Inertial Response from Remote Offshore Wind Farms Connected Through VSC-HVDC Links: A Communication-less Scheme

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Abstract—A communication-less scheme that allows remote offshore wind farms connected through HVDC links to participate in primary frequency control and contribute to system inertia is discussed in this paper. As a HVDC link decouples the offshore system from the onshore side, real-time communication of onshore frequency is normally required for the primary frequency control loop of the wind farms. Dependence on remote communication which could be unreliable at times is a problem. To obviate the need for communication, appropriate droop control on the offshore and onshore converters is used in this paper to translate the variation in onshore frequency to an equivalent variation on the offshore end. Thus the need for communicating onshore frequency to the offshore side is obviated which ensures reliable operation. Such a communication-less scheme is compared against the conventional approach involving remote communication of onshore grid frequency to the wind farm site. Alongside physical and analytical justification, a case study is presented to demonstrate that the communication-less scheme performs similar to the conventional one in terms of reducing grid frequency variations.

Index Terms—Primary frequency control, inertial response, droop, offshore wind farms, VSC-HVDC, communication

I. INTRODUCTION

F ast primary control of wind farms decouples their mechanical side from the electrical (network) side. Hence, the mechanical inertia effect of the wind turbines are not felt by the network. With large number of onshore and offshore farms set to displace decommissioned fossil-fuel power stations, the overall inertia of future power systems would decrease significantly. As a result of this the variations in grid frequency would be more than before for a given disturbance. With significant penetration of wind, large reduction in overall inertia could result in unacceptable excursions of grid frequency outside the specified tolerance which is a cause of major concerns for utilities.

With appropriate supplementary control around the primary control loops of wind farms, it is possible to force the wind farms to contribute to system inertia and thus participate in primary frequency control. Several methods for achieving this have been proposed and demonstrated [1], [2], [3], [4], [5], [6]. Although there are subtle differences each of these methods rely on measuring the grid frequency for adjusting the active power/torque reference of the wind farms to counteract the variations in measured frequency. For onshore wind farms this is relatively straightforward as the grid frequency measured locally at the point of common coupling (PCC) can be readily used. The same is possible for nearby (less than 30-40 kms into the sea) offshore wind farms with AC connection to the shore.

For remote offshore wind farms, high voltage direct current (HVDC) is the only option for connection to main onshore grid. Voltage source converter (VSC) is arguably the only choice of HVDC technology in such cases [7]. An HVDC link is asynchronous which decouples the frequencies on the onshore and offshore end. Thus a variation in onshore grid frequency is not reflected on the offshore side. So the remote offshore wind farms cannot rely on frequency measured locally on the offshore side (at the PCC) to contribute to inertia and participate in primary frequency control) like the onshore wind farms. One option is to remotely communicate the onshore grid frequency to the offshore wind farm site in real time as has been reported in [8], [9] in the context of line commutated converter (LCC) based HVDC link. However, the reliability of communication channels in terms of latency, reduced data rate or complete drop could pose difficulties. With large number of offshore wind farms envisaged especially, in Europe a reliable and effective solution to this problem is critical.

In this paper, a technique is demonstrated which enables offshore wind farms connected through VSC-HVDC link to contribute to system inertia and primary frequency control without having to rely on remote communications. The idea is based on using appropriate droop control on the offshore and onshore HVDC converters to translate the variation in onshore frequency to an equivalent variation at the offshore end. Thus the need for communicating onshore frequency to the offshore side is obviated which ensures reliable operation. The concept is illustrated with a case study on a multi-machine onshore AC system with one large offshore wind farm connected through a VSC-HVDC link. First the need for inertial response from wind farms in reducing the frequency variation is illustrated to set the context. Then the communication-less scheme is shown to perform very similar to a conventional scheme which relies on remote communication of onshore grid frequency. Finally, the challenges of the communication-less scheme in terms of potential variations in DC link voltage are highlighted.

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II. Active Power Control for Wind Farms

Doubly-fed induction generators (DFIG) are used for the wind farms throughout this paper. In particular, GE 1.5 MW wind turbine generator (WTG) model [10] is adopted and an aggregated model combining the WTGs within the wind farm as a single unit is used. A conceptual schematic of the active power control for the WTGs is shown in Fig. 1 [2], [1], [10].

![Fig. 1. Active power control of WTGs](image)

Using the pitch angle and the tip-speed ratio, the wind power model calculates the mechanical power extracted from wind. The mechanical power input and the generator (electrical) power output is used in the two mass (for turbine blades and generator shaft) rotor model to derive the turbine speed and the rotor speed. The deviation of this rotor speed from its reference value actuates the pitch and torque control blocks. The pitch compensation block generates a pitch angle error signal depending on the deviation of actual power order from the rated value. The torque order out of the torque control block and the rotor speed is used to derive the active power order, $P_{ord}$ for the WTG which is passed on to the converter control block.

III. Inertial Response from Remote Offshore Wind Farms

Wind farms could participate in primary frequency control and contribute to system inertia by releasing the stored kinetic energy in response to a drop in grid frequency. The usual approach is to use the deviation in grid frequency from its nominal value to vary the active power output of the wind farm as discussed below.

A. Conventional scheme

Several schemes have been proposed in the literature for deriving inertial response from wind farms. Although there are subtle differences between these approaches the basic philosophy is similar. The idea is to use the deviation in grid frequency to modulate the active power output from the wind farms as shown in Fig. 2 [10].

The deviation in measured grid frequency ($f_{meas}$) from its nominal values ($f_{nom}$) is taken through a dead-band block to avoid responding to regular small variations in grid frequency. A gain and low-pass block is used to scale this frequency deviation appropriately. Rate limits and wind-up limits on the allowable range of change in power order is used to derive the required change in power order ($\Delta P_{ord}$) which acts through the supplementary input (shown in Fig. 1) to modulate the active power order ($P_{ord}$) of the wind farm.

For remote offshore wind farms connected through a VSC-HVDC link the grid frequency ($f_{meas}$) is communicated to the wind farm site for use in the control loop shown above. The modulation in active power output of the wind farm is propagated onto the onshore main grid by having the offshore HVDC converter under AC voltage-frequency control while the onshore HVDC converter maintains the DC link voltage constant. With reliable and fast communication links in place, this scheme (termed 'conventional scheme') works satisfactorily allowing remote offshore wind farms to participate in primary frequency control.

B. Communication-less scheme

For offshore wind farms connected to the main grid using VSC-HVDC links the offshore converter is usually set to maintain a constant AC voltage at a given frequency so that power coming from the wind farm side is transmitted on the DC side. The onshore converter is set to control the DC link voltage to a constant value so that the incoming power is transferred on to the onshore AC system.

The basic idea behind the communication-less scheme is to use appropriate droop characteristics on both the onshore and offshore converters to ensure that the frequency variation on the offshore side is proportional to that on the onshore side. The frequency-voltage droop characteristics is used to derive the DC link voltage reference ($V_{on}$) and frequency reference ($f_{off}$) settings for the onshore and offshore converters, respectively as shown in Fig. 3.

The objective is to derive a variation in DC link voltage on the onshore end which is proportional to the onshore frequency variation (with respect to nominal value denoted by the superscript ‘nom’) and translate that on the offshore end after compensating for the voltage drop across the DC cable (Fig. 3(b)). This voltage variation at the offshore end results in a proportional amount of variation in offshore frequency (Fig. 3(b)). The measured quantities (denoted by the superscript ‘m’) used for the droop control schemes in Fig. 3 are all local. Thus without any need for remote communication the onshore frequency variation propagates on to the offshore side allowing communication-less primary frequency control from remote offshore wind farms.
Thus the offshore frequency variation with respect to he nominal value is proportional to the onshore frequency variation. Hence, the local offshore frequency variation can be used for the primary frequency control loop of the wind farms.

The values of $K_{off}$ and $K_{on}$ are to be chosen to ensure that the variation in DC link voltage is limited within the allowable range for expected levels of variation in onshore frequency. Otherwise, operational limits on DC link voltage would disrupt the proportionality between onshore and offshore frequency variations. The hard limit on onshore DC link voltage reference $V_{on}$ is usually set to $\pm 10\%$ of the rated value. From (3) it is clear that by setting $K_{off}K_{on} = 1$, it is possible, in principle to exactly replicate the onshore grid frequency variation on the offshore end provided the nominal frequencies are the same which is usually the case.

IV. CASE STUDY

A case study was carried out on the test system described next using the DiGSIILENT PowerFactory software. Loading of the onshore AC system was increased to cause decrease of grid frequency from its nominal value of 60 Hz.

A. Test System

The well-known 4-machine, 2-area system described in [11] was used for the case study. A number of modifications were made to the original system to suit the present case study. Three tie-lines as shown in Fig. 4 were considered. Each area consists of two coupled generation units, each having a rating of 600 MVA and 20 kV. Two scenarios were considered - one with conventional generation and no wind farm and the other where one of the conventional power plant was replaced by an equivalent offshore wind farm connected through VSC-HVDC link as described below:

1) Scenario I: Conventional generation, no wind farm:
All the units are equipped with steam turbine-governor system [11]. Frequency dependent load models were considered. In steady state, each unit dispatch 500 MW with the loads Ld1 = 600 MW and Ld2 = 1358 MW resulting in a tie-line flow of 380 MW.

2) Scenario II: One conventional power plant displaced with an offshore wind farm: The base case described above was modified by replacing a conventional power plant (G2) with an offshore wind farm radially connected to bus 6 via $\pm 150$ kV bipolar VSC HVDC link with length 100 km, as shown in Fig. 5. The wind farm comprises of 350 aggregated wind turbine generators (WTGs) individually rated at 1.5 MW, 0.69 kV. In steady state, the total wind farm power output is 500 MW. The VSC HVDC converters are rated at 550 MVA. When considering the conventional scheme, the grid frequency is communicated from bus 6 to the offshore wind farm controls (see red trace).
B. Inertial Response from Wind farms

The impact of displacing conventional synchronous with wind farms is shown in this section. Fig. 6 compares these cases for two load events (7% and 14% increase in system load). The impact of these two events can be observed in Fig. 6. Synchronous machines inherently contribute to system inertia, whilst without additional control, wind farms do not participate in primary frequency control. Due to the reduction in net system inertia with wind farms, the grid frequency deviates more (first several seconds) from its nominal values. This phenomena is due to the facts that synchronous machine turbines rotate at system frequency with nearly constant rotating speed, whereas wind turbines are not synchronized to the grid but are controlled to provide maximum active power.

![Inertial Energy Recovery](image)

The wind turbines contribute to primary frequency control by releasing the kinetic energy stored in the rotating mass. The stored kinetic energy is larger at higher wind speeds. Once the stored energy is exhausted, the wind turbines would have to recover that by producing less than rated power which is termed the recovery phase.

As shown in Fig. 7, for higher wind speed of 14 m/s due to larger stored kinetic energy, the recovery phase is almost not there. But for a lower wind speed of 11 m/s the recovery phase is prominent. Although this has very little influence on the primary frequency control in terms of the maximum deviation in grid frequency from its nominal value, the frequency recovery phase beyond 7-8 s is affected as shown in Fig. 7.

![Frequency Recovery](image)

C. Effect of Latency on Conventional scheme

Inertial control from offshore wind farm using remote communication scheme is demonstrated here. Fig. 8 shows that inertial control significantly reduces the deviation of grid frequency from its nominal value by increasing the output of the wind plants by up to a maximum of 10% of the rated turbine power.

Latency in communicating the grid frequency to the wind farm site could be in the range of 150 to 500 ms in the worst case. Although pessimistic, those high values of latencies were considered to demonstrate the effect of latency on frequency control from remote offshore wind farms. Even with latencies as high as 500 ms the deterioration in performance is found to be very little. The deterioration is caused due to violation of the 10% limit on top of the rated power.

D. Communication-less scheme

The primary frequency control with the communication-less scheme is compared against the conventional scheme in Fig. 9. The comparison is made in the backdrop of the frequency variation without any inertial control. For the conventional scheme, a latency of 150 ms (which is pessimistic but possible) is considered in communicating the onshore grid frequency to the remote wind farm site. It can be seen that the performance is quite similar with the two schemes which highlights the fact that it is possible to derive frequency control from remote offshore wind farms without requiring fast and reliable communication.

The active power output of the wind farm is also shown which is limited within 10% of the wind farm rating of 500
The variation in DC link voltage at the onshore end for the communication-less scheme is shown in the lower subplot. This is caused due to the frequency-voltage droop control loop on the onshore converter which reacts to variation in onshore grid frequency. The conventional scheme do not rely on frequency-voltage droop and hence, the onshore end DC link voltage remains constant.

Here we have chosen $K_{on}$=1 and the nominal frequencies on the onshore and offshore ends are the same. Hence, as explained in SectionIII-B, the variation in offshore frequency is almost identical to that of onshore frequency and is therefore, not shown separately.

The performance of the communication-less scheme for different values of onshore converter droop coefficient $K_{on}$ is shown in Fig. 10.

As $K_{on}$ is increased from 6 to 25, the dip in grid frequency reduces for an ideal situation with no lower limit on DC link voltage. However in practice, for $K_{on}$=25, the DC link voltage is clipped at its allowable minimum (from converter modulation index point of view) resulting in significant deviation in grid frequency from its nominal value. Better frequency control (i.e. lesser variation from nominal value) for higher values of $K_{on}$ is due to increased sensitivity of propagation of onshore frequency variation on to the offshore end. However, this is achieved at the expense of larger variation in DC link voltage which is not allowable beyond a certain range (see hard limits on $V_{on}$ in Fig. 2) from cable over voltage and converter modulation index considerations [7].
V. CONCLUSION

A communication-less scheme is demonstrated that allows remote offshore wind farms connected through HVDC links to participate in primary frequency control. Fast and real-time communication of onshore grid frequency is required for the primary frequency control loop of the remote offshore wind farms. Appropriate droop control on the offshore and onshore converters is shown to translate the variation in onshore frequency to an equivalent variation on the offshore end. Thus the need for fast and reliable communication is obviated which ensures reliable operation. Such a communication-less scheme is compared against the conventional approach involving remote communication of onshore grid frequency to the wind farm site. Along side physical and analytical justification, a case study is presented to demonstrate that the communication-less scheme work similar to the conventional one in terms of reducing grid frequency variations.

One challenge with the communication-less scheme is it relies on DC link voltage variation as a means of obtaining a offshore frequency variation proportional to that on the onshore side. Depending the chosen droop gains, limits on DC link voltage could disrupt the proportionality between onshore and offshore frequency variations. Further work is necessary to address these issues properly with a more realistic case study.

REFERENCES