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Optimum design of transmissions systems for offshore wind farms including decision making under risk

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ABSTRACT

The power transmission system of an offshore wind farm constitutes the infrastructure that allows the electricity produced by the power plant to be injected into the onshore power transmission network. The design of this transmission system depends on numerous factors: the rated power of the wind farm, wind conditions at the location, the distance from the shore, the cost of electrical equipment, the price of energy, the maintenance costs, the failure rate of the equipment, and so forth. At the design stage, most of these factors remain defined with a degree of uncertainty that, in many cases, may lead to major deviations (risk) with respect to the planned economic performance of the facility. The objective for the project team of the transmission system is the determination of the most suitable configuration of the evacuation infrastructure by selecting the technology, either HVAC or HVDC, and by sizing the electrical equipment: the cables, substations or converter stations, compensation units, among other pieces. To this end, the approach developed in this work includes the assessment of a broad range of feasible scenarios (probabilistic approach) and then the selection of the optimal configuration based on a method of decision-making, taking into account the main technical and economic aspects of the infrastructure.

1. Introduction

Growing interest in renewable energy along with the maturity of technology are the main reasons for the significant growth in offshore wind energy in recent years. The offshore capacity installed in Europe has risen from 4.95 MW in 1991 to 3813 MW in mid-2012. In addition, in the coming years, it is expected that the installed capacity will grow at a yearly rate of about 35%, reaching a total amount of 40 GW by 2020 [1].

The reduced friction provided by the water surface and the absence of obstacles make wind conditions more favourable out at sea. As a result offshore wind power plants have two main advantages over onshore facilities: the wind blows more strongly and is less turbulent. These factors lead to an increase in energy production and also to a reduction of fatigue on the blades and the structural components of the wind turbines (WTs), thereby increasing their availability and reducing maintenance costs. There are also other key advantages, such as the availability of large sea areas and the reduced visual and noise impact from those offshore facilities at a greater distance from shore.

Currently, (mid-2012), the rated power of offshore wind farms (OWF) in operation is relatively small. The largest OWF is Walney Offshore Wind Farm in the UK, with 367 MW [2]. However, the progressive reduction of costs renders it increasingly more attractive to enhance the size of OWFs. Furthermore, as rated power increases, installations located at greater distances from the coast is also expected. This progressive increase in both the rated output and at the distance to the coast in the offshore plants makes the use of HVDC-VSC in power transmission systems (TSs) increasingly attractive. During the year 2012, it is expected that Bard Offshore wind farm, with a rated power of 400 MW at a distance of 111.9 km, will come into operation. Bard Offshore will then become the first OWF with an HVDC-VSC power transmission system in operation [3].

Table 1 shows the typical cost breakdown of an OWF, compiled and adapted from Refs. [4–7]. As shown, the cost of electrical infrastructure is typically between 15% and 30% of the total cost of an OWF. This infrastructure consists of three differentiated parts: internal distribution network, transmission network to the shore, and substations (HVAC technology) or converter stations (HVDC-VSC technology). The fraction of costs for each of these parts can vary considerably depending on the rated power of the OWF and its distance from the shore. As a general rule, the higher the rated power of the OWF and the longer the distance from the shore, the

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Table 1
Typical initial cost breakdown of an offshore wind farm.

Item		%
Wind turbines		30–50
Substation and electricity infrastructure		15–30
Inner electrical distribution installation	2–5%	
Substation	2–4%	
Grid connection	15–18%	
Foundations		15–25
Component installation		0–30
Other		8
Overall wind turbine cost (€/kW)	1200–1850	

greater the proportion of cost for the TS and the lower the internal distribution cost [8].

To date, there are several studies that have performed an economic analysis of the various TSs used in OWFs. In 2004, Junginger et al. performed a study on possible future developments and cost reductions for the several parts that constitute an OWF [4]. With regard to the network connection to the shore, the authors determined the experience curve of the costs of HVDC cables and VSC converters, foreseeing a quick decline in the equipment costs related to such technology. Negra et al. [9] carried out an assessment of losses for several TS configurations in HVAC and HVDC considering various combinations of power ratings of OWFs, average wind speeds and distance from shore. Bresesti et al. [10] performed an economic comparison between HVAC and HVDC-VSC options, by carrying out a sensitivity analysis on various parameters such as distance from shore, equipment costs and failure rates. The Centre for Sustainable Electricity and Distributed Generation (SEDG) from the United Kingdom published a methodology for optimal design based on a Cost-Benefit analysis of power TS for offshore facilities [11]. Their work examines, from a deterministic point of view, a set of OWFs of a variety of power ratings and distances from shore, and provides certain guidelines and recommendations about the design of the TS electrical equipment, mainly related to reliability.

Previous work has addressed the problem from a deterministic point of view, assuming that the design variables are known with certainty. However, in a real situation, during the design and planning of an OWF, there is a high degree of uncertainty involved in these variables. Therefore, the methodologies available for the design of a TS-OWF can be significantly improved by addressing the uncertainty in the design variables.

This work strives to act as a complement to previously reported research, by introducing a new methodology for the design of the optimal configuration of the system of power transmission of OWFs. This new approach takes into account the main risk-management aspects derived from uncertainty in the information for the design. The relative scarcity of such facilities, the complexity of the technology and its continuous evolution complicates the accurate estimation of the actual costs of the different TS facility equipment and components at the project stage. In addition, offshore installations tend to be subject to severe weather conditions, thereby rendering it very difficult to assess the possible failures and repair times, and the installation cost (laying of submarine cables), among other factors. On the other hand, the random nature of wind prevents the designer from ascertaining the amount of annual energy produced by the OWF. This means that the degree of uncertainty in the main variables considered at the design stage is very high. The uncertainty in the initial information spreads by means of the economic model of the facility, thereby polluting the prediction of its economic life (the evolution of the cash flows of the project over its life span) with a significant degree of uncertainty.

In this paper, a new methodology for the design of the TS-OWF has been developed. The objective is to determine the most suitable configuration by taking into account, on the one hand, the characteristics of the wind farm (nominal power, type of WT, geographical arrangement of WTs, distance to the shore, etc.) and, on the other hand, uncertainty existing in the different design variables (wind behaviour, acquisition costs of equipment, sale price of energy, failure rates, etc.). To this end, several design alternatives of TS-OWF will be economically evaluated for a set of scenarios representative of the behaviour of a range of variables. In order to carry out the economic evaluation, it has been necessary to develop several models for the calculation of concepts such as net produced energy by the OWF, cost of electrical equipment, and losses in the system. Finally, the most appropriate TS-OWF configuration will be selected based on a method of decision-making under the presence of risk. This methodology allows solutions to be obtained with better behaviour under the presence of risk than the performance of configurations obtained by deterministic approaches developed to date.

After this introduction, the paper is organized as follows. Section 2 introduces the new methodology developed. The procedure for calculating the electrical losses and, consequently, production of energy by the wind farm is described in Section 3. The cost model of the electrical equipment that forms the transmission system is given in detail in Section 4. Test cases and conclusions are provided in Sections 5 and 6.

2. Proposed method

Fig. 1 shows a flow diagram of the proposed method. As can be seen, there are two initial processes: the generation of scenarios and alternatives of design. These two blocks supply a Monte Carlo simulation block where the economic performance of each design alternative for every scenario is evaluated. These economical and technical evaluations consider the initial and installation costs of the electrical equipment, the present value of the electrical losses, and the performance reliability of each possible solution. The last step in this methodology is the choice of the optimal solution using a suitable decision criterion that leads to the selection of the most appropriate TS configuration, by taking into account the risk derived from the uncertainty in the information.

2.1. Generation of scenarios

Each scenario is a possible *State of Nature*, composed of a random value for each of the variables of the problem. The variables and parameters used in the design of the TS of an OWF have been modelled as Gaussian random variables characterized by their mean, μ, and standard deviation, σ. These variables are classified into four main types, according to their nature:

- *Wind behaviour*. The behaviour of the wind affects the net energy production of the OWF and, therefore, also affects the electrical losses in the TS. As is common practice, a Weibull distribution is considered to describe the wind speed. The Weibull distribution is defined by the shape parameter, K, and scale, C, which are considered as Gaussian variables. The wind direction is also considered as a random variable characterized by the probability of occurrence, p, for each of the sectors of the wind rose.
- *Economic indicators*. The economic variables have a direct influence on economic behaviour of the OWF. The selling price of energy, p_{kWh}, interest rate, i, and lifetime of the installation, L, are considered as subject to uncertainty.