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Effect of non-standard operating frequencies on the economic cost of offshore AC networks

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ABSTRACT

The effect of choosing a non-standard operating frequency on the equipment and infrastructure costs of an offshore AC network is investigated. The offshore AC network considered is similar in design to the European SuperGrid "SuperNode". It is designed to connect several large wind arrays to multiple HVDC converters through which power may be transmitted to shore. As the offshore AC network is isolated from onshore networks by the use of HVDC links, it may be operated unsynchronised at any desired frequency. The cost associated with operating the network at a fixed frequency in the range 20–120 Hz is investigated, focusing on the frequency-cost scalings of electrical devices (such as cables, transformers and reactive compensation) and offshore infrastructures. A case study is presented based upon Tranche A area of Dogger Bank, UK, where a minimum point in the total cost of the offshore network is found at 93 Hz.

1. Introduction

A European SuperGrid [1–4] will allow the connection of offshore renewable energy sources in remote locations to existing onshore networks. It has been recognised that offshore wind resources will play an important role in determining the design and placement of SuperGrid infrastructure. In order to provide large power transmission capacity over long distances it is proposed that the connection of offshore wind farms to onshore networks is performed by high-voltage direct-current (HVDC) links [5].

Multi-terminal HVDC (MT-HVDC) technology [6–8] is one technical solution that allows the connection of multiple offshore wind farms to one or more onshore connection points. In order to provide adequate system reliability, an MT-HVDC system must be capable of blocking faults that occur in the DC grid [9,10]. Advances in hybrid DC breaker technology have recently been reported [11], however, the lack of a commercially proven DC circuit breakers may be a major barrier to the implementation of MT-HVDC systems. Some VSC topologies have been proposed that promise inherent fault blocking capability, however these remain to be commercially proven and suffer additional complexity and potentially higher losses [12,13].

An alternative or complementary option for the European SuperGrid is the "SuperNode concept" and is the focus of this paper. A SuperNode is an offshore network which allows the connection of multiple wind arrays and HVDC substations via an AC-hub arrangement and which does not require DC fault blocking capability [14]. Fig. 1 is a high-level representation of the SuperNode concept. The AC-hub arrangement eliminates the requirement for DC circuit breaking by employing only point-to-point HVDC links [15]; in this case AC circuit breakers located on the AC-hub and in the onshore AC network may be used to isolate faults occurring on any individual HVDC link whilst leaving other links operational. A further potential advantage of the AC-hub arrangement is the opportunity to use current-source converter (CSC) point-to-point technology in place of more costly voltage source converter (VSC) MT-HVDC technology. CSCs generally offer higher power transfer capability and greater efficiencies at a given cost point than VSCs [15] although they require significant reactive compensation and additional harmonic filtering which increases their overall space requirements. It should be noted that in an AC grid composed only of power electronic converters, at least one VSC or STATCOM will be required in order to provide a reference voltage source and enable black-start capability.

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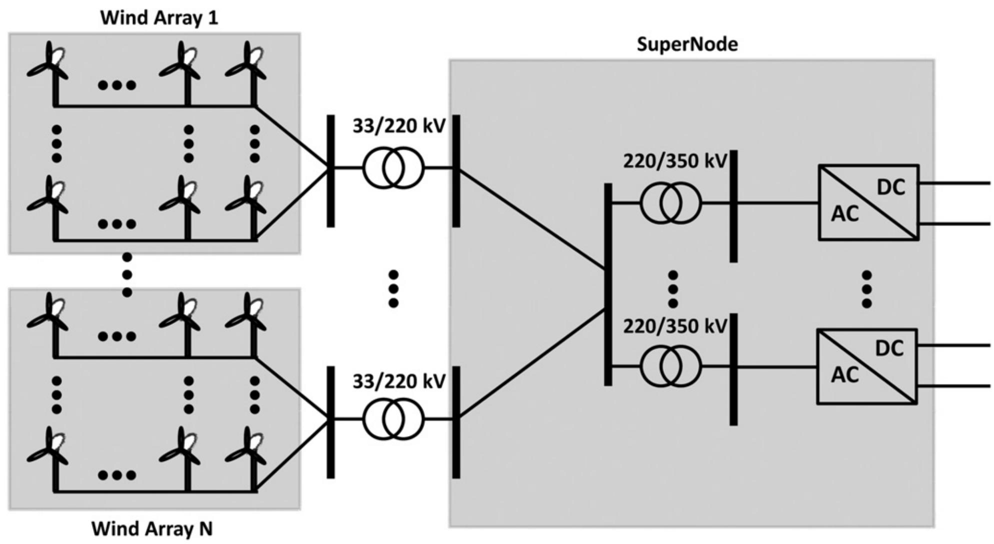

Fig. 1. Single line diagram of the SuperNode based on the HVDC2000 scheme from National Grid [17].

As the SuperNode is connected to onshore AC networks only through point-to-point HVDC links, the offshore AC-hub may run unsynchronised with onshore networks. Indeed, in some cases synchronism with one onshore AC network (e.g., mainland Europe) may preclude synchronism with another (e.g. the UK). A further observation is that there is no requirement for the hub to operate at the same nominal frequency as any onshore network and that operation at non-standard frequencies (i.e., not 50 or 60 Hz) may confer technical and economic advantages. For instance, an operational frequency below 50 Hz can offer lower transmission losses and allow the use of longer cables, whilst an operational frequency above 50 Hz can reduce transformer sizes, in turn reducing offshore platform sizes.

This paper considers operation of a SuperNode at non-standard fixed nominal operating frequencies in the range 20–120 Hz (dynamic variable frequency operation is not considered). An analysis of some of the technical and economic effects of operating at a non-standard frequency are examined. Tranche A of Dogger Bank [16] is used as a case study to highlight the potential economic advantages of operating at non-standard frequencies.

2. What is the SuperNode?

The SuperNode scheme proposed in this paper is loosely based on the HVDC2000 scheme appearing in [17]. The HVDC2000 scheme suggests the connection of several wind arrays to one offshore HVDC substation with one HVDC link to deliver the generated power onshore. The SuperNode concept as described here is an extension of the HVDC2000 scheme: It includes additional HVDC point-to-point links and a greater number of wind arrays. At a high-level, the SuperNode may be described as a group of wind farms connected radially to their wind array substation, which are in turn connected radially to the main offshore substation containing multiple HVDC converters, as shown in Fig. 1.

In the analysis presented here, all wind turbine interfaces are assumed to be of the fully-rated type, allowing the assumption that the offshore AC-hub is completely isolated from both the wind turbine instantaneous dynamics and the onshore grid by means of power electronic converters.

3. Frequency-cost dependence of SuperNode components

3.1. Cables

Operation at non-standard frequency implies variation in the impedances and the ratings of the cables due to factors such as skin effect, proximity factor and thermal capacity as discussed in IEC60287 [18]. The wind array to transformer substation connections are proposed at MV, whereas the transformer substation is connected to the SuperNode substation at HV (see Fig. 1). It is important to note that parameters for standard 50/60Hz cables are used in the following analysis and that the cable designs have not been modified to reflect use at non-standard operating frequencies. This analysis is based upon cable data found in [17,19,20] and values including the effect of cable geometry from [21].

The system has been analysed assuming a cable utilisation factor between 0.85 and 0.99 [16,22]. The cable utilisation factor (ρ) is defined as [23]

$$\rho = \frac{I_{\text{amp}}^2 - I_c^2}{I_{\text{amp}}^2} \tag{1}$$

where I_{amp} is the ampacity of the cable and I_c is the cable charging current. The reactive current is considered to be solely the result of cable capacitance for both HV and MV cables (i.e., cable inductance is neglected [20,21]). In this study, the cable charging current is assumed to be shared equally between both ends of the cable, therefore I_c is maximum and equal at either end of the cable. For a fixed cable utilisation factor, this assumption results in a cable twice as long when compared to a scenario in which the charging current is delivered only by one end of the cable (e.g., if the cable were to feed a simple resistive load [24]).

3.1.1. Cable ampacity variation with frequency

IEC60287 provides standard formulas for calculating the maximum current capacity (ampacity) of a cable for varying frequency and for different cable geometries. In Fig. 2, the relationship between the ampacity of several cables and the operating frequency is plotted. The dotted lines represent the frequencies above which the accuracy of IEC60287 is not assured [18]. Segmented conductors with $k_s = 0.435$ and $k_p = 0.37$ are assumed as defined in IEC60287.