DC Voltage Collection for DFIG-based Offshore Wind Farms Using HVDC Compliance with the Power System Operator’s Power Control Requirement

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Abstract—This paper proposes a new configuration to DFIG-based offshore wind farms using HVDC for electricity transmission. This configuration is built based on a DC collection system in an offshore grid. Advantages and disadvantages of this new configuration are analyzed and compared to conventional one using an AC offshore grid. In addition to the new configuration, this paper also suggests a new control strategy scheme so that the offshore wind farm meets the system operator’s power control requirement. In this recommended scheme, the onshore station side takes on the output power adjustment while the offshore side carries out maintaining a constant voltage on HVDC system. With this control method and new configuration, the onshore station fulfils power adjustment with a minimum communication between the offshore side and the onshore one or between the offshore side and the system operator. The efficiency of the new control strategy and the new configuration will be evaluated in both steady state and dynamic condition through simulation results in MATLAB/SIMULINK.

Index Terms—DC voltage collection, DFIG-based offshore wind farm, offshore grid, power control.

I. INTRODUCTION

Recently, the generation of electricity using wind power has received much interest and considerable attention all over the world. According to EWEA reporting on the wind industry target for the EU-27 in 2020, between 11.6% and 14.3% of the total EU electricity demand will be met by wind power [1]. Nowadays, with the development of wind farm industry, beside onshore wind farm that has been exploited widely, offshore wind farm (OWF) is also being considered and exploited efficiently because of the plenty of available wind energy at offshore areas. Many countries like German, UK, Sweden, Demark and so on have successes in the installation and the exploitation of OWF with the up to GW capacity.

For large OWFs, the use of a high voltage alternative current (HVAC) transmission system over a long distance creates a number of technical challenges for operators and developers. These challenges include the restriction in the transmission capacity of AC marine cable, high power losses, the increase in voltage at the onshore and the offshore station due to reactive power produced by AC marine cable [2]-[3]. Therefore, the implementation of a high voltage direct current (HVDC) transmission system in large OWF with a long transmission distance was researched in [4]-[15] and it has been well known as an effective alternative method of the HVAC system. This transmission system solved the difficulties of power transmission from the offshore station to the onshore one.

For variable speed wind turbine-based OWFs using HVDC, DC voltage collection in the offshore grid applied in [16]-[20]. In this new configuration, a DC/DC converter plays the role of a transformer in the AC collection system. The authors of reference [16] indicated some structures of DC collection system. Unfortunately, in above-mentioned references, only synchronous generator like PMSG is applied. Until now, a DC offshore grid configuration for DFIG-based OWF has not yet been proposed. Comparing to PMSG and SCIG, DFIG is used more popular due to some benefits such as low weight, small size and so on. Therefore, proposing a DC configuration to DFIG-based OWF is necessary.

Nowadays, with higher and higher wind power penetration in power system, the grid code has required large wind farms must have active and reactive power control ability [21], the same as that of a conventional power plant. Concerning to this requirement, references [22]-[24] suggested that the power regulation command and order quantity of the power system operator (PSO) must be sent to the control
center of wind farm. At the control center, power reference for the individual generators will be calculated and then be sent to each turbine. This method has just applied to onshore wind farms [22]-[23] or OWF, which is located several kilometers from the main land and uses HVAC for interconnection [24]. In the case of an OWF using HVDC with a long distance, if this method is applied the power output of onshore station can be below than the order quantity due to power loses in the offshore grid, HVDC system and converters. Authors in reference [25] offered that the rectifier at offshore platform will receive the power regulation command and it will control amount of active power supplying to HVDC system among the order quantity. However, this method did not suggest any schemes to adjust generators’ production. Therefore, an active power imbalance within offshore grid is unavoidable. This imbalance makes the offshore grid’s frequency be over operating range and the offshore grid may be, therefore, unstable. Obviously, for OWFs using HVDC, a more complete power control scheme, that helps it satisfy the operator’s power control requirement, need to be researched.

In this paper, a new configuration for DFIG-based OWF that uses DC voltage collection in the offshore grid is going to point out. Advantages and disadvantages of this configuration are compared to a conventional configuration, which uses the AC offshore grid. Additionally, the new control strategy is proposed to help OWF using HVDC meet PSO’s power control requirement. This configuration and the new control system will be evaluated under two conditions, steady state operation and dynamic one, via simulation results.

II. NEW CONFIGURATION FOR DFIG-BASED OFFSHORE WIND FARM WITH HVDC SYSTEM

In conventional DFIG-based OWF using HVDC, as shown in [6], [11], [26], to synchronize between the rotor side of DFIG and the offshore grid, an AC/DC/AC converter is installed in the rotor side of each generator. The benefit of this configuration is that a small size converter, 30% of generator rating, is required. However, this configuration has some disadvantages. Firstly, the electricity in the rotor side must be converted from DC to AC at the grid side converter and then it is converted back to DC gain at the offshore station. It means that a part of this electricity must be lost in the grid side converter of DFIG and the rectifier at the offshore platform. Secondly, if the power rating of the grid side converter is assumed 30% of generator rating, investment costs for the grid side converters and 30% of the rectifier’s rating at the offshore platform are wasted. Additionally, reactive power flow in the offshore grid is the reason of increase in power losses, the cross-section area of collection cable and other equipments’ capacity in the offshore grid.

Fig. 1. New configuration for DFIG –based OWF using HVDC system.
To overcome above-mentioned drawbacks, a new configuration for DFIG based OWF is proposed in Fig 1. In this configuration, a DC offshore grid is built and each generator is connected to the offshore grid via two rectifiers, one in the rotor side and another in the stator side, and their total capacity is equal to DFIG’s rating. The rectifier in the stator side is a diode-based full bridge whose investment is lower than that of an IGBT full bridge [19]. These rectifiers are connected in parallel. Each group is linked to a DC/DC converter that plays the role of a step-up DC transformer. Note that in this paper, the DC/DC converter steps up to the voltage level of HVDC system and it can be installed on the basement at one tower in a group.

There are many benefits drawn from this configuration. Firstly, only active power is transmitted in the offshore grid so power losses and DC cable’s cross-section in the offshore grid are expected to be lower than that in the conventional configuration. Secondly, this configuration also contributes to reducing the equipments’ rating. A comparison in equipments’ capacity between the new configuration and that in the conventional one is shown in Table 1. It is clear that with the new configuration, the total capacity of equipments is lower than that in the conventional one. Thirdly, because only two-phase cable is used for the DC distribution system while for AC one, three-phase cable is required, the structure of the offshore grid is simpler than that in the conventional configuration. Additionally, no transformer required in the nacelle of each turbine contributes to reducing the weight and the size of wind turbines. Finally, with the above-mentioned configuration, a small offshore platform is required because no converter and no transformer are installed in there. This allows the investor to decrease the pre-investment cost for construction.

In this paper, an 108MW OWF is investigated. OWF consists of 30 wind turbines – 3.6 MW DFIG and they are divided into 6 groups. The distance from the offshore to the onshore is 80km. The voltage rating of HVDC system is designated 115kV, this voltage level is preferred for OWFs with rating of around 100MW and transmission distance of up to 145km [27]. In this configuration, a half-full bridge DC/DC converter is chosen. OWF is connected to 155kV onshore grid, which is presented by a voltage source with the short-circuit ratio of 20, through two 50km-over-head lines. Note that configuration of DC/DC converter in DC offshore grid and its controller are not taken into account in this research because they were researched in [16]-[20].

I. CONTROL STRATEGY FOR NEW CONFIGURATION

As above mentioned, during operation, depending on the status and the operation schedule of power system, PSO can require large OWFs to regulate both active power and reactive power or only active power or only reactive power, the same as a conventional plant. The order quantity \( P_{ord} \) or \( Q_{ord} \) or both of them, calculated based on OWF’s available power, are sent to OWF and OWF’s production delivering to the main grid must somehow follow that order. This section will propose a new control scheme so that OWF using HVDC meets PSO’s power control requirement with a minimum communication between the onshore and the offshore side. This scheme applies to the new configuration of DFIG-based OWF proposed in the previous section.

A. Overall Control System

The new control system includes two control levels, onshore station level and offshore side level. Generally, the first level is to response PSO’s requirement while the second one is to maintain the balance of active power in HVDC system. In this research, the commands and order quantities are sent to the onshore station and only one signal is required to communicate between the onshore station and the offshore side. With this signal, the offshore side control level will recognize exactly the time that generators need to participate in maintaining a constant DC voltage on the HVDC system. Comparing to the conventional method, the proposed scheme allows reducing pre-investment cost for the communication system. Moreover, with this scheme, the inverter shoulder controlling power output at the point of common coupling (PCC) among the order quantities so the power output at PCC is always satisfied PSO’s requirement in spite of power losses in the offshore grid, HVDC and the conversion system. Overall control system of OWF is indicated in Fig.2a.

As can be seen from Fig.2a, PSO’s commands and order quantities are sent directly to the onshore station. The commands include \( Signal_1 \) and \( Signal_2 \), which respectively represents for active power control and reactive power control. If \( Signal_1 \) or \( Signal_2 \) or both are equal to one, the power output at PCC must be controlled to match the order quantities, \( P_{ord} \) and \( Q_{ord} \), by the inverter at the onshore station. If \( Signal_1 \) is equal to zero, OWF must generate with maximum power output as possible and the inverter will carry on a rated DC voltage on HVDC system. In the case of \( Signal_2 \) of zero, the inverter will must keep the PCC voltage at the rated value. The duty of the offshore control center is to decide the power reference for the controller of rotor side converter (RSC) of each generator depending on \( Signal_1 \), as shown in Fig.2b. If \( Signal_1 \) is equal to zero, the power reference for \( RSC_\text{th} \) generator \( (P'_{r_{th}}) \) is designated by its rotor speed and the MPPT curve. In other words, in this case, DFIGs will generate with maximum power as possible. When PSO requires OWF to adjust active power output, \( Signal_1 \) is set equal to one. In this case, DFIGs must participate in maintaining the
rated DC voltage at the offshore grid. Therefore, the $P_{i,ref}^*$ is designated by DC voltage error via a PI controller and a weighting factor $\alpha_i$. This weighting factor reflects the ability of each generator in the DC voltage adjustment and it is defined as equation (1). In this equation, $P_{i,avail}^*$ is the power available of $i^{th}$ generator and $n$ represents for the number of generators in the wind farm.

$$\alpha_i = \frac{n P_{i,avail}^*}{\sum_{i=1}^{n} P_{i,avail}^*}$$  \hspace{1cm} (1)

From above-analysis, depending on the operator’s command, the control system is operated in one of four modes. Table 2 summarizes the objective of controllers.

Mode 1: When the operator does not require OWF to control power output, the inverter is controlled to maintain the rated DC voltage on HVDC and the PCC voltage rating.

In this case, the power reference for each DFIG is designated based on the maximum power point tracking (MPPT) curve.

Mode 2: Controllers only operate in this mode when PSO requires OWF to regulate both active and reactive power. In this case, the inverter will be controlled so that power delivering to the main grid is equal to the power requirement. The power reference for each DFIG is designated based on DC voltage error and its weighting factor.

Mode 3: This mode occurs when PSO only requires OWF to control active power. In this mode, the inverter’s controller will adjust active power output and PCC voltage while DFIG operates the same as that in mode 2.

Mode 4: When the operator only requires controlling reactive power, the inverter is adjusted to maintain the rated DC voltage on HVDC and to meet the reactive power requirement. In this case, DFIG operates the same as that in mode 1.

Fig. 2. Overall control system of OWF (a) and the function of offshore control center (b).
A. Control Diagram for Inverter at Onshore Station

As above-mentioned, depending on Signal\(_1\) and Signal\(_2\), the inverter’s controller will designate to control DC voltage or active power and PCC voltage or reactive power. In \(dq\) frame, which \(d\) axis is aligned with the inverter’s AC voltage vector and \(q\) axis is head of 90° of \(d\) axis [28], the control diagram applying to the inverter is indicated in Fig.3a. In this figure, \(L, U, I, P, Q\), and \(\omega\) are the inductance of filter, voltage, current, active power, reactive power and the main grid’s angle speed, respectively. Subscripts, \(dc\), \(g\), \(PCC\), \(d\) and \(q\) respectively represent for the DC side, the grid side of the inverter, the PCC, \(d\)-axis and \(q\)-axis. Superscript "*" stands for the reference value.

In this diagram, in the case of active power control, the reference \(d\)-axis current component, \(i_{dq}^*\), is decided by the difference between \(P\) \(_{ord}\) and \(P\) \(_{PCC}\) via a PI controller while in the case of DC voltage control, this reference is calculated from DC voltage error via a PI controller. It is noted that \(U\) \(_{dc2}\) is set at the rated value 1pu. Likely, the reference current component \(i_{qr}^*\) is decided by the difference between \(P\) \(_{ord}\) and \(P\) \(_{PCC}\) via a PI controller. The reference PCC voltage value \(U\) \(_{PCC}\) is set at 1pu.

II. CASE STUDY AND DISCUSSION

To evaluate the control ability of the new configuration and the efficiency of the new control scheme, both steady state and dynamic condition need to be tested. The first condition aims to evaluate the new configuration and controller system in the operating modes and transferring ability from this mode to another one. The second one is to test the response of the proposed configuration when fault on the main grid occurs. Note that to increase simulation speed in MATLAB/SIMULINK, all wind turbines have the same wind speed or the weighting factor of each generator is equal to one. In this simulation, the voltage magnitude at the infinity bus of the power system is always set at 1pu. The wind speed profile and PSO’s order quantities used in simulation are correspondingly depicted in Fig.4a and Fig.4b.
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A. OWF in Steady State Operation

1) OWF with maximum power generation (mode 1)

In this situation, it is assumed that PSO does not require OWF to regulate power output. In this case, both Signal$_1$ and Signal$_2$ are set at zero and the inverter is, therefore, designated to maintain the rated DC voltage on the HVDC system and the rated PCC voltage. At the offshore side, DFIG is expected to generate with the MPPT curve. Simulation results are indicated in Fig.5.

As can be seen from Fig.5a, the power output of DFIG always approaches to the power reference computed from rotor speed through the MPPT curve. The stator voltage is maintained at the rated value, Fig.5b. This proves that the objectives of controller applied to RSC are fully achieved and DFIG can operate the same as it in the conventional configuration.

During simulation period, the DC voltage on the HVDC system at the onshore station is kept at the rated value, Fig.5c. This proves that no energy is stored in the HVDC system. Fig.5d shows that during operation, the main grid must supply reactive power so that the PCC voltage is sustained at the rated value, Fig.5e. It means that objectives of the inverter’s controller are completely reached.

Generally, under this condition, this OWF has a good performance. This proves that the proposed configuration for DFIG-based OWF can completely replace a conventional one in practice to achieve benefits mentioned in section II.

2) OWF with both active and reactive power control (mode 2)

In this circumstance, PSO requires OWF must participate in both the active and reactive power control. In this subsection, it is assumed that PSO sends command to the onshore station in an interval, from 10s to 50s as shown in Fig.4b. Simulation results are demonstrated in Fig.6.

As can be seen from Fig.6, before 10s, OWF is stable operation in mode 1. While the DC voltage at the onshore station is equal to 1pu, Fig.6c, the DC voltage at the offshore grid is higher than 1pu, Fig.6d, because of voltage drop on the HVDC system.
the DC voltage control one. In other words, the inverter tries to deliver to the main grid the same as ordered power while DFIG must reduce the power output to remain the DC voltage in the offshore grid at 1pu. As a result, from 10s to 50s, the active and reactive power output at the PCC completely match the power orders, Fig. 6a. In this mode, the PCC voltage is not controlled during the interval of adjusting reactive power, the PCC voltage is higher than the rated value, Fig. 6b. The main reason is the voltage loses caused by

![Graphs showing power output, PCC voltage, DC voltage at onshore, and DFIG voltage and output.](image)

Fig. 6. Simulation results in mode 2: (a) power output at PCC, (b) voltage at PCC, (c) DC voltage at the onshore
station, (d) DC voltage at offshore grid, (e) stator voltage of DFIG, (f) power output of DFIG.

active and reactive power flow on the connection line. In this period, the DC voltage at the onshore station is a little lower than the rated value, Fig.6c, while the DC voltage at the offshore grid is kept at 1pu, Fig.6d. The main reason is that a part of DC voltage is dropped on the transmission DC cable system. Thanks to trying to maintain the offshore grid DC voltage at 1pu, the power output of DFIG almost follows the power order, Fig.6f.

At 50s, PSO stops requiring OWF to adjust power output. Both Signal1 and Signal2 are set at zero. It is means that OWF needs removing from mode 2 to mode 1. Therefore, the inverter’s controller will transfer to the DC voltage control and the PCC voltage control from the active power control and the reactive power control, respectively. At offshore side, signal1 of zero makes the power reference be calculated based on the maximum power control function instead of the DC voltage control function. As a result, the DC voltage at the onshore station will be increased to 1pu and DFIG’s production reaches to the MPPT curve. After a short time of transient, OWF becomes stable in mode 1. Note that during operation, the stator voltage of DFIG is always maintained at the rated value, as shown in Fig.6e.

3) Active power control and PCC voltage control (mode 3)

In this case, the operator requires wind farm only participates in active power control and no reactive power request. It is assumed that the active power ordered by PSO is the same as Fig.4b. Simulation results are demonstrated in Fig.7. Generally, the operation of OWF in this mode is almost the same as that in mode 2 except that the reactive power output at the PCC and the PCC voltage are different.

At 10s, only Signal1 changes from zero to one so the inverter’s controller transfers from DC voltage control to active power control while at the offshore control center, the maximum power control function is replaced to the DC voltage control. As a result, the same as mode 1, the active power output at the PCC will go down rapidly and then it meets the active power order quantity, Fig.7b. Because in this mode, the PCC voltage is controlled at the rated value, Fig.7a, the onshore grid must supply reactive power in order to compensate for voltage drop caused by the active power flow on the connection line, Fig.7b. Thanks to the objective of RSC, the DC voltage at the offshore grid U_{dc1} is kept at 1pu, Fig.7d, while the value measured at the onshore station is below than 1pu due to voltage lose on HVDC system, Fig.7c. The power output of DFIG follows the power output at the PCC, as shown in Fig.7e.

At 50s, the same as in mode 2, the inverter’s controller removes from the active power control to the DC voltage control. At the same time, the power reference for RSC’s controller is designated by the maximum power control function. After a short time, OWF successfully removes from mode 3 to mode 1 and then it is stable operation in mode 1.

It is clear that in mode 3, the DC voltage on HVDC system, the power output of DFIG and the stator voltage are completely the same as that in the mode 2. Only the PCC voltage, Fig.7a, and the reactive power output at the PCC, Fig.7b, are different from the mode 2. The main reason is that because PSO only requires OWF control the active power, the inverter still maintains the PCC voltage at 1pu during investigated period.
As can be seen from Fig.8, from 10s to 50s, OWF operates in mode 4 and the reactive power output at PCC matches PSO’s order quantity, Fig.8a. This reactive power flow makes the PCC voltage become higher than the rated value, Fig.8b, because the voltage magnitude at the infinity bus of the power system is maintained at constant during simulation interval. Out side this period, the reactive power flow on the connection line is the same as mode 1.

Fig.8 Simulation results in the case of maximum power generation: (a) power output at PCC, (b) voltage at PCC

In conclusion, with the proposed control scheme, OWF can be stable operation in all modes and it allows OWF to transfer from this mode to another mode conveniently. This indicates the efficiency of the recommended control method in the steady state.

B. Response of OWF for three-phase fault on the onshore grid

To test the response of the controllers in the case of fault on the main grid, it is assumed that a three-phase fault occurs at 7.5s, at point N in Fig.1 while OWF is operating in mode 1 and after 100ms, it is isolated. Simulation results are depicted in Fig.9.

As can be seen from Fig.9, when fault occurs, the PCC voltage approaches to zero, Fig.9a. Thanks to the PCC voltage controller applying to the inverter, after fault clearance, it supports a large amount of reactive power to restore the PCC voltage, Fig.9b.

During fault period, since the active power delivering to the main grid is reduced to zero, Fig.9b, while DFIG still generates with the MPPT curve, Fig.9d. As a result, all production of DFIGs is stored in the HVDC system and this stored energy makes DC voltage on the HVDC system increase, Fig.9c. At 7.6s, the fault is cleared and after a short time, the PCC voltage is recovered completely. Around

Fig. 7. Simulation results in mode 3: (a) PCC voltage, (b) power output at PCC, (c) DC voltage at the onshore station, (d) DC voltage at the offshore grid, (e) power output of DFIG

4) Maximum active power production and reactive power control (mode 4)

In this situation, PSO requires OWF only participates in reactive power control and no active power request. The reactive power order used in this subsection is the same as that in Fig.4b. Simulation results are performed in Fig.8.
7.78s, the power output at the PCC is completely recovered. At this time, the energy stored in the HVDC system is released gradually to the onshore grid. This makes the active power output at the PCC become higher than normal value and the DC voltage on the HVDC reduce again. Until around 9s, DC voltage completely returns to the rated value and then OWF continues stable operation in mode 1.

It is clear that with this new configuration, OWF behaves the same as that in a conventional one under dynamic condition.

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### APPENDIX

**Table 1. Comparison in Equipment’s Capacity**

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Conventional Configuration</th>
<th>New Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformer</td>
<td>&gt;3pu&lt;sup&gt;a&lt;/sup&gt;</td>
<td>&gt;1pu</td>
</tr>
<tr>
<td>AC/DC converter</td>
<td>1.3pu</td>
<td>1pu</td>
</tr>
<tr>
<td>DC/AC converter</td>
<td>1.3pu</td>
<td>1pu</td>
</tr>
<tr>
<td>DC/DC converter</td>
<td>0pu</td>
<td>1pu</td>
</tr>
</tbody>
</table>

<sup>a</sup>1pu is equal to OWF rating

**Table 2. Operation modes of controllers**

<table>
<thead>
<tr>
<th>Mode</th>
<th>Command</th>
<th>Objective of controller applied to</th>
<th>Objective of controller applied to</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Signal&lt;sub&gt;1&lt;/sub&gt;=0, Signal&lt;sub&gt;2&lt;/sub&gt;=0</td>
<td>DC voltage at onshore station and PCC voltage</td>
<td>Maximum power</td>
</tr>
<tr>
<td>2</td>
<td>Signal&lt;sub&gt;1&lt;/sub&gt;=1, Signal&lt;sub&gt;2&lt;/sub&gt;=1</td>
<td>Active power output and reactive power output</td>
<td>DC voltage at the offshore grid</td>
</tr>
<tr>
<td>3</td>
<td>Signal&lt;sub&gt;1&lt;/sub&gt;=1, Signal&lt;sub&gt;2&lt;/sub&gt;=0</td>
<td>Active power output and PCC voltage</td>
<td>Maximum power</td>
</tr>
</tbody>
</table>

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### III. CONCLUSION

This paper contributes a new configuration for DFIG-based OWF that uses a HVDC system for transmission. This configuration allows reducing pre-investment cost, power losses in the offshore grid compared to the conventional one. Additionally, in this research, a new control strategy is proposed so that OWF meets the power control requirement of PSO. In the proposed scheme, the inverter at the onshore station shoulder output power adjustment while maintaining a constant DC voltage on HVDC system is consigned to RSC of DFIG. With this scheme, PSO’s commands and order quantity is sent to the onshore station and only a communication signal is sent to the offshore side from the onshore side. From simulation results, it is clear that DFIG and whole OWF is stable operation and the power output at the PCC completely meets PSO’s order quantity. In addition, this OWF is still stable operation after a three-phase fault occurs on the main grid. Therefore, the proposed configuration and control method are able to replace the conventional configuration and it can be implemented in practice.
<table>
<thead>
<tr>
<th>Signal1=0</th>
<th>DC voltage at onshore station and reactive power output</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal1=1</td>
<td>DC voltage at the offshore grid</td>
<td></td>
</tr>
</tbody>
</table>

**REFERENCES**


