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Power generation efficiency analysis of offshore wind farms connected to a SLPC (single large power converter) operated with variable frequencies considering wake effects

Mikel de Prada Gil [a,*], Oriol Gomis-Bellmunt [a,b,c], Andreas Sumper [a,b,c], Joan Bergas-Jané [c]

[a] IREC Catalonia Institute for Energy Research, Jardins de les Dones de Negre 1, 2a.,C. Josep Pla, 2, edifici B2, Planta Baixa, 08930 Sant Adrià de Besòs, Barcelona, Spain
[b] Centre d'Innovació Tecnològica en Convertidors Estàtics i Accionaments (CITCEA-UPC), Departament d'Enginyeria Elèctrica, Universitat Politècnica de Catalunya EU d'Enginyeria Tècnica Industrial de Barcelona, C. Comte d'Urgell, 187, Pl. 1, 08036 Barcelona, Spain
[c] Centre d'Innovació Tecnològica en Convertidors Estàtics i Accionaments (CITCEA-UPC), Departament d'Enginyeria Elèctrica, Universitat Politècnica de Catalunya ETS d'Enginyeria Industrial de Barcelona, Av. Diagonal, 647, Pl. 2, 08028 Barcelona, Spain

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ABSTRACT

This paper deals with the power generation efficiency analysis of a proposed offshore wind farm topology, consisting of a SLPC (single large power converter) that simultaneously controls a group of generators. This common converter can operate at a VF (variable frequency) or at a CF (constant frequency). The results are compared with the conventional onshore wind farm scheme, where individual power converters are connected to each turbine, guaranteeing maximum power generation for the entire wind farm. A methodology to analyze different wind speed and direction scenarios, and to compute the optimal electrical frequency for each one, is presented and applied to different case studies depending on the wind farm size. In order to obtain more realistic values of wind speeds, the wake effect amongst wind turbines is considered. A wake model considering single, partial and multiple wakes inside a wind farm and taking into account different wind directions, is presented. Both wind farm topologies are analyzed by means of simulations, taking into account both wind speed variability in wind farms and the number of wind turbines. The possible resulting benefits of simplifying the MPCs (multiple power converters) of each turbine, namely saving costs, reducing losses and maintenance and increasing the reliability of the system, are analyzed, focusing on the total power extraction. The SLPC-VF scheme is also compared with a CF scheme SLPC-CF, and it is shown that a significant power increase of more than 33% can be obtained with SLPC-VF.

1. Introduction

In recent years, wind power generation has experienced tremendous growth throughout the world, thanks to the environmental benefits, technological advance of wind power and government incentives [1–4].

The increasing size of the turbines and the greater penetration of wind power into the utility networks [5,6] have encouraged the use of power electronic converters, in order to smooth the operational concerns that may arise due to the intermittent nature of wind [7]. Thereby, power converters play a very important role as an enabling technology to operate at variable speeds [8,9], providing more effective power capture than their fixed speed counterparts [10,11]. In addition, the inclusion of power converters as an interface between the generator and the AC grid enables a change of the conception of wind farms and the start of a thought process about wind power plants [12], which not only are able to generate active power, but also to provide support for grid voltage [13] and frequency [14], thus contributing to power system stability.

Trends point to a growing importance of offshore wind farms [15] because the wind speeds are potentially higher and more constant than the onshore ones, which leads to a much higher energy production [16]. Moreover, due to environmental and social aspects, the future offshore wind farms might be significantly larger and most likely further away from shore [17].

Theoretically, offshore wind farms at distances below 60 km can be connected using either an AC or DC link, whereas at greater distances, only the HVDC stands as the most suitable solution [17]. This technology can be based on Line Commutated Converters LCC-

* Corresponding author. Tel.: +34 933562615; fax: +34 933563802.
E-mail address: mdeprada@irec.cat (M. de Prada Gil).

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List of acronyms

CF	Constant Frequency
DFIG	Doubly-Fed Induction Generator
HVDC	High Voltage Direct Current
LCC-HVDC	High Voltage Direct Current – Line Commutated Converter
VSC-HVDC	High Voltage Direct Current – Voltage Source Converter
MPCs	Multiple Power Converters
SLPC	Single Large Power Converter
VF	Variable Frequency
WTs	Wind Turbines

HVDC [18–20] or Voltage Source Converters VSC-HVDC [16,21,22]. In both cases, HVDC systems require a full power converter at the wind farm connection point, allowing a centralized control for the entire wind farm and making a different wind farm topology possible, consisting of one common power converter that simultaneously controls several generators. Unlike the conventional scheme, which uses individual power converters for each turbine, guaranteeing maximum power generation [23], the proposed configuration provides a lower power extraction efficiency, since the operating point of the wind farm is moved away from the optimum when the wind speed differs between WTs. However, this concept implies cost savings since the individual converters and their associated controls are not required, losses and maintenance are reduced, and system reliability is increased. Some offshore wind farms propose only this central power converter with squirrel cage induction generators [24] or synchronous generators [25], while others combine a central power converter with individual converters and doubly-fed induction generators [22,26] in each wind turbine.

Vrionis et al. [24] propose a VF (variable frequency) wind farm grid in order to maximize power generation during dynamically changing frequencies and to observe power changes. Nevertheless, this method presents the drawback that a possible operation at local maximums may generate much less power than an absolute maximum in certain cases. On the other hand, in Ref. [27], this problem is solved, searching throughout a sweep of electrical frequencies and choosing the best option. In Ref. [28], a further step is carried out implementing an optimum electrical frequency search procedure depending on the measured wind speeds in all wind turbines that guarantees maximum power extraction in an offshore wind farm, therefore avoiding unnecessary calculations of suboptimal frequencies. However, the wind speeds of Ref. [28] are statistically obtained without taking into consideration both wind directions and wake effects.

In this paper, the methodology presented in Ref. [28] is enhanced with the aim to analyze a more realistic wind model in which the wake effect of different wind farm scenarios is considered. The advantage that results from a wind farm containing only one power converter is discussed, taking into account both wind speed variability in wind farms and number of wind turbines which it is composed of. The performance of the SLPC (single large power converter) topology, operated at a VF or at a CF (constant frequency), is compared. It is important to point out that the paper focuses on the energy capture analysis; other extremely important issues related to VF wind farm engineering, stability and control are out of the scope of this paper.

This paper is organized as follows. In Section 2, the different wind farm alternatives are presented. In Section 3, the wake model used is described. A system analysis, both for a single wind turbine and a wind farm, is shown in Section 4. In Section 5, the evaluation methodology is explained in detail. Finally, the performance of both wind farm topologies is analyzed in Section 6, and the conclusions are summarized in Section 7.

2. Wind farm concepts analyzed

This section has been explained in detail in Ref. [28]. Thus, a brief summary is included here for the sake of completeness.

As mentioned in Ref. [28], two wind farm topologies are considered according to the power converters layout being used:

- *Conventional topology MPCs*: This scheme consists of a wind farm with MPCs (multiple power converters), one for each wind turbine, and another VSC-HVDC or LCC-HVDC for the entire wind farm (Fig. 1). This proven topology [29] guarantees that the wind farm generates the maximum power available from the wind, regardless of wind speed variability in wind farms, since it enables independent speed control for each wind turbine.
- *Proposed topology SLPC*: This scheme is displayed in Fig. 2. The wind farm is based on a single large power VSC-HVDC or LCC-HVDC (SLPC) connected to all the wind turbines, avoiding individual power converters in each one. Each turbine is coupled to a synchronous generator. The main advantage of this concept is that individual power converters are not required for each wind generator, thus implying wind farm cost savings, reduction of losses and maintenance and an increase in system reliability. However, using a single power converter to control all wind turbines causes a loss in power generation,

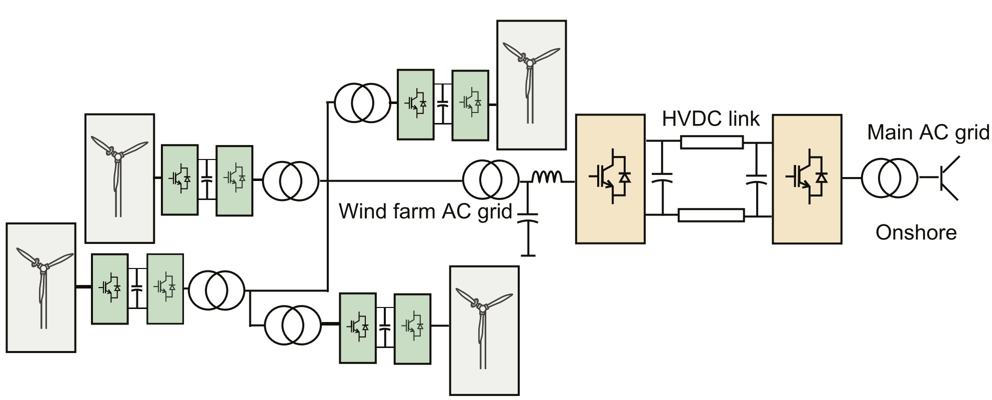

Fig. 1. Wind farm with individual power converters for each wind turbine (MPCs). The wind farm is connected to the main grid by means of HVDC.