AC Grid Forming by Coordinated Control of Offshore Wind Farm connected to Diode Rectifier based HVDC Link – Review and Assessment of Solutions

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20th European Conference on Power Electronics and Applications (EPE'18 ECCE Europe), , Riga, Latvia

Preliminary version

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Acknowledgments

This research work was conducted at the SuperGrid Institute which is funded by the French National Research Agency.

Keywords

≪Windgenerator systems≫,≪Control methods for electrical systems≫, ≪Power management≫, ≪HVDC≫

Abstract

Diode Rectifier (DR) based HVDC transmission can significantly reduce system costs and foot print of an HVDC power station for Offshore Wind Farms (OWFs), but as a consequence, the control of the offshore AC grid becomes challenging. The replacement of the offshore Voltage Source Converter (VSC) by a passive DR leads to major research questions pertaining to the control of the offshore AC grid. To achieve the wind farm operation and seamless power extraction, many grid forming solutions have been devised. This paper reviews a few of the major control solutions for AC grid forming and operation of DR-HVDC based OWFs, following which a comparison is made between them. Then two of these solutions are selected and implemented in a study case OWF model. By using the simulation results and further analysis, the approaches adopted by these two solutions are elaborated further and the various challenges regarding the operation and control of the DR-HVDC based OWF are highlighted.

Introduction

With the current pace of Offshore Wind Farm (OWF) development, cumulative installed capacity in Europe could be more than 49 GW by 2030 and considering certain positive scenarios[1], it might even reach 98 GW by 2030. OWFs over long distances are generally connected to the AC grid through HVDC transmission. The Voltage Source Converter (VSC) is the preferred converter technology over Line Commuted Converter (LCC) for power conversion applications due to various advantages[2] like avoidance of harmonic filters and reactive power sources, black start capability, ability to use Crossed Linked Polyethylene (XPLE) cables etc.

The Modular Multilevel Converter (MMC) is the extensively used VSC HVDC technology today for grid integration of distant OWFs. The relevant wind generator types today for HVDC based OWFs are the Type 3 or Doubly Fed Induction Generator (DFIG) and the Type 4 or Full Scale Converter (FSC) coupled with Permanent Magnet Synchronous Generators (PMSGs)[2]. The latter technology is prominent in the case of larger wind turbines (capacity greater than 5 MW). The offshore AC grid voltage and frequency is controlled by the offshore VSC converter in this architecture. This VSC operates in grid forming mode, while the wind generators inject power into the established AC grid and thus operating in grid following mode. The capital cost, foot print and control complexities of the MMC based HVDC transmission technology have always been matters of great concern in driving the offshore projects forward.

The introduction of Diode Rectifier (DR) as the offshore converter for HVDC transmission or the DR-HVDC is advantageous in terms of cost, foot print and losses[3]. But, newer challenges arise, for instance, the control of the offshore AC grid voltage and frequency, synchronization of Wind Electric Generators (WEGs) etc., among others. Also the HVDC voltage is controlled by the onshore VSC and thus the DR output DC voltage must surpass this aforementioned voltage to allow its conduction and the transfer of power to the onshore station. The OWF operation and control in the case of DR-HVDC, can be achieved either by changes in the architecture by including a start-up power supply with external synchronization mechanism, or by using offshore storage system for energization [4] and / or by modifying the control algorithms of the wind electric generators (WEGs) to tap their inherent grid forming capabilities. Another interesting approach is to employ an offshore VSC in series (on the DC side) with the DR, to exploit the grid forming capability of this VSC [5] thus permitting the WEGs to retain their grid following control scheme. Additionally, this offshore VSC can act as an active filter, targeting the characteristic harmonics pertaining to the DR.

Fig. 1 shows the electrical architecture of the DR-HVDC based OWF. Multiple WEGs are connected in strings to form clusters. Multiple clusters are integrated at the Point of Common Coupling (PCC) with reactive power compensation (capacitance bank $\boldsymbol{C_g}$) and harmonic filters (denoted as $\boldsymbol{Z_f}$). The collection network until PCC is generally at Medium Voltage (MV) level (66 kV). Then the DR transformer steps up the voltage to the desired value and this transformer can be of different configurations (two winding or three windings with zig zag connections for necessary phase shifts in the secondary windings) depending on the HVDC system voltage design and the use of 12 or 24 pulse DRUs (Diode Rectifier Units). Additional equipment for the start-up could be included as part of the network, for instance additional energy storage near DRU stations or at WEGs, AC umbilical cables (indicated in the figure) etc.

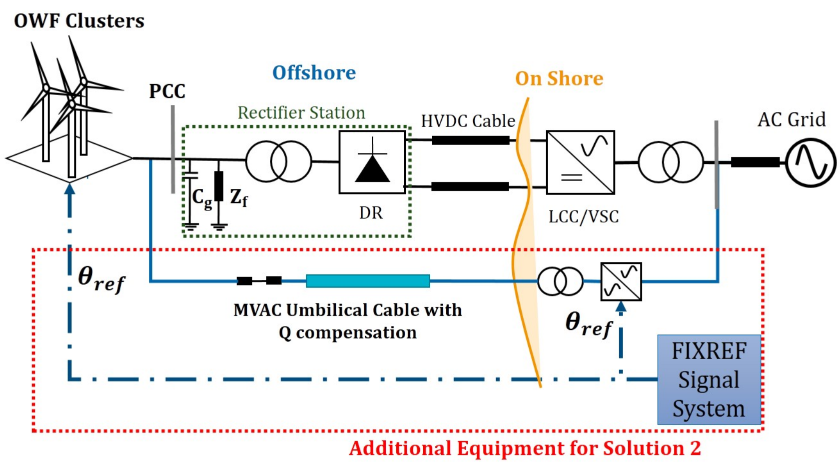


Fig. 1: Overview of DR-HVDC based OWF Architecture

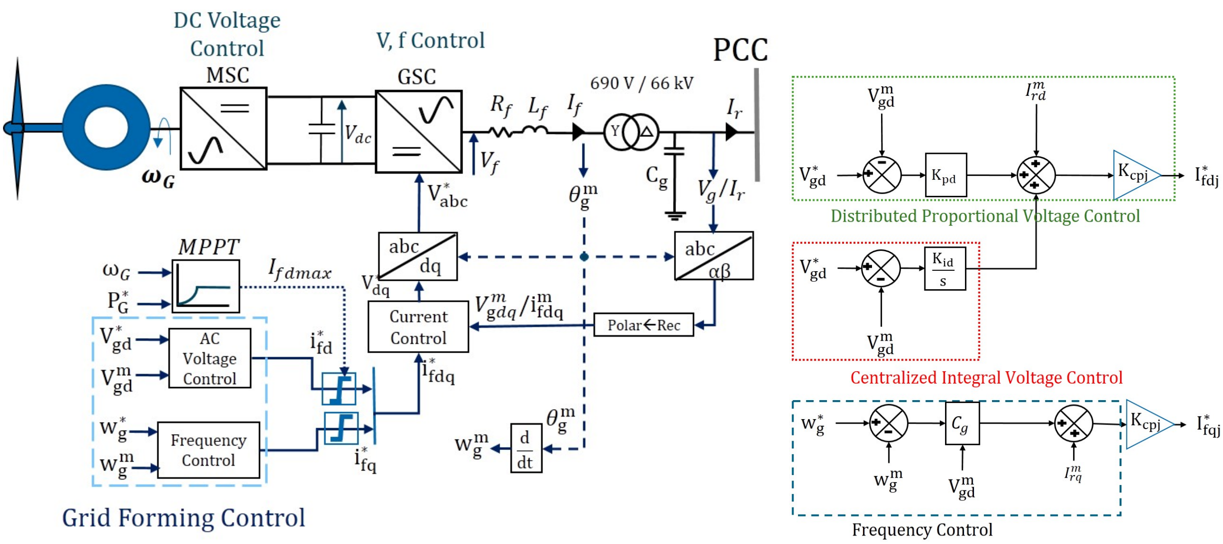
This paper reviews in general, some of major solutions ([6] - [8]) tackling the control challenges of the DR-HVDC based OWF and then compares the grid architectural changes and converter control strategies implemented to achieve the grid integration of the offshore wind energy. A comprehensive comparison is made between these three solutions, in order to present clearly, the differences in their approaches. Then two of three aforementioned solutions ([6], [7]) are simulated in an OWF study case model using MATLAB Simulink and the results show how these solutions achieve the control and power management goals. By using simulation results, further analysis and comparisons are presented. The major challenges that have been solved and that continue to persist are highlighted.

Control Solutions for AC Grid Forming in the DR-HVDC based OWF

Solution 1 – Distributed Control of Frequency and the PCC Voltage

The first solution [6] was initially proposed with LCC based HVDC converter onshore, while a later work showed a successful implementation using a VSC HVDC converter model onshore[9]. This solution proposes changes in the control of the WEG converters (considering only type 4 generators) in order to provide grid forming capability to the Grid Side Converters (GSCs). The onshore VSC converter control functions are not especially modified, meaning its primary function is the control of the HVDC link voltage. The voltage control at the offshore PCC is achieved by setting appropriate d-axis current references for the GSCs of the WEGs, taking advantage of the dynamic coupling between the AC voltage and the active power produced by the WEG. The frequency control is achieved by setting appropriate q-axis current references for the GSCs, thanks to the dynamic coupling between the grid frequency and the exchanged reactive power. This type of control scheme has been well demonstrated in the work [10], considering the converter fed low voltage micro grids with a prominent capacitance in the PCC.

A single aggregated grid forming WEG connected to the PCC is shown in the Fig. 2(a). The DC bus voltage ($\boldsymbol{V_{dc}}$) of the back to back converter interface of each WEG is controlled by the Machine Side Converter (MSC), while the GSC is involved in controlling the AC voltage and frequency at the offshore capacitance bus, which is located in the PCC. Once the AC grid is formed and DR starts conducting, the AC voltage control loop becomes saturated and in-turn irrelevant. Then, the GSC begins to perform the maximum power point tracking (MPPT) by dynamically setting the limit of the d-axis current, according to the power set point. This along with the pitch control of the wind turbine, ensures the optimal power extraction for all wind speeds below the rated speed and also, the rated power production above the rated wind speed.



(a) (b)

Fig. 2: (a) Grid Forming Solution Proposed for Multiple Wind Generators[6] (b) Distributed and Centralized Parts of the Controllers

In case of multiple WEGs, each GSC participates in the grid forming according to its participation coefficient. These participation coefficients $\boldsymbol{K_{cpj}}$ are calculated according to the equation (1) for each WEG, in a wind farm with a total of $\boldsymbol{J}$ wind turbines.

$$K_{cpj} = \frac{Rated\ power\ of\ the\ generator\ j}{Total\ power\ capacity\ of\ the\ OWF} \quad where \quad \sum_{j=1}^{J} K_{cpj} = 1 \tag{1}$$

The static error of the PCC voltage is eliminated using a centralized integral controller action for all WEGs. The proportional part of the controllers are distributed across the GSCs as shown in Fig. 2(b). Thus all GSCs are operating in grid forming mode. This solution doesn't provide the details of how exactly the synchronization is achieved among the WEGs. Also since this solution controls the AC voltage at the offshore pilot bus (PCC) the measurement and communication of this AC voltage to all the WEGs is necessary.

Solution 2 Grid Forming by Fixed Reference Frame and AC Umbilical Cable

This solution has been proposed for both type 3 and type 4 generators [7]. This solution provides the WEGs with grid forming capability to the WEGs while enabling the GSCs to retain the conventional current control scheme (V_{dc} control). This is done by providing a fixed reference frame in dq (and thus the name FIXREF) for all GSCs, using GPS / radio signal, to have high accuracy. The conventional closed loop current control is modified into an open loop system with the removal of the PLL and use of the external angle by all the GSCs. Theoretically, instability problems cannot occur in this open loop scheme for synchronization due to the elimination of the closed loop synchronization scheme of the PLL [11]. The control scheme for a single WEG is shown in Fig. 3.

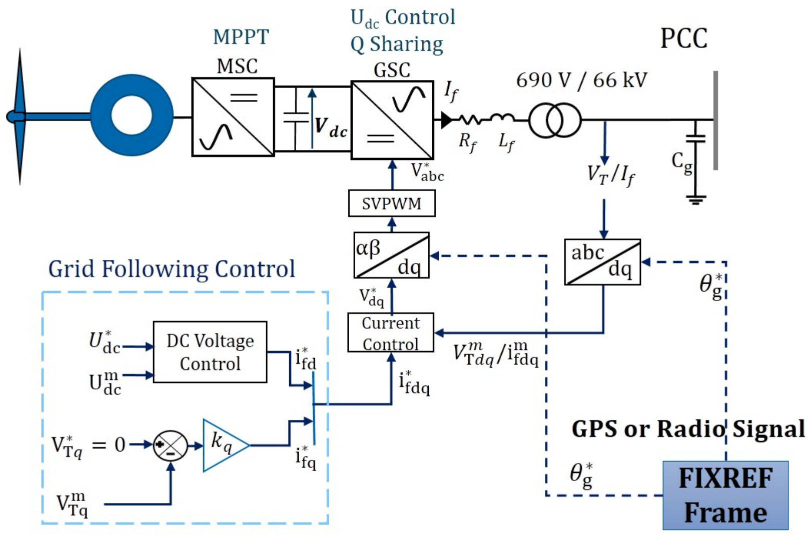


Fig. 3: Control Scheme for Solution 2

The start-up / black start operation is ensured by additional equipment in the offshore grid. An MVAC cable with an AC/AC converter from onshore grid is connected to the offshore PCC, as indicated in Fig. 1. This converter also uses the same FIXREF signal. A droop factor ($\boldsymbol{k_q}$) is introduced in the control scheme for the reactive power sharing among the GSCs as shown in Fig. 3. For a particular WEG, this droop factor can be set such that the WEG with lower active power production participates more in the reactive power contribution than the one with higher active power production. This solution relies on the availability of a robust communication network (GPS / radio based) in order to transmit the FIXREF angle in real time to all the GSCs, to ensure seamless OWF operation.

Solution 3 Grid Forming by PLL based Distributed AC Voltage and Frequency Control

The solution described in [8] uses the PLL already available in the Type 4 WEGs in order to enable synchronization. The startup of the offshore network is achieved by using these WEGs with additional storage and then the remaining WEGs are connected and synchronized with the network by using the proposed control scheme shown in Fig. 4. Each WEG is equipped with an LC filter and controls the voltage and frequency at its terminal ($\boldsymbol{C_f}$) and synchronizes with other WEGs when connecting with the network. Thus a distributed control of the AC voltage and frequency is achieved by using the local control actions of each WEG. The offshore PCC voltage is built up as a consequence of this distributed control, leading to the DR conduction and eventually, the power transfer to onshore AC grid. The voltage references (V_{fd}^*, V_{fq}^*) are derived by the power control loops as shown in the Fig. 4. The reactive power sharing is achieved by a droop scheme as shown in the same figure. Similar to solution 1, this work exploits the dynamic relationship between the grid frequency and the reactive power contributions of the WEGs.

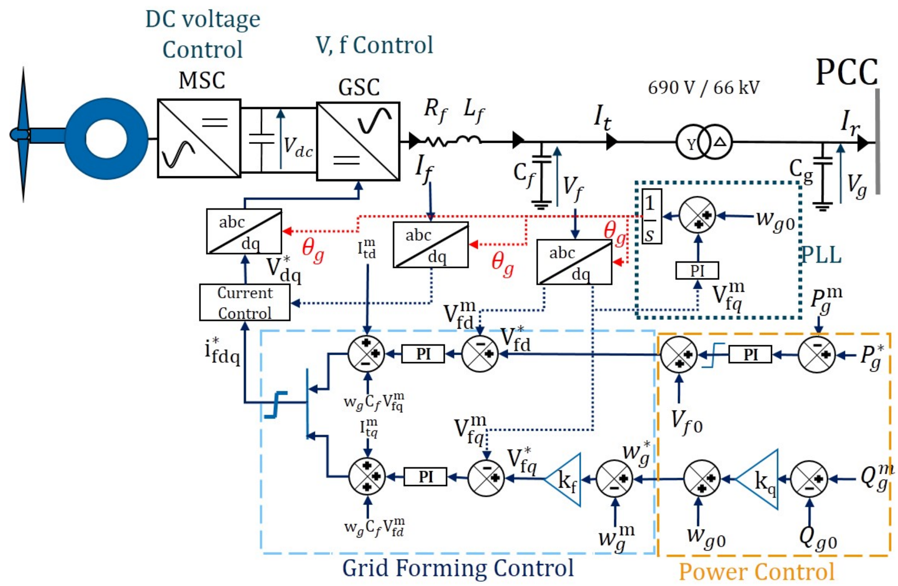


Fig. 4: Control Scheme for Solution 3

The reference for frequency is derived by using the equation (2), for a nominal reactive power (Q_{g0}) and the measured reactive power (Q_g^m).

$$\omega_g^* = k_q(Q_g^m - Q_{g0}) + \omega_{g0} \tag{2}$$

The problem of synchronization is solved by setting the V_{fq}^* according to the frequency setting for the AC network. The frequency droop controller is expressed as follows in the equation (3), for the measured frequency.

$$V_{fq}^* = k_f(\omega_g^* - \omega_g^m) \tag{3}$$

In this solution, there is no need of any remote measurements to enable grid forming and each WEG can operate independently and be synchronized using an appropriate q-axis current injection.

Comparison of the Grid Forming Solutions for DR-HVDC OWF

Following the brief description of each solution, Table I presents the major differences between the solutions. The biggest motivation of adding an Umbilical AC cable and an external signal source for synchronization of GSCs in Solution 2, is to keep the conventional MSC and GSC control functions unchanged. The major difference between the solutions 1 and 3 is that in the former the PCC voltage (remote voltage) is controlled by multiple WEGs while in the latter, local AC voltage at individual WEG terminal is controlled. The solutions 1 and 3 also differ in the aspects of start-up, synchronization and requirement of remote measurements for control (for solution 1).

Simulation and Analysis of the Grid Forming Solutions

In order to provide further analysis of the reviewed solutions, the electrical architecture for the interconnection of three aggregated WEG strings (with inter-array and string cables) as shown in Fig. 5 is modelled with appropriate control implementations. The parameters for the offshore network compone-

Table I: Comparison of the Grid Forming Solutions for DR-HVDC OWF

Characteristics	Solution 1 [6]	Solution 2 [7]	Solution 3 [8]
GSC Control functions	PCC Vf control & MPPT	DC link voltage & reactive power control	Local Vf control & MPPT
Synchronization	Problem not addressed	External dq reference frame provided by Radio/ GPS signal(s)	PLL-based
MSC major Control function	DC link voltage control	MPPT	DC link voltage control
Data communication requirement	For sending PCC voltage measurement to the WEGs	For FIXREF signal reception by the WEGs instantaneously	Not required
Black Start of Offshore AC network	By WEGs	By AC Cable and FIXREF	By additional energy storage in WEGs

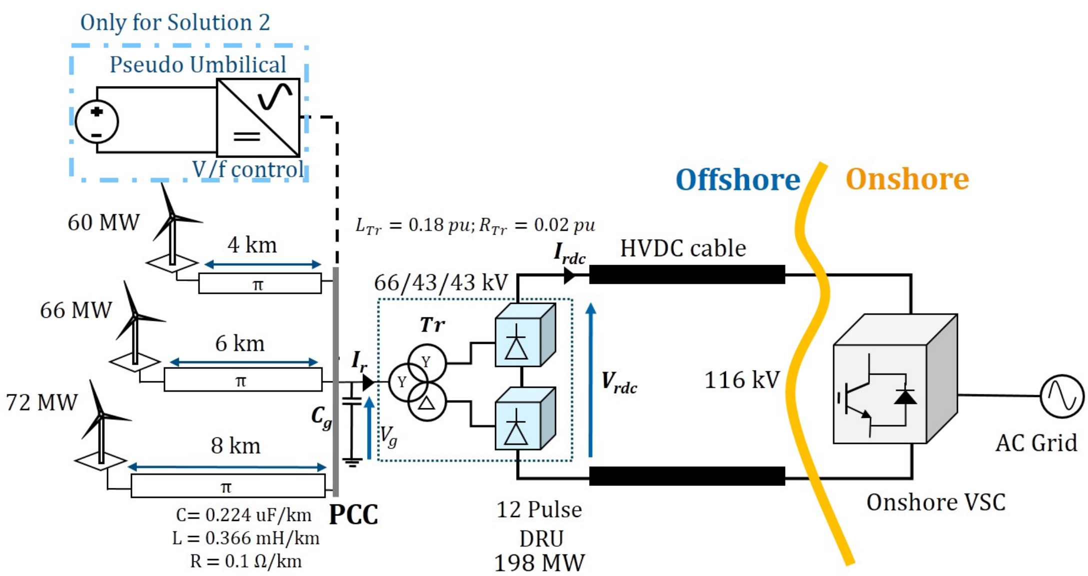


Fig. 5: Study Case Electrical Architecture with relevant network parameters

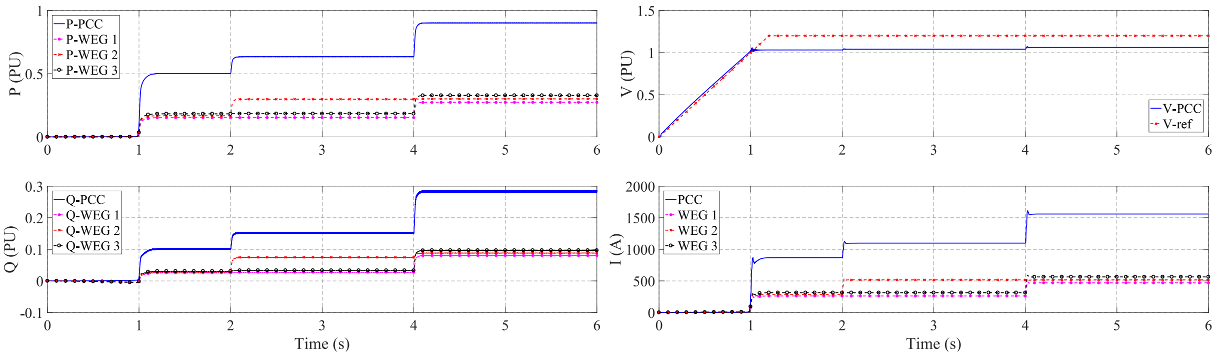
nents like the DR transformer and AC cables are obtained from [12] and are depicted in the Fig. 5. Certain simplifications made in the dynamic models include – assuming a constant DC voltage for the inner DC bus of the GSC in case of the solution 1 and assuming good HVDC voltage control by Onshore VSC. These assumptions were done in order to focus on the analysis of the offshore AC collector network control and operation. The GSCs were modelled by using the average value model of the two level VSC and the DR was modelled by using a switched model. The aggregated submarine cables were modelled using the pi-model of a transmission line. Simulations were conducted in MATLAB Simulink environment. The different simulation cases considered for the implementations of solutions 1 and 2 are indicated in Table II. The simulation and analysis of the solution 3 are not done in this paper.

Table II: Simulation Cases Selected for the two Solutions

Solution	Case 1	Case 2
Solution 1	Without 66 kV collection network model	With 66 kV collection network model
Solution 2	Without reactive power droop $k_{q1} = k_{q2} = k_{q3} = 1$	With reactive power droop $k_{q1} = 0.6; k_{q2} = 0.3; k_{q3} = 0.1$

Results and Analysis of Solution 1

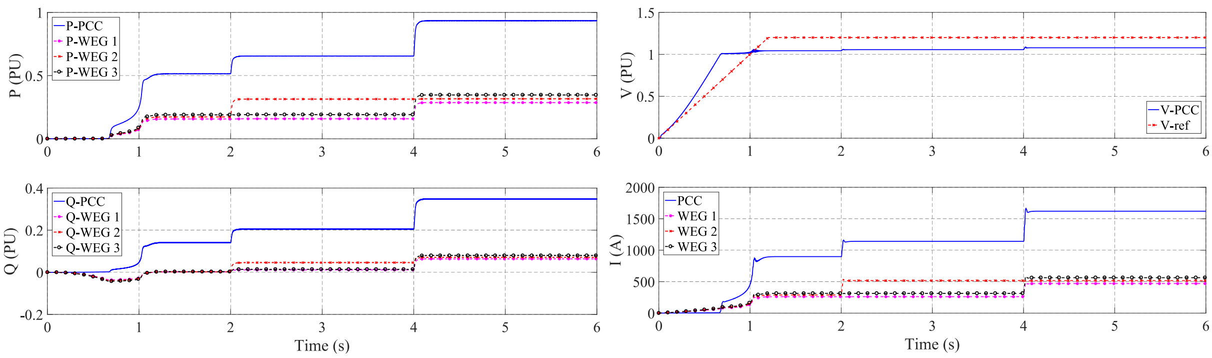
The results for the implementation of the solution 1 proposed in [6] with above assumptions taken into account are presented below. In the simulation case 1 (Table II), the 66 kV collection network model (AC sub-marine cables) is not included between the WEGs and the PCC. The distributed voltage and frequency control illustrated in Fig.2 (b) has been implemented for all the aggregated WEG models. The WEGs are assumed to produce 50% their rated capacities when the diode starts conducting at t=1s and then higher power references are set at t=2 s for WEG 2 (to 90% capacity) and finally at t = 4 s for WEGs 1 and 3 (to 90% of their own capacities); the active and reactive powers at the PCC and at various WEG terminals are shown in Fig. 6 (a). There is a small increase in RMS voltage seen at PCC in Fig. 6(b) due to the effect of overlapping angle during diode commutation. Though it looks to have changed due to power injection events, the RMS rated voltage is below 1.1 pu which is generally the upper limit for the AC voltage during normal operation.



(a) (b)

Fig. 6: (a) Solution 1-Case 1 (a) Active and Reactive Power at various terminals in the OWF (b). Per Unit voltage at PCC and RMS currents at various terminals

The next simulation (Solution 1 case 2 in table II) was performed with inclusion of inter-array cables (in aggregated form) and also cluster cables. The results are shown in Fig. 7 (a) and Fig. 7 (b) for measured quantities at PCC and at each WEG terminal. It is seen that the RMS AC voltage at PCC reaches 1 pu (Fig. 7 (b)) before the voltage reference (V-ref) reaches 1 pu. Although the tuning of the controllers could be done to achieve a better control performance, the tuning of each WEG controller to achieve the goal is rather a complicated approach. The control of a remote bus (PCC) voltage is observed to be not the best approach in dealing with OWF control, especially also because the OWF collection network impedance is pre-dominantly capacitive.



(a) (b)

Fig. 7: (a) Solution 1-Case 2 (a) Active and Reactive Power at various terminals in the OWF (b). Per Unit voltage at PCC and RMS currents at various terminals

Results and Analysis of Solution 2

The solution 2 [7] is simulated with the same electrical architecture in Fig.5 i.e., with the aggregated AC submarine cable models. It is assumed that the MSC of each WEG performs satisfactory power control (MPPT) along with the pitch control of the wind turbine. This allows the simplification of the DC bus of each WEG by using a current source with a capacitance in parallel in the model. The start-up for this solution requires an Umbilical AC cable from onshore as shown in Fig. 1.

The function of this AC umbilical is modelled by a GSC connected directly to AC offshore PCC to control the AC voltage and frequency. This Pseudo Umbilical(shown in Fig. 5) acts as the slack bus to the entire network during the start-up. The active power of this pseudo umbilical cable is limited to 5% of the total capacity of the wind farm (in Fig.8 active, reactive powers of pseudo-umbilical are shown as P-M, Q-M respectively). Also in Fig. 8 the reactive power at the PCC terminal due to the offshore transformer and DR operation is shown as Q-PCC. Using the pseudo umbilical cable, the voltage and frequency of offshore AC grid is controlled, leading to the DR conduction eventually at t=1s shown by the PCC RMS voltage at 1 pu in the Fig. 8 (bottom). Also in Fig. 8 (top), it is seen that after the grid forming at t=1s, until t= 3s, the pseudo-umbilical GSC is injecting a reactive power of 0.12 pu and compensating for all the cluster / inter array cables capacitive impedances. Then at t=3 when the WEGs start the injection of active and reactive power (seen in one of the simulation cases in Fig. 9), reactive participation by the pseudo umbilical drops to around 0.07 pu. An analysis of the effect of reactive power droop implementation has been made. Two different simulation cases as indicated in the table I are considered for the solution 2. The AC voltages at the WEG terminals were observed to be the same in the simulation cases 1 and 2 and they are presented in the Fig. 8 (bottom).

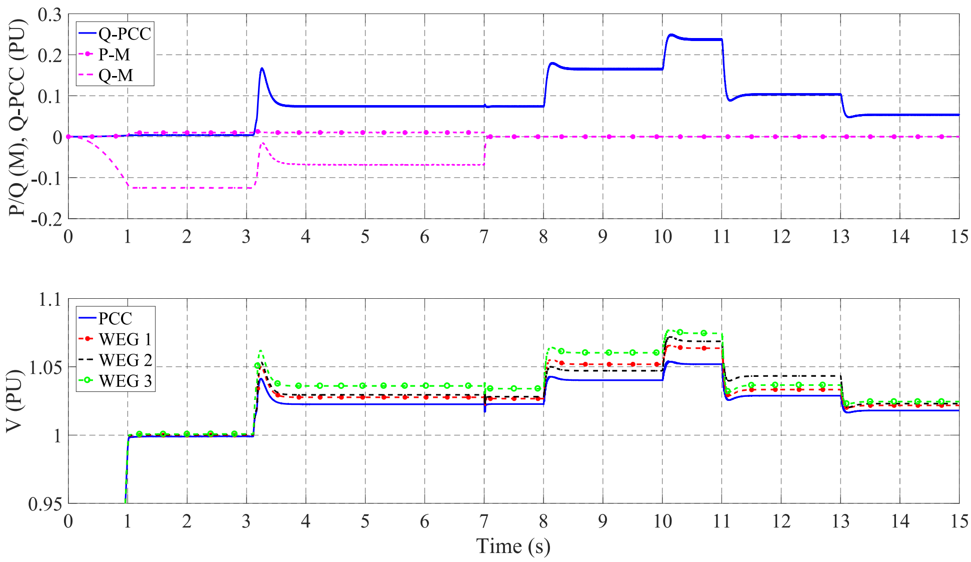


Fig. 8: (Top) P, Q injection by the Pseudo Umbilical and Q at PCC; (bottom) RMS AC voltage at various terminals

The results for simulation of case 1 (without reactive power sharing) is shown in Fig. 9 with different power steps for all the WEGs. At t=10s all WEGs are producing at 80% their rated capacities (Fig. 9 top). A few seconds after time t=3s when the WEGs start injecting power, the pseudo-umbilical GSC is switched off at t=7s (as shown with P-M and Q-M tending to zero in Fig. 8). The reactive power contributions by the WEGs correspond to their power rating and they increase uniformly due to the increase of the wind power production. For instance, from t=3s until t=10s, WEG 3 (with the highest power rating) contributes higher to the reactive power sharing than the remaining WEGs in this time interval. The major disadvantage in this kind of reactive power sharing is that, the GSC with the highest active power injection has the highest reactive power load; this leads to possible overloading one or few of the GSC, when they are injecting rated active power. The other WEGs with lower power production could compensate for this additional reactive power requirement.

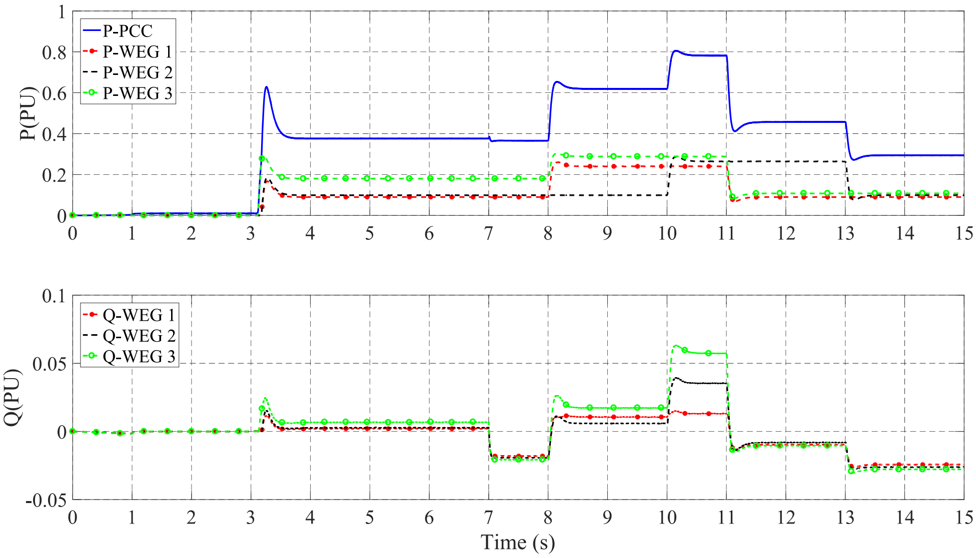


Fig. 9: Solution 2, Case 1: Without Q droop implementation - P and Q at various terminals

The case 2 of solution 2 has been implemented with the reactive power droop parameters set for each WEG (as in Table II). These droop parameters are not modified throughout the simulation, but they should be dynamically, according to real time active power production of the WEGs. The active and reactive power at various terminals are shown in Fig. 10. Again the same power generation scenario is considered for all the WEGs as in the simulation case 1 explained previously, for an easy comparison. The reactive power participation of WEG1 is higher from t = 7s until t = 15 s as seen in Fig. 10 (bottom), compared to the case 1 results in Fig. 9. Between t = 7s and t = 8 s, when WEG 3 injects the maximum active power compared to the other WEGs, the WEG 1 contributes the maximum for reactive power sharing. Again, the WEG 1 and WEG 2 contribute more to reactive power sharing, for time interval between t = 11 s and t=13 s, compared their contributions in simulation case 1 (Fig. 9). Thus, particularly in these two time intervals (7-8 s; 11-15 s), the higher participation of WEG 1 due to higher droop factor (k_{q1}) is evident (as in Fig. 10). This could be the main advantage achieved in the design of WEG reactive power droop compared to the Solution 1 and this permits to avoid the GSC overloading in case of full capacity power production in some of the WEGs and also to avoid unwanted circulation of reactive power in case of multiple clusters / strings.

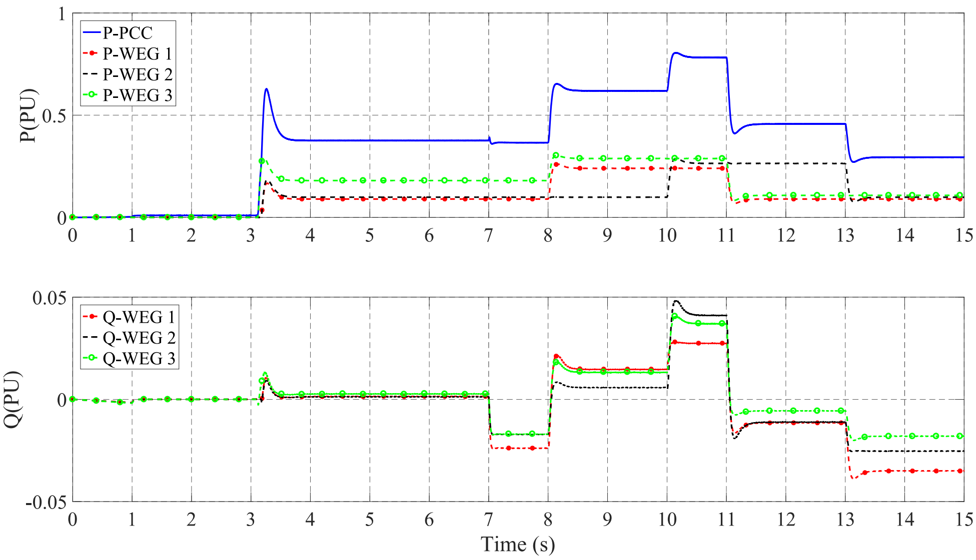


Fig. 10: Solution 2, Case 2: With Q droop implementation - P and Q at various terminals

Conclusion

Though DR-HVDC is economically quite interesting, many challenges arise if the control capabilities of the offshore VSC station is lost. The objective of this paper has been to shed light on the different possible approaches (in this case three solutions have been selected) to solve the various challenges of the DR-HVDC based OWF. Two of these solutions have been simulated and analysed in a study case OWF model. Regarding the solution 1, the approach to control the remote PCC AC offshore voltage could become quite complicated, especially when AC submarine cables are connected in the offshore network and this issue has been demonstrated in this paper. Considering solution 2, the need for an Umbilical AC cable and a robust communication network to enable grid forming (FIXREF) are highlighted while the operation of the network in case of failure of the communication network is not dealt. However the reactive power sharing using droop implementation is found to be useful, especially to avoid GSC overloading when some of the WEGs inject full power. This advantage has also been explained in the paper through simulations. Although the solution 3 has not been implemented, it seems to address some of the major challenges - control using local measurements and synchronization. In this solution, start-up is said to be achieved using additional storage devices but its design aspects have not been clearly explained. Also the impact of grid forming control schemes on the wind turbines have not been discussed in detail. The research on DR-HVDC OWF is a work in progress and it is important that further development of any solution have to account for the most if not all the aspects of the challenges namely - start-up, synchronization, and communication-less control.

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