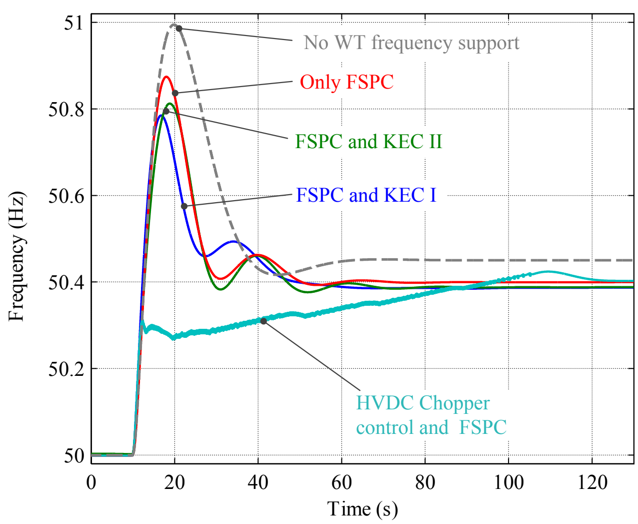

Fig. 16. Comparison results for different overfrequency limiting strategies

The chopper control strategy shows the best results and can significantly limit the RoCoF during the primary frequency response. The best response is achieved by combining the chopper solution to limit the RoCoF as long as possible combined with output power reduction by the FSPC strategy. A possible combination of the chopper control and one of KEC strategies do not bring any improvement when compared to the frequency response with only chopper control.

IV. Conclusion

The large scale concentrated offshore wind power generation in the north of Germany will be transferred through new corridors of HVDC lines to the load centers in the southern part. The risk of overfrequency events might increase as a result in the northern part.

The FSPC method provides power reduction by increasing the pitch angle which is typically limited to a certain rate, thus FSPC will have limited ability to reduce the transient frequency overshoot in low-inertia grids. Two KEC methods are utilized and evaluated for the overfrequency limiting purpose. By a certain control sequence the kinetic energy in the rotor can be controlled in a way to limit the frequency overshoot. Both methods KEC I and KEC II are able to limit the frequency overshoot, the main concerns about applying these strategies are the strong dependency on the wind speed level and the difficulty of tuning the control parameter for a grid with high wind share. FSPC and KEC strategies can be combined for an improved frequency response.

The strategy employing the DC chopper in the HVDC system and the FSCG based WTs offers an attractive alternative to the previous strategies and provides the best performance regarding the limitation of the transient overfrequency. One important aspect here is that this solution is temporary and can be applied for certain period of time corresponding to the maximum energy absorption capability of the DC chopper. Proper control settings can avoid extra costs due to over-dimensioning the DC chopper.

A future solution incorporating an energy storage system could replace the DC chopper to provide frequency control in both over and underfrequency events. The energy storage system should handle as well the original functionality of the DC chopper during grid faults. This solution is not considered feasible as long as no real breakthrough occurs in this technology regarding cost and expected operation lifetime issues.

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