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Power Flow Analysis of HVAC and HVDC Transmission Systems for Offshore Wind Parks

Filipe Faria da Silva and Rui Castro

Abstract

As the onshore wind resource is running shorter, wind power promoters are paying attention to the offshore resources. As in most cases there is no load offshore, wind power must be transmitted to the main land. To do so, two options are available: HVAC and HVDC transmission systems. In this paper, the two options are analysed from a power flow point of view. The influence in the voltage regulation of the onshore connection busbar is investigated in a 57 bus test power system. The simulation results obtained for each one of the above mentioned transmission system configurations allow the conclusion that HVAC solution is limited by the distance to shore and by the wind transmitted power. HVDC options do not show these limitations, but are more expensive and more delicate to deal with, because there is a lack of operational experience, so far.

KEYWORDS: offshore wind power, power flow, HVAC, HVDC

I. INTRODUCTION

Offshore wind farms are a matter of discussion for decades. Higher and more stable winds, together with low surface roughness and turbulence, were found to be important reasons to consider going offshore.

The first offshore wind generators were conceived in the 70's and the first small-scale offshore wind farms were built between 1991 and 1997 in Sweden, Denmark and Nether-lands. However, it was only in the beginning of the XXI century that the first commercial projects appeared. All these installations are small sized (maximum around 50 MW) and located near shore (from hundreds of metres to some kilometres).

Given the short supply of good windy sites in land, both the size of offshore parks and distance to shore were increased and a new generation of offshore wind parks was born. From these ones, the most famous is perhaps Horns Rev in Denmark, in operation since December 2002 with 160 MW installed (80 wind generators of 2 MW each) and located 14 to 20 km far from land. Recently, new projects came to force, mainly in the Netherlands, in Belgium and in the UK, with increasing sizes and distances.

Overall offshore wind power databases indicate that around 1500 MW are operational and almost the same are under construction, pointing to a scenario of 3000 MW offshore wind in the near future. This shows that the installation of offshore wind parks is the next step of the development towards an even more widespread use of wind power.

In what concerns the electrical system point of view, one of the key issues is the available options for connection to shore. A list of the type of interconnection to the onshore grid of operating (either commercially or as demonstration projects) offshore wind parks is presented in Alegría et al. (2008).Until now, for economical reasons, all commercially off-shore wind farms are connected to shore through traditional HVAC (High-Voltage Alternating Current) links and only a few have offshore substations. It is worth to mention that the sole operating HVDC installation is the Tjaereborg HVDC Project (Skytt et al., 2001) consisting of an offshore demonstration wind park with 4 turbines of different types with a total installed capacity of 6.5 MW. The interconnection of this wind park is performed both by an AC cable and by an HVDC installation.

However, as the size and distance to shore increase, another transmission option is coming forward. In 2009 is scheduled to start working the first offshore wind farm which is to be shore connected via a HVDC (High-Voltage Direct Current) link. This project aims at interconnecting a 400 MW offshore wind park to E.ON transmission grid using a HVDC set-up, comprising 128 km of sea cable plus 75 km of land cable (Pan et al, 2008). This may be the first step to a more general use of HVDC in the connection of offshore wind farms to the shore.

HVAC and HVDC are two quite different technologies. Therefore, it is very important to be able to quantify the impacts each one introduces in the existing AC system, namely in the voltage profiles. Several studies have been published in the literature addressing this particular subject. Wright et al. (2002) and Grainger and Jenkins (1998) discuss the options for the electrical connection to mainland of offshore wind farms. Andersson et al. (2007) and Van Roy et al. (2003) present application results to specific national power systems. Barberis Negra et al. (2006) show a comparison of transmission losses for the different solutions of interconnecting large offshore wind farms. Finally, Panosyan and Oswald (2004), describe a modification to conventional load flow algorithms to incorporate HVDC transmission systems.

It is apparent that the subject has been largely addressed in the literature. However, a joint power flow analysis of both HVAC and HVDC transmission to shore solutions has not been found, so far.

This paper intends to contribute to diminish this identified lack by assessing the impacts on the voltage profiles caused by the two mentioned transmission solutions; special emphasis is put on the highlight of the respective differences. With the help of a well known bulk test power system, two case-studies are discussed: the connection to the main land through a conventional HVAC system and using the HVDC solution, which is expected to come in force shortly. The obtained results, namely in what concerns the influence on the onshore bus voltage, are presented and commented. Moreover, a comparison of both transmission systems types is carried out with the purpose of quantifying the differences regarding each one's performance.

II. Review of Transmission Technologies

Both HVAC and HVDC technologies have advantages and disadvantages, as well as several technical differences.

AC systems are the most common mode of transmitting electrical energy since the beginning of the XX century and are used all over the world. Under these circumstances, it is not bizarre that today all offshore wind farms make use of HVAC systems to connect to the shore.

In general terms, an HVAC transmission system needs the following equipment: three core XLPE HVAC cables (several cables in parallel can be used to transmit large quantities of power); offshore station (transformers and reactive compensation); onshore station (transformers and reactive compensation); AC connection point (point to where all the wind farm power flows). For short distances to the shore it may be not necessary to have offshore and/or onshore stations. In some cases, additional dynamic reactive power compensation, such as SVC or STATCOM, may be required, to provide voltage control.

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Regarding HVDC, it should be mentioned that the market offers two different technologies (Xu and Andersen, 2006), (Normark and Nielsen, 2005): HVDC Line Commutated Converters (HVDC LCC), which uses thyristors in the converters and HVDC Voltage Source Converters (HVDC VSC), which uses IGBTs (Insulated-Gate Bipolar Transistor).

HVDC LCC is a mature technology used to transmit large quantities of power over long distances, to frequency coordination or submarine connection. It was used for the first time in Sweden in 1954 to connect mainland Sweden to the island of Gotland. Converters work properly if a commutation voltage is provided; normally, synchronous compensators, or the more recent STATCOM, are used with this purpose.

Broadly, HVDC LCC requires the following equipment to be installed: converter transformer; DC filters; AC filters; smoothing reactor; auxiliary power set (Diesel generator); a source of reactive power (STATCOM or capacitor banks); valves – thyristors (to perform the AC/DC and DC/AC conversion); DC cable.

HVDC VSC is a recent technology in which thyristors have been replaced by IGBTs. It was only made available for use in commercial applications a few years ago. This technology was first used in Sweden, in 1997, mostly to test its reliability.

In normal operation, the task of the onshore VSC station is to control the DC link voltage so that the collected offshore energy can be transmitted. Meanwhile, the offshore VSC station is gathering the generated energy and controlling the voltage and frequency of the wind farm AC network.

HVDC VSC comprises the following equipment: transformer; converter reactors; DC capacitors; AC filters; DC filters; high-frequency filters; valves (IGBTs); DC cable.

In what concerns the balance of advantages and disadvantages, HVAC is a cheaper technology, has fewer losses for small distances and does not need auxiliary power sets. Furthermore, as it is used more extensively than HVDC, there is more operational experience concerning its behaviour, thus allowing a better knowledge about its problems and limitations. On the other hand, HVAC cables have a very high capacitance, which implies large reactive power generation for long cables. This undesirable feature makes the length of the submarine cables be limited by their losses and generation of reactive power.

Compared with HVAC, both HVDC technologies have the advantages of allowing an asynchronous connection, the length of the cables is not limited by the transmission losses and they provide control of active and reactive power, thus allowing the participation of the wind farms in the grid voltage control. If HVDC VSC is used, there are some extra more features available, one of the most important is that it provides independent control of the active and reactive powers. On the disadvantages side of HVDC, it should be mentioned that it is a more expen-

sive technology, it presents additional losses due to the converters and filters are required to cope with the harmonics generated in the conversion AC/DC and DC/AC. Finally, an important drawback is that this technology was never used before to connect offshore wind farms to the grid.

III. Power Flow Assumptions and Data Description

In order to assess the impact of both HVAC and HVDC transmission technologies in the voltage profile of a bulk network, the 57 bus IEEE test network was selected as a test system. This power network represents a portion of the American Power System, in Midwestern area, in the 60'. A schematic of the system is shown in Fig.1.

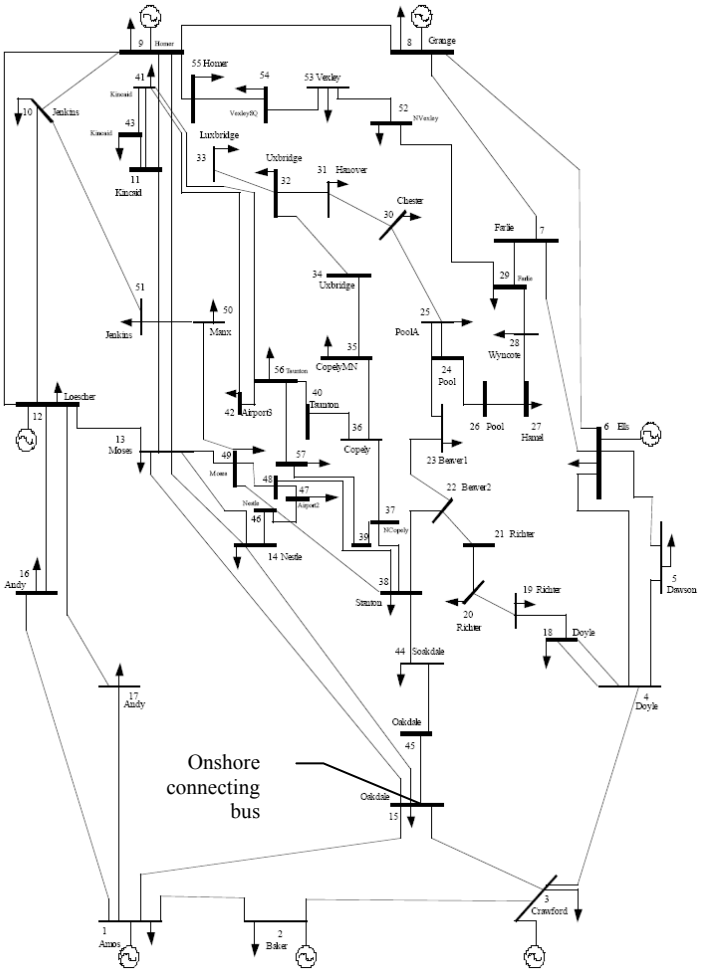

Fig.1. 57 bus IEEE test network scheme

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The system has 6 generators plus a swing bus. Only three out of the 6 generators produce active power, the remaining ones acting as synchronous compensators. The load total active power is around 1250 MW and there are a total of 42 loads in the system.

The simulations were run for different wind farm rated powers – 180, 300, 400 and 500 MW. It was assumed that no reactive power was generated nor absorbed by the wind farm. As one of the main aims of using renewable energy sources is to reduce the use of more polluting and expensive generators, the conventional generated power was reduced accordingly to the specific wind farm rated power.

As far as the HVAC power flow is concerned, two PQ buses were added to the original network, giving it a total of 59 buses. The wind farm is connected in the first extra bus; then the offshore transformer in series with the HVAC cable(s) are connected between the first bus and the second one; the onshore transformer is connected between the second extra bus and bus#15 (it is pointed out in Fig.1). For the two transformers, a common value of 5% for the short-circuit voltage was used.

Regarding the HVDC power flow, a slightly different approach was taken. The "equivalent" wind farm was directly connected at bus#15. By "equivalent" wind farm it is meant the wind farm itself plus the offshore converter, the DC cable and the onshore converter. Bus#15 was simulated as a PQ bus, for which the values of the generated active and reactive powers are the simulated wind farm rated power minus the overall losses. To perform the losses evaluation, an auxiliary program was used to compute the losses in both the offshore and onshore converters and in the DC cable. As a result of this approach, no additional buses were required.

IV. HVAC Power Flow

Three different nominal voltage levels of the submarine cables were considered in the simulations: 132 kV, 220 kV and 400 kV. Table I displays the main parameters of the considered cables.

TABLE I: CABLES PARAMETERS

	132kV	**220kV**	**400kV**
Resistance [Ω/km]	$48x10^{-3}$	$48x10^{-3}$	$45.5x10^{-3}$
Inductance [H/km]	$0.34x10^{-3}$	$0.37x10^{-3}$	$0.39x10^{-3}$
Capacitance [F/km]	$0.23x10^{-6}$	$0.18x10^{-6}$	$0.18x10^{-6}$

A cable has a limited power transmission capacity, which is dependent on the allowed maximum operation temperature. Therefore, to transmit all the entire wind farm generated power, several parallel cables can be required. Table II shows the number of cables in parallel needed, as a function of the voltage level and the rated transmitted power. As expected, for higher voltages fewer cables are required.

TABLE II: NUMBER OF PARALLEL CABLES

MW	132kV	220kV	400kV
180	1	1	1
300	2	1	1
400	2	2	1
500	3	2	1

To describe a line or a cable in power flow studies, a representation through a pi-model is desirable. The classical solution is to use the classical so-called *nominal pi equivalent model*. In this model, the exact model parameters **A** and **B** are approximated through, respectively, the first two and first terms of the series development. This yields to:

$$\begin{aligned} B &= Z_L \\ \frac{A-1}{B} &= \frac{Y_T}{2} \end{aligned} \tag{1}$$

In equation (1), $\boldsymbol{Z_L}$ is the total longitudinal impedance and $\boldsymbol{Y_T}$ is the total transversal admittance of the cable.

It is known that this model is inaccurate for long cables. However, the use of the exact cable model is possible if the cable parameters ($\boldsymbol{Z_L}$, $\boldsymbol{Y_T}$) are replaced by the modified ones ($\boldsymbol{Z'_L}$, $\boldsymbol{Y'_T}$), as noted by Das (2002):

$$\begin{aligned} B = Z'_L &= Z_L \frac{\sinh(\gamma l)}{\gamma l} \\ \frac{A-1}{B} = \frac{Y'_T}{2} &= \frac{Y_T}{2} \frac{\tanh\left(\frac{\gamma l}{2}\right)}{\frac{\gamma l}{2}} \end{aligned} \tag{2}$$

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In equation (2) γ and l stand for the propagation constant and length of cable, respectively. Using equation (2) accurate results are obtained even for long cables.

The main difficulty encountered with the power flow analysis was related with the reactive power control, as a consequence of the joint behaviour of the HVAC submarine cables and the complex network to which they are connected. Therefore, some sort of reactive power compensation is required. This compensation can be either capacitive or inductive, depending on the cable's length, the voltage level and the transmitted active power. For that purpose, two variable compensation shunts were installed at both ends of the submarine cable(s), simulating the behaviour of STATCOM devices.

The reactive power generated or absorbed by these compensation shunts was evaluated after a prior calculation of the reactive power generated or absorbed by the cable(s). As an example, Table III shows the reactive power compensation at each shunt for a 300 MW rated power wind farm as a function of the voltage level and distance to shore (cable's length). In Table III positive values refer to capacitive shunt, whereas negative refer to inductive shunt.

TABLE III: REACTIVE POWER COMPENSATION (Mvar);
300 MW WIND FARM

km	132kV	220kV	400kV
10	16	19	-13
30	-6	-7	-100
50	-30	-34	-185
100	-73	-87	-406
150	-125	-134	-616

It may be seen from Table III that really huge quantities of reactive power may be involved in the connection of an offshore wind farm to the mainland.

Examples of the results of the power flow in what relates to the voltages in the wind farm and onshore connection busbars are depicted in Figs.2 to 4, for different distances to shore. Figs.2 and 3 concern the case of a 300 MW wind farm connected to shore through two 132 kV parallel cables and a single 220 kV cable, respectively, and Fig.4 is related to the connection of a 400 MW wind farm via two 132 kV parallel cables transmission system. Further simulation results can be found in Faria Silva (2008).

From an operational point of view, the objective is to keep the voltage in the buses below 1.05 pu. This aim is achievable only up to a certain distance to the shore, as it is apparent from Figs 2 to 4.

The cable generated reactive power increases with its length; so, the longer the cable is, more difficult is to provide adequate reactive power compensation and voltage control becomes impossible. For an offshore transmitted power of

around 300 MW, the maximum allowed distance to shore is about 50 km; for longer distances, the voltage at the offshore wind farm bus can not be contained within acceptable limits (Figs.2 and 3). However, if proper management of the reactive power compensation is conducted, the onshore voltage can be kept under control.

It is worth to mention that, as far as the voltage regulation is concerned, the performance of the transmission system options 2x132 kV versus 1x220 kV is very similar.

As it is apparent from Fig.4, the maximum allowed distance to shore dramatically reduces, as the transmitted wind power increases. For instance, if a 400 MW nominal wind park is to be considered, the voltage at the offshore 132 kV AC busbar is unacceptable, even for a 30 km distance to shore. Once again, the explanation can be found in the high levels of required reactive power that makes impossible to control the voltage.

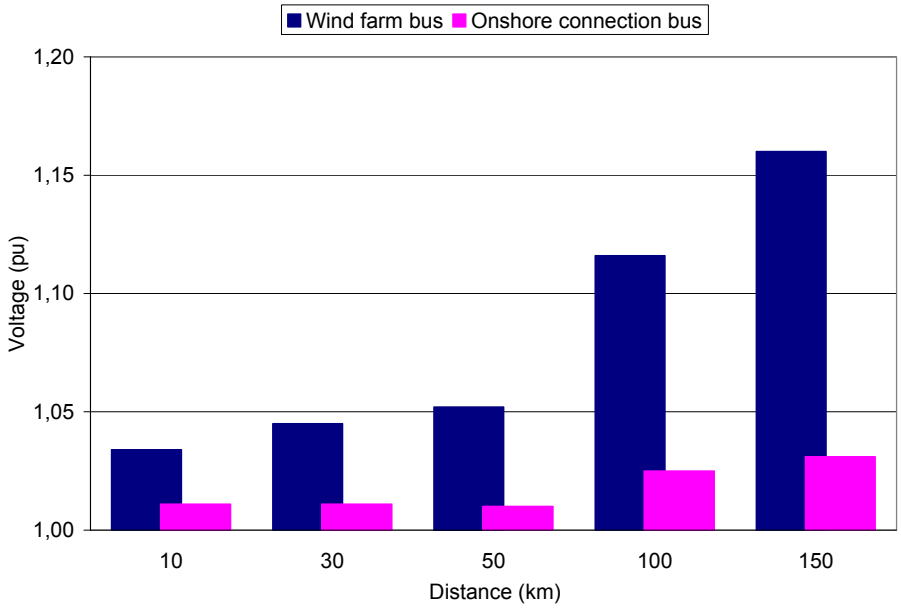

Fig. 2: Voltage profile at the wind farm and onshore connection buses; 132 kV voltage level (2 parallel cables); 300 MW wind farm.

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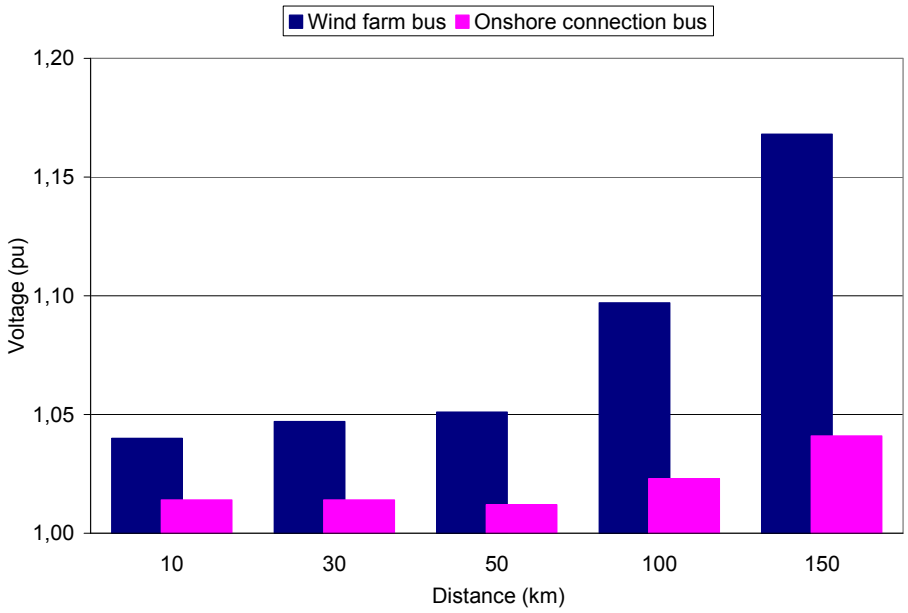

Fig. 3: Voltage profile at the wind farm and onshore connection buses; 220 kV voltage level (1 single cable); 300 MW wind farm.

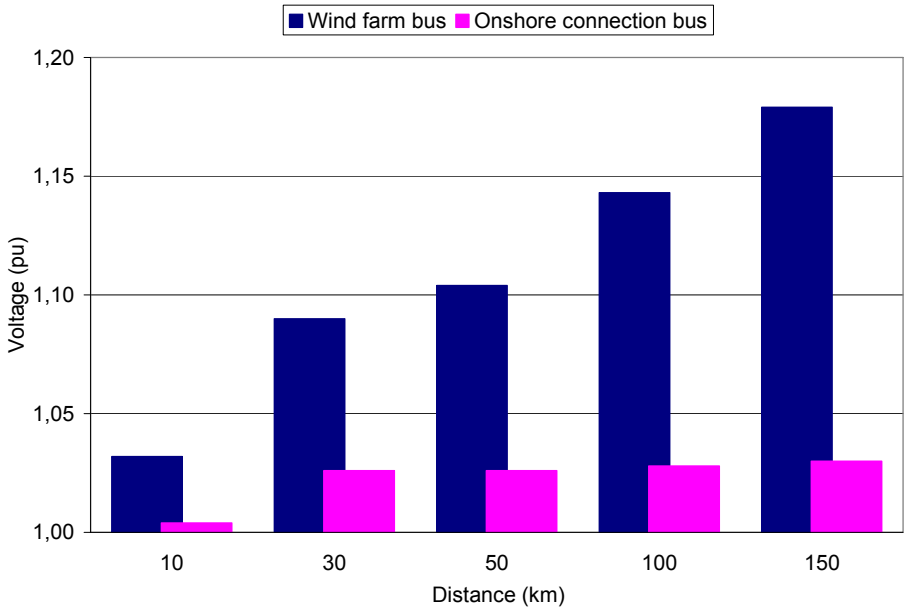

Fig. 4: Voltage profile at the wind farm and onshore connection buses; 132 kV voltage level (2 parallel cables); 400 MW wind farm.

V. HVDC POWER FLOW

As it was mentioned before, there are two HVDC technologies that can be used to connect the offshore wind farm to the mainland network: HVDC LCC and HVDC VSC. In this paper, the power flow analysis was restricted to the HVDC LCC technology. However, for the purpose of the study, the differences between the two technologies are not very relevant. The most important difference concerns the losses in the semiconductors, which are inferior in the HVDC LCC than in the HVDC VSC (at full load, typically 0.7% of the converter nominal power against 1.65%) (ABB, 2008).

Table IV displays the characteristics of 4 HVDC LCC systems currently in operation around the world.

TABLE IV: HVDC LCC SYSTEMS CHARACTERISTICS

Converter		**L1**	**L2**	**L3**	**L4**
Rated power	MW	130	250	300	440
Voltage level	kV	150	250	285	350
Max. sending power	MW	260	500	600	880
Nominal current	kA	0,867	1	1,053	1,257
Section	mm2	800	1000	1200	1400
Resistance @20ºC	ohm/km	0.0224	0.0176	0.0151	0.0126
Max. operating temp.	ºC	55	55	55	55

A prior evaluation of the transmission system losses (converters and DC cable) was performed, as stated before.

As far as the converters losses were concerned, two assumptions were made: (i) the firing and extinction angles of the rectifier and inverter, respectively, were set equal to 20º; this is a conservative approach, as usually those angles are regulated to a value less than 20º; (ii) assuming the losses limit values of 0,1% of the nominal power, at no-load, and 0,7%, at full-load, a linearization was made for the situations that lay in between.

Regarding the DC cable, it was considered that the DC current was ideal, with no harmonics. As a consequence, Joule losses were evaluated, taking into consideration the resistance values presented in Table IV.

Another issue is the reactive power consumption of the converters. In what concerns the offshore rectifier, it was considered that its reactive power consumption was locally completely compensated through an appropriate device (e.g. STATCOM). Regarding the onshore inverter, its reactive power consumption is (γ is the inverter extinction angle, and P is the transferred active power):

$$Q = P\tan(\gamma) \tag{3}$$

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A reactive power compensation device located at the onshore connection bus provides approximately the inverter required reactive power. Table V shows the considered reactive power compensation, as well as the selected type of converter for each wind farm nominal power, as in Table IV.

TABLE V: HVDC LCC TYPES AND
REACTIVE POWER COMPENSATION (Mvar)

Wind farm power	**MW**	180	300	400	500	600
Type of converter		L1	L2	L2	L3	L4
Reactive power comp.	Mvar	50	80	185	225	320

A positive characteristic of HVDC systems when compared with HVAC systems is that the reactive power that must be provided to the transmission system is not distance to the shore dependent. Therefore, the onshore connection bus voltage is expected to remain fairly constant with respect to the distance to shore variation. This has been confirmed by the simulations performed by Faria Silva (2008), some results of which are displayed in Table VI. As no relevant voltage changes with the distance to shore were found (distances up to 300 km were simulated), the distance parameter was omitted in Table VI.

TABLE VI: ONSHORE CONNECTION BUS VOLTAGE (pu)

Wind farm power	**MW**	180	300	400	500	600
Voltage	pu	0.995	0.997	1.025	1.02	1.044

As it can be seen from Table VI, one of the advantages of HVDC transmission systems is that it is possible, up to a certain level, to control the inverter so as it maintains the desired voltages. Therefore, in opposition to HVAC, the cable's length is not a limitation when choosing a location for the offshore wind farm, as the voltage almost does not depend on the distance to shore.

As far as the voltage regulation is concerned, the objective is still to keep the voltage below 1.05 pu. Due to the generation of reactive power in the cable, in HVAC transmission systems it is possible to achieve that aim only for small distances to the shore and/or to limited wind farm's injected power. In HVDC systems, as there is no generation of reactive power in the cable, those limitations are much attenuated. So, as can be seen in Table VI, it is possible to keep the onshore connection bus voltage within the desired band regardless of the distance to shore.

It must be stressed that the wind farm's nominal power influences the voltage value in the onshore connection bus: it increases when the injected wind power in the network increases. For instance, for a 600 MW wind farm Table VI shows that it goes very close to 1.05 pu. However, in practice this situation could be improved by adjusting the fire and extinction angles of the electronic convert-

ers; it should be kept in mind that the considered values of these angles were set to very conservative values. A smart management of the reactive power compensation device would also help the voltage regulation objective.

VI. CONCLUSIONS

In this paper, a power flow analysis has been carried out with the aim of evaluating the voltage regulation capabilities of both HVAC and HVDC transmission systems from offshore wind parks to mainland.

It was concluded that the reactive power compensation systems play a major role in this matter. In HVAC systems, these devices are required to compensate the reactive power generated by the AC cables and therefore to prevent the increase of bus voltages; however, this objective is attained only up to fairly limited distances to the shore and/or wind farm injected power. In HVDC systems, both the converters located at the ends of the DC cable do consume reactive power, which must be supplied by appropriate devices. Nevertheless, the reactive power compensation is not an issue as it is not distance to shore dependent.

Comparing the two technologies, it seems that HVDC transmission systems have more technical advantages: in general, they allow for an easier voltage control, and for higher distances to shore and/or to large offshore wind parks they became the only technically possible option. On the other hand, HVAC transmission systems are cheaper and they are not a source of harmonic pollution.

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