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DFIG-based offshore wind power plant connected to a single VSC-HVDC operated at variable frequency: Energy yield assessment

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ABSTRACT

The existence of HVDC (High Voltage Direct Current) transmission systems for remote offshore wind power plants allows devising novel wind plant concepts, which do not need to be synchronized with the main AC grid. This paper proposes an OWPP (offshore wind power plant) design based on variable speed wind turbines driven by DFIGs (doubly fed induction generators) with reduced power electronic converters connected to a single VSC-HVDC converter which operates at variable frequency and voltage within the collection grid. It is aimed to evaluate the influence of the power converter size and wind speed variability within the WPP on energy yield efficiency, as well as to develop a coordinated control between the VSC-HVDC converter and the individual back-to-back reduced power converters of each DFIG-based wind turbine in order to provide control capability for the wind power plant at a reduced cost. To maximise wind power generation by the OWPP, an optimum electrical frequency search algorithm for the VSC-HVDC converter is proposed. Both central wind power plant control level and local wind turbine control level are presented and the performance of the system is validated by means of simulations using MATLAB/Simulink®.

1. Introduction

Offshore wind is a promising energy source which has attracted worldwide attention in recent years as a consequence of various circumstances, such as the lack of available onshore locations (mainly in Europe), the potentially higher and more constant wind speeds at sea than their onshore counterparts (enabling a greater wind power generation) and the fact that space limitations offshore are a less critical issue than inland, which allows the possibility of using larger turbines [1–3].

Thus far, most of the existing offshore wind farms are of a relatively small up to medium sized rating (up to few hundreds MW), and are close enough to the shore that it is feasible transmit the power through HVAC submarine cables [4,5]. The fact that offshore wind farms are increasingly larger in size and located further away from shore is leading towards the utilization of HVDC (High Voltage Direct Current) technology. Several studies have demonstrated that if the distance between an OWPP and its grid connection point at the PCC (Point of Common Coupling) exceeds a certain critical distance (55–70 km), HVDC transmission becomes the most suitable solution, since it reduces cable energy losses and decreases reactive power requirements [6–8]. There is currently one offshore HVDC project in operation (Bard 1) located about 130 km off the German coast in the North Sea [9].

This trend towards constructing larger wind turbines and locating the OWPPs (offshore wind power plants) increasingly further from shore is posing technical, economic and political challenges that must be overcome to be fully competitive in the long term compared to other types of electricity generation [10,11]. According to [12], the current LCOE (Levelised Cost of Energy) for offshore wind power is estimated to be between 119 and 194 €/MWh, whilst for onshore wind it ranges from 45 to 107 €/MWh. These figures highlights the necessity for cost reduction, which can be achieved, inter alia, through a commitment from government

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and industry to encourage the development of novel wind power plant designs more cost–effective than the existing ones.

Various researchers propose different innovative concepts in the attempt of cutting down the LCOE. Some of these suggest to extend the DC nature of the high voltage transmission to the collection grid and to consider the possibility of having an entire OWPP in DC [13–15]. Other alternatives aim to consider the offshore collection grid in AC by operating at a non–standard frequency [16]. Likewise, some authors propose a different OWPP topology based on connecting a single large VSC-HVDC converter to the entire AC offshore collection grid (or a wind turbine cluster) which operates at variable frequency [17–24]. Similarly, other studies take advantage of the presence of HVDC technology and its ability to electrically decouple the OWPP from the onshore power system to investigate the dynamic performance of an innovative concept based on a DFIG-based OWPP with reduced power electronic converters connected to a VSC-HVDC converter which operates at variable frequency [25] or at rated V/f operation [26].

This paper deals with the feasibility analysis of this novel concept for OWPPs from the static and dynamic point of view aiming to maximise its energy generation. An optimum electrical frequency search algorithm for the VSC-HVDC converter is proposed and the impact of power converter size of each DFIG-based WT and wind speed variability within the OWPP on the energy yield efficiency, is assessed. Moreover, a coordinated control is implemented between the single large VSC-HVDC converter and all the reduced power converters of each wind turbine. Applying the designed control strategy, the common VSC-HVDC converter provides variable speed control to the WPP by operating it at constant rated V/f [27], while the reduced size power converters inside each DFIG (Doubly Fed Induction Generator) wind turbine are in charge of partially or totally compensating the wind speed difference among turbines due to the wake effect. Consequently, improved reliability, increased efficiency due to the lower losses and a cost reduction are expected to be achieved, whereas wind energy captured may be reduced owing to the narrower speed range that can be regulated by a smaller power converter.

2. Description of the proposed concept

Fig. 1 shows the proposed wind power plant concept assessed in this paper.

As it can be seen, this wind power plant proposal combines DFIG wind turbines with reduced size power converters (approximately 5–10% instead of 25–35% of the rated power) and a single VSC-HVDC converter which dynamically changes the collection grid frequency (f^*) as a function of the wind speeds of each turbine. This significant reduction of the power converter size is expected to be achieved as a consequence of the variable speed control provided by the common VSC (Voltage Source Converter) to all the wind turbines. This novel concept requires an HVDC transmission link to decouple the WPP collection grid from the electrical network and it is especially worthwhile for OWPPs where the wind speed variability among turbines is assumed to be lower than in onshore.

The proposed WPP design allows each DFIG-based wind turbine to rotate at different speed within a certain range defined by the size of its partial scale power converter. Thus, depending on the wind speed variability among the wind turbines and the power converter capacity, it is possible to ensure that each wind turbine operates at its optimum point. As an illustrative example, Fig. 2 shows the range of speeds at which all wind turbines can rotate to guarantee its maximum power extraction for a given optimum

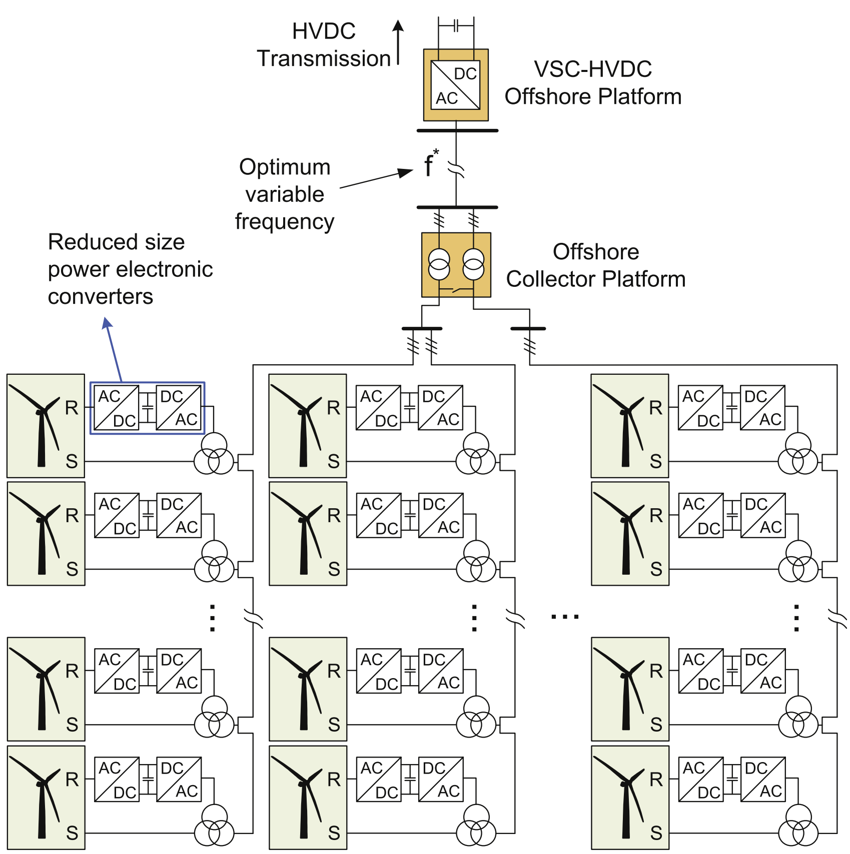

Fig. 1. Proposal AC variable frequency OWPP with DFIG wind turbines.