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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Keywords

Wind energy, Wind generator systems, Generation of electrical energy, Power management, HVDC

Abstract

Diode Rectifier (DR) based HVDC transmissions can significantly reduce system costs and foot print of an HVDC based Offshore Wind Farm (OWF), but 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 stable wind farm operation, 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. Then these solutions are compared based on their approach in solving the major challenges involved. Then two of the solutions are selected for implementation in a study case electrical architecture. Using the simulation results and further analyses, the approaches adopted by these two solutions are elaborated further and the various challenges of DR-HVDC based OWF technology 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 become 98 GW by 2030. Wind farms over long distances are generally connected through HVDC transmission to the AC grid. The VSC (Voltage Source Converter) is the preferred converter technology over LCC (Line Commuted Converter) for HVDC offshore transmission applications due to various advantages[2] like avoidance of harmonic filters and reactive power sources, black start capability, ability to use XPLE cables etc.

The VSC technology used extensively today for grid integration of distant OWFs is the MMC (Modular Multilevel Converter) HVDC. The relevant wind generator types today for HVDC based OWFs are Type 3 or DFIG (Doubly Fed Induction Generator) and Type 4 or FSC (Full Scale Converter) coupled generators [3]. 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, in turn 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 reduction of costs, foot print and losses[4]. But, newer challenges

arise, for instance, the control of the offshore AC grid voltage and frequency, synchronization of WEGs etc., among others. In case of DR-HVDC based OWF, the HVDC voltage is controlled by the onshore VSC and thus the DR output DC voltage must surpass this aforementioned voltage to allow conduction and transfer of power to the onshore station. This functionality can be enabled either by changes in the architecture to have 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 (or current control scheme). Additionally, the offshore VSC can act as an active filter, targeting the characteristic harmonics pertaining to the DR.

The 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 $\boldsymbol{Z_g}$). The collection network until PCC is generally at Medium Voltage 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 winding 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 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.

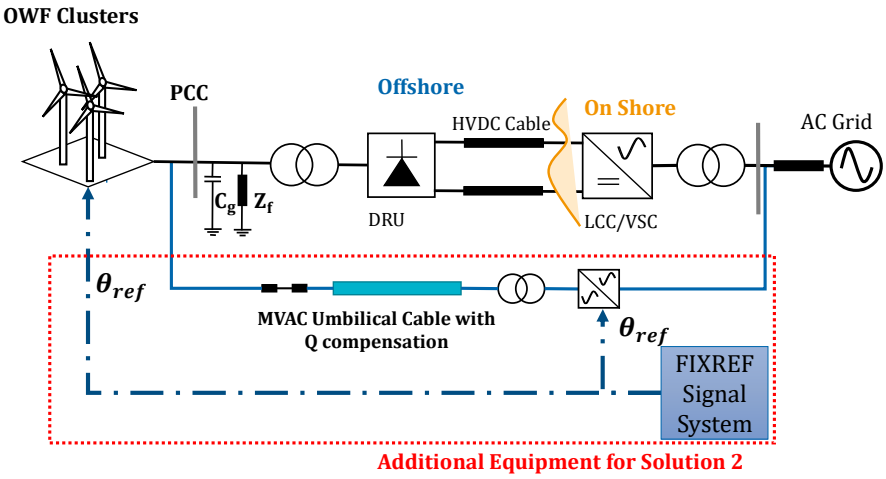


Fig.1: Overview of DR-HVDC based OWF Architecture

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

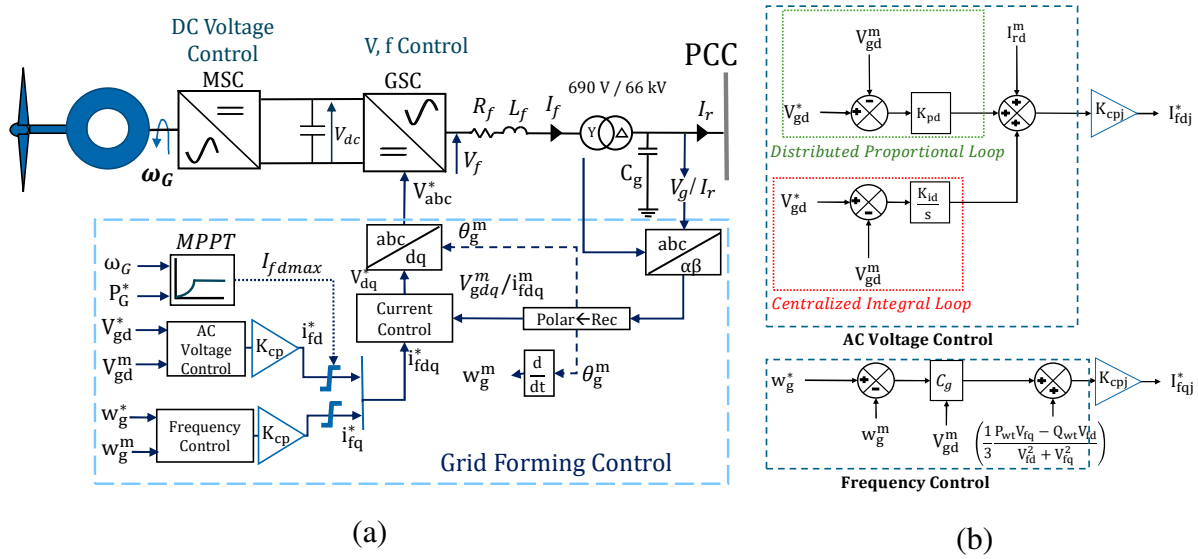
Control Solutions for AC Grid Forming in the DR-HVDC based OWF

Solution 1 – Distributed Voltage and Frequency Control

The solution 1 ([6], [7]) was initially proposed with an LCC based HVDC converter onshore, while a later work showed 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 GSCs (Grid Side Converters). 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 reference of the GSC, taking advantage of the dynamic coupling between voltage and active power. The frequency control is achieved using appropriate setting of the q-axis current of the GSC, thanks to the dynamic coupling between frequency and reactive power. This type of control scheme has been well demonstrated in works like [12], related to converter interfaced micro grids with a prominent capacitance in the network PCC.

A single aggregated grid forming WEG connected to the Point of Common Coupling (PCC) is shown in the Fig.2 (a). The DC bus voltage ($\boldsymbol{V_{dc}}$) of the back to back converter interface is controlled by the MSC, while the GSCs are involved in controlling the voltage and frequency at the offshore capacitance bus, which is the PCC. Once the AC grid is formed and DR starts conducting, the 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 necessary power set point. This along with the pitch control of the wind turbine, ensures optimal power extraction for all wind speeds below rated speed and 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, their GSCs divide the grid forming responsibility using participation coefficients. These participation coefficients $\boldsymbol{K_{cpj}}$ are calculated according to the equation (1) for each wind generator in a wind farm with a total of $\boldsymbol{J}$ wind turbines. The integrator part of PI controller for AC voltage control is centralized while the proportional parts of the controllers are distributed across the GSCs as shown in Fig.2 (b). Thus all GSCs are operating in grid forming mode.

$$K_{cpj} = \frac{Rated\ power\ of\ the\ generator\ 'j'}{Total\ power\ capacity\ of\ the\ OWF} \qquad where \sum_{j=1}^{J} K_{cpj} = 1 \qquad (1)$$

This solution doesn't provide details of how exactly the synchronization is achieved among the WEGs. Also there is a requirement of measuring and communicating the AC voltage at PCC to all the WEGs.

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 while enabling the GSCs to retain the conventional current control scheme (DC bus voltage 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 [12]. The control scheme for a single WEG is shown in Fig.3.

The start-up / black start of the network is provided by additional equipment in the offshore grid architecture. A Medium voltage AC (MVAC) cable with an AC/AC converter from onshore grid is connected to the offshore PCC, as indicated in Fig.1. This allows provision of auxiliary power supply for energizing the transformers, charging cables, powering up DFIGs (if part of the OWF) and supporting losses during the OWF start-up [7]. This converter also uses the same FIXREF signal for start-up. A droop factor (k_q) is introduced in the control scheme for 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 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 synchronization and seamless extraction of wind power.

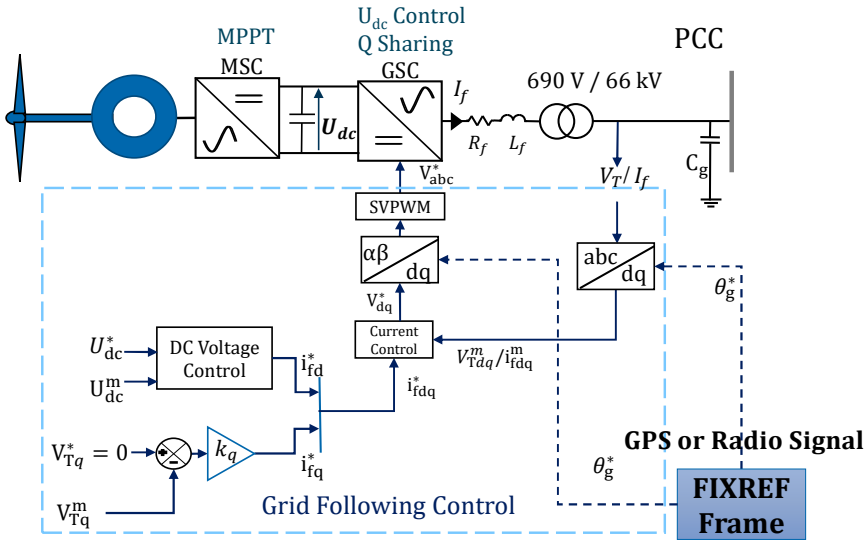


Fig.3: Control Scheme for Solution 2

Solution 3 – Distributed PLL based Control

The solution described in [8] uses the PLL already available as part of the Type 4 WEGs in order to enable synchronization. The startup of the offshore network is achieved using these WEGs with additional storage and then the rest of the WEGs connect and synchronize with the network using the proposed control scheme shown in Fig.4.

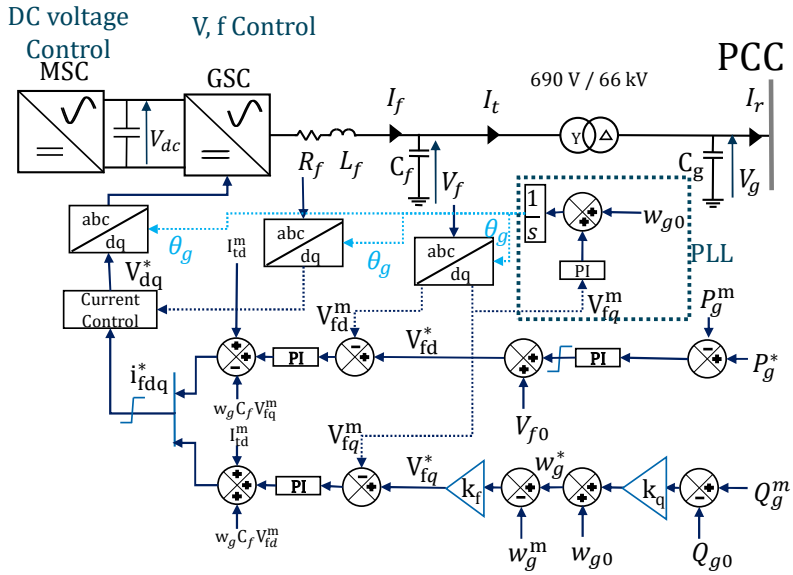


Fig.4: Control Scheme for Solution 3

The voltage references (V_{fd}^*,V_{fq}^*) are derived by control loops for active and reactive power respectively. A PI controller is used to set the power reference (P_g^* set according to the outputs from optimal power tracking algorithm) for the WEG eventually providing the reference value of V_{fd}^*. The reactive power sharing is achieved by a droop scheme as shown in the Fig.4. An additional reactive power loop is used along with the droop for setting the frequency reference. Similar to solution 1, this work exploits the dynamic relationship between frequency and reactive power. The reference for frequency is derived using the following equation (2).

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

The problem of synchronization is solved by setting the V_{fq}^* according to the frequency setting of the AC network. Thus the q-axis voltage reference is set accordingly when the measured frequency deviates from its reference. This kind of control can be implemented across all the GSCs to synchronize them. The additional frequency droop controller added is expressed as follows in equation (3)

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

In this solution, there is no need of any remote measurements to enable grid forming and the WEGs can function independently and auto synchronize using appropriate q-axis current injection.

Comparison of the Grid Forming Solutions

With the brief description of each solution, a table is presented (table I) showing the major differences among 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. It is seen that solution 1 and 3 are almost similar, except for the aspects of start-up, synchronization and requirement of remote measurements for control.

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

Characteristics	**Solution 1**	**Solution 2**	**Solution 3**
Method Name	Distributed Vf Control	Fixed Reference Frame (FIXREF)	Distributed PLL-based Control
GSC Control functions	Vf control & MPPT	DC link voltage and reactive power control	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	Yes, for sending PCC voltage measurement to the WEGs	Yes, for reception of FIXREF signal in real time by all the WEGs	Not required
Start Up /Black Start of Offshore AC network	By WEGs	By AC Umbilical and FIXREF	By additional energy storage in WEGs

Simulation and Analysis of the Grid Forming Solutions

In order to provide further analysis of the reviewed solutions, the electrical architecture shown in Fig.5 is modelled with appropriate control implementations. Each of the three clusters were aggregated (along with their inter array and cluster cable parameters) to represent three WEGs.

The parameters for the offshore network like the DR transformer and AC cables, were obtained from [13] and are depicted in the Fig.5 directly. Other simplifications were made in the dynamic models involved assuming a constant DC voltage for the inner DC bus of the GSC in case of the solution of solution 1 [14] and assuming good HVDC voltage control performed 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 using average value model of the two level VSC and the DR was modelled using switched models. 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 implementation and analyses of the solution 3 is not done in this paper.

Table II: Simulation Cases Selected for the two Solutions

Solution	**Case 1**	**Case 2**
Solution 1	Without AC marine cables	With AC marine cables
Solution 2	Without reactive power droop $k_{q1} = 1\,;\ k_{q2} = 1;\ k_{q3} = 1;$	With reactive power droop $k_{q1} = 0.6\,;\ k_{q2} = 0.3\,;\ k_{q3} = 0.1\,;$

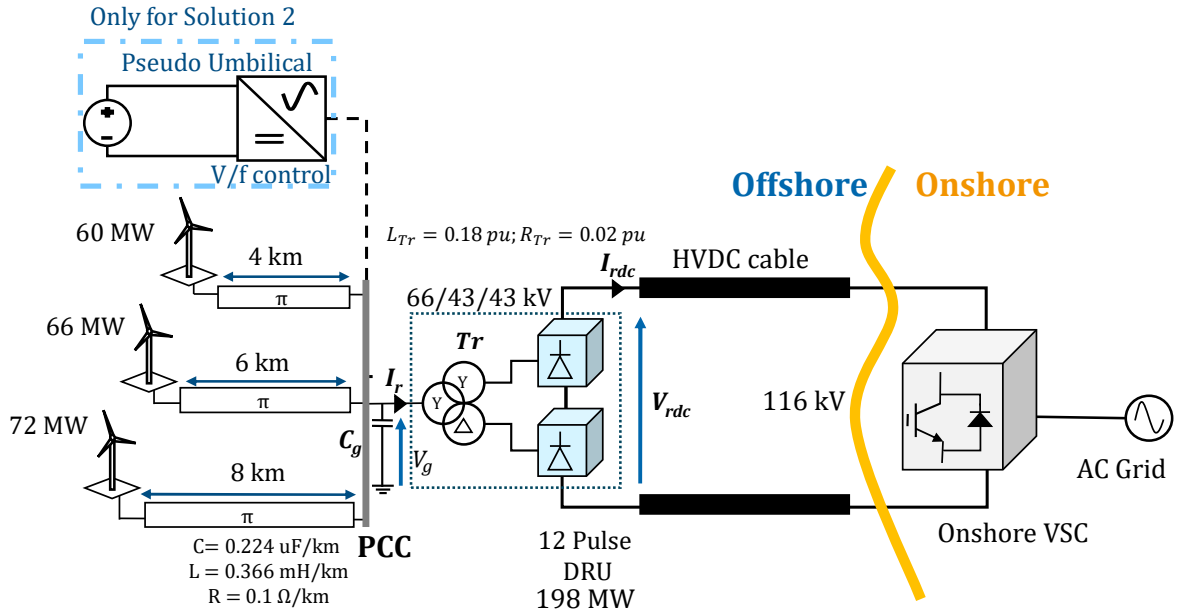
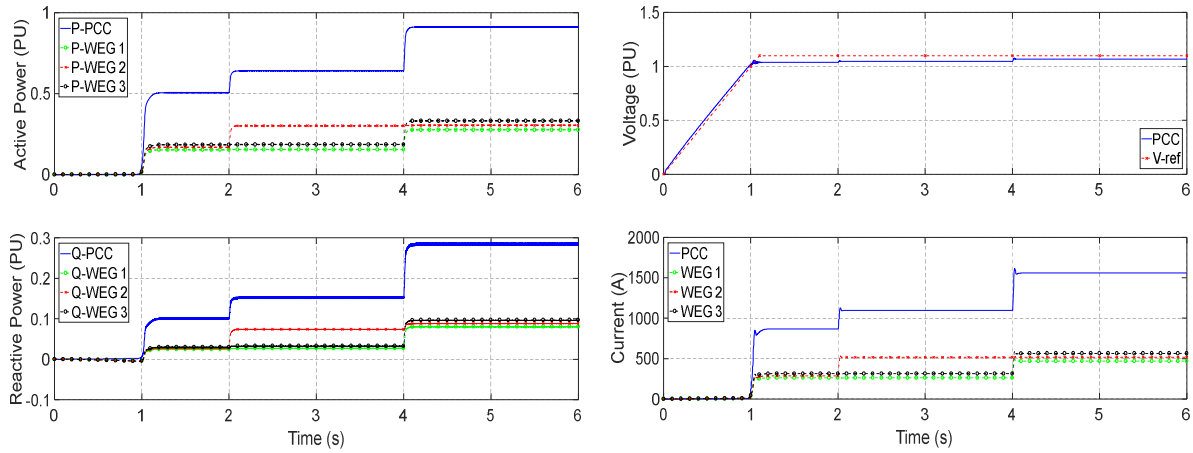


Fig.5: Study Case Electrical Architecture with relevant network parameters

Results and Analysis of Solution 1

The results for implementation of the solution 1 proposed in [14] with above assumptions taken into account are presented below. In the case 1 simulation of solution 1, no AC marine cables are 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 is 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 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 upper limit for normal operation for voltage.

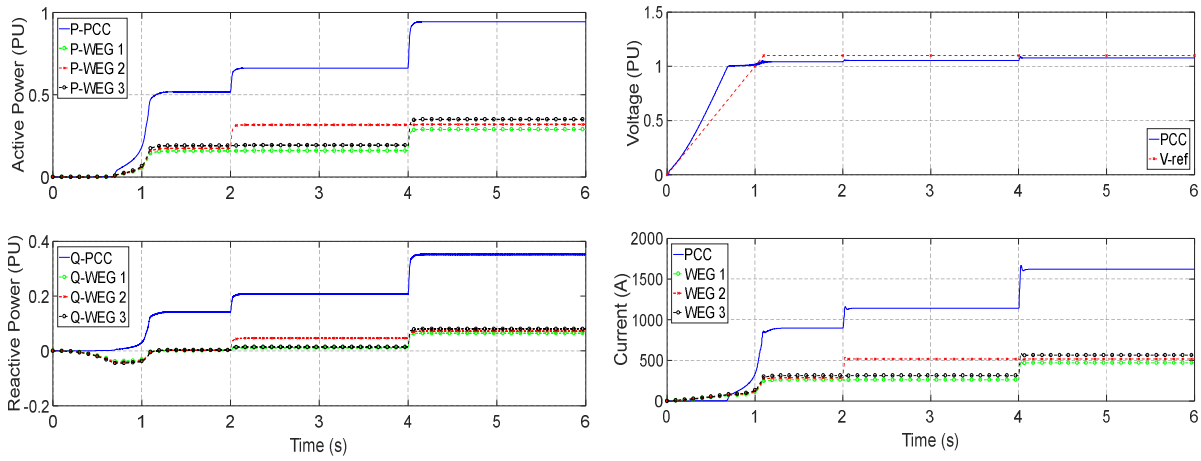


(a) (b)

Fig.6: Solution 1-Without AC Marine Cables (a) Active and Reactive Power at various terminals in the OWF (b). PU 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 capacitive impedance included in the network because of the AC marine cables cannot be taken into account in the control for each WEG and thus the remote PCC voltage control may not be successfully achieved in all cases. This effect of cables could be crucial because the coordinated and precise control of the wind generators is necessary to ensure stable AC grid operation. Thus control of a remote bus (PCC) voltage is rather not the best approach in dealing with OWF control, especially also because the OWF collection network dominantly capacitive.



(a) (b)

Fig.7: Solution 1 – With AC Marine Cables (a) Active and Reactive Power at various terminals in the OWF (b). PU voltage at PCC and RMS currents at various terminals

Results and Analysis of Solution 2

The solution 2 [12] is simulated with the same electrical architecture in Fig.5, considering the aggregated AC marine cables. It is assumed that the MSC of each WEG performs satisfactory power control along with the pitch control of the wind turbine (MPPT). This allows to simplify DC bus of each WEG using a current source with a capacitance in parallel. The start-up for this solution requires an Umbilical AC cable from onshore as shown in Fig.1.

The function of this umbilical is mocked by a GSC connected directly to AC offshore PCC to control the voltage and frequency. The Pseudo Umbilical acts as the slack bus to the entire network during the start-up (shown in Fig.5). The active power of this pseudo umbilical 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 PCC terminal due to the offshore transformer and DR operation is shown as 'Q-PCC'. Using the pseudo Umbilical the voltage and frequency of offshore AC grid is controlled leading to DR conduction eventually at t=1s shown by the PCC RMS voltage at 1 pu in Fig.8 (bottom).

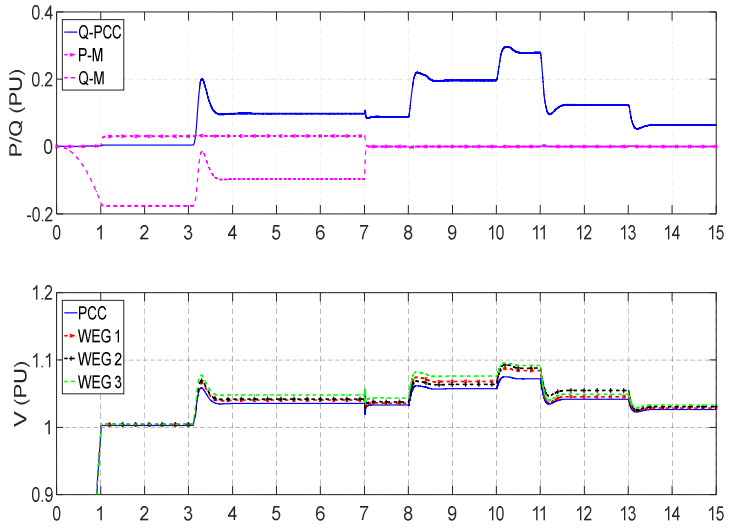


Fig.8: (Top) P, Q injection by the Pseudo Umbilical and Q at PCC; (bottom) RMS AC voltage at various terminals

Also in Fig.8 (top), it is seen that after grid forming at t=1s, until t= 3s, the pseudo-umbilical GSC is compensating for all the cluster / inter array cables' capacitive impedances (close to 0.18 pu). Then at t=3 when the WEGs start injecting active and reactive power (seen in Fig 10), reactive participation by the pseudo umbilical drops close to 0.08 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.

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 increase in power production of the entire wind farm. For instance, from t=3s until t=10s, WEG 3 (with the highest power rating) contributes higher reactive power than that of the rest of the 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.

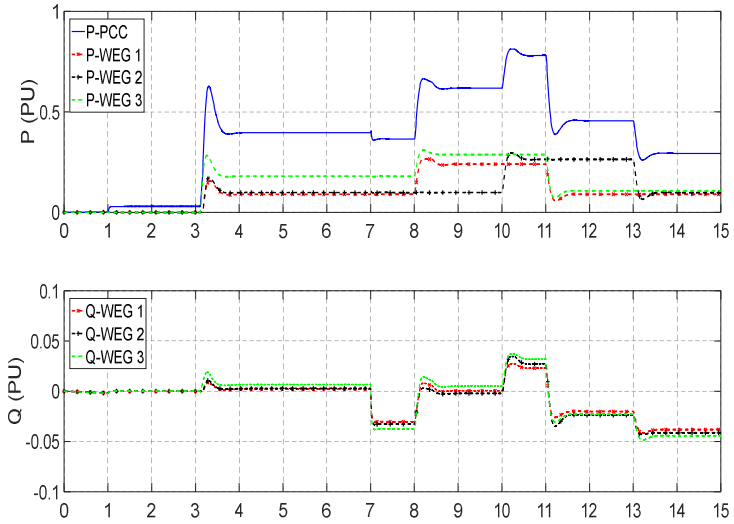


Fig.9: Solution 2, Case 1: Without Q droop implementation – P and Q at various terminals

The second simulation case has been then implemented with the reactive power droop parameters set for each WEG (as in Table I). These droop parameters are not modified throughout the simulation, but they could be dynamically set if necessary, according to real time active power production of the WEGs. The active and reactive power at various terminals are shown Fig.10. Again the same power generation scenario is considered for all the WEGs as in simulation case 1 explained previously, for easy comparison. The reactive power participation of WEG1 is higher from t = 7s until t = 15 s as seen in Fig.10 (bottom). The contribution of WEG1 is deemed advantageous between t = 7s and t = 8 s, when WEG 3 injects the maximum active power. Again the WEG 1 contributes more than other WEGs during time interval between t = 11 s and t=13 s, when WEG 2 injects maximum active power. Thus, particularly in these two time intervals (7-8 s; 11-13 s) an optimal reactive power contribution is achieved among the WEGs, and the participation of WEG 1 due to higher droop factor ($\boldsymbol{k_{q1}}$) is evident (comparing reactive power contributions in Fig.9). This could be the major advantage achieved in design of WEG reactive power droop compared to the Solution 1 and this permits to avoid GSC overloading in case of full capacity power production in some of the WEGs.

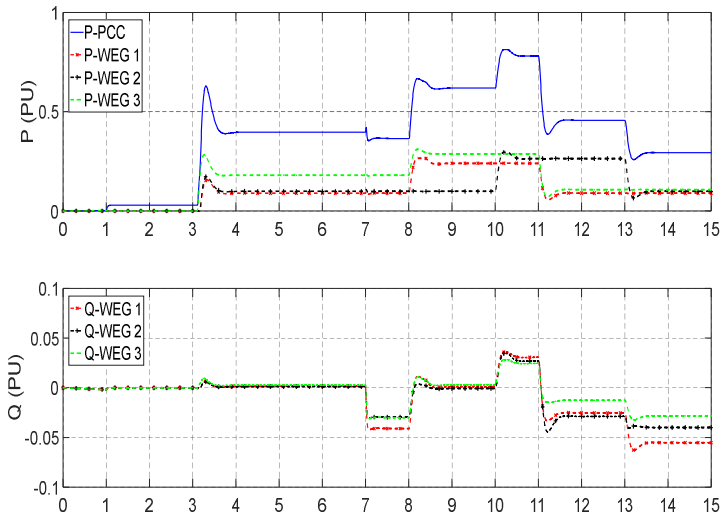


Fig.10: Solution 2, Case 2 – With Q droop implementation – P and Q at various terminals

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 OWF. Two of these solutions have been implemented in a study case architecture with simulation results and analyses. Regarding the solution 1, although the modification of the control scheme in order to enable grid forming by the GSC and also perform MPPT at the GSC terminals are quite advantageous, the practical questions of clear solutions for start-up and synchronization remain to be solved. The approach to control the remote PCC AC offshore voltage could become quite complicated, especially when AC marine cables are involved and this has been demonstrated in this paper. Considering solution 2, the need for an Umbilical AC cable and a sophisticated communication network to enable grid forming (FIXREF) are highlighted while the functioning 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 different 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 most of the challenges – control without remote measurement, local voltage control and synchronization. The start-up is said to be achieved using additional storage devices but the design aspects behind this have not been clearly dealt. From all these solutions, it is clear that enough progress has been made with research on DR-HVDC OWF and it is important that further development of any solution have to account for the all engineering aspects of all the challenges– start-up, synchronization, communication-less control.

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