The Role of Modularity Inside the North Sea Transnational Grid Project: Modular Concepts for the Construction and Operation of Large Offshore Grids.

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Keywords: offshore wind power, multi-terminal network, VSC, HVDC, modularity, DC grids.

Abstract **–** Offshore wind energy is expected to have a steep grow in Europe due to increase demand for electricity originated from renewable sources. If the sector is to fulfil the expectations, Europe will have to install yearly circa 4.1 GW of offshore wind for the next ten years. As a consequence, future offshore wind farms will need to be larger in size and installed increasingly away from shore. In this scenario, an European offshore grid network will be needed in order to efficiently integrate large amounts of offshore wind into the different European countries' transmission networks. This work discusses the role of modularity and standardization for the construction and development of large offshore grids. Lastly, a load-flow case study is carried out in order to study the operation aspects of offshore networks, with special attention given to the North Sea.

1. Introduction

Energy is a key component to modern societies and worldwide the need for energy is increasing, while electricity supply is becoming ever more important. Global energy consumption levels, given current policies, is projected to increase by 44% in the following years until 2035 [1]. In developing countries, electricity is one of the most important tools for promoting welfare. In fact, the demand for electricity, led primarily by those countries, is projected to steeply increase due to economic and population growth.

Nevertheless, in Europe the scenario is not very different. With an average growing rate of only 2%, the demand for electricity in Europe could, by 2050, result in an electricity consumption level which is two times bigger than current levels.

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However, the difference in the European case will be that, given its policies and regulatory schemes towards energy, there will be a higher necessity for exploring and allocating more renewable energy resources in comparison to other locations in the world.

The EU climate and energy package – known as the 20-20-20 target – places Europe as a world leader in the field of sustainable and renewable energy. By 2020, the continent could add circa 600 TWh in new renewable electricity generation through different technologies such as biogas, biomass, solar, hydro, wave and wind energies [2].

Initial expectations forecasted that circa 1/3 of all the renewable primary energy generation in Europe would come from electrical sources. In addition it was predicted that wind energy would represent 1/3 of all renewable electricity generation, whilst offshore wind farms would correspond to 1/3 of all wind energy production share [3].

Nonetheless, the recently released EU-27 National Renewable Energy Action Plans contains an even more optimistic scenario for the renewable electricity industry. Electricity from renewable sources may account for 42% of total renewable energy production, while wind energy has the potential to be responsible for the supply of 41% of all renewable electricity.

The document also reviewed the predictions for the offshore wind energy and claims that by 2020 offshore wind will be responsible for 28% of the entire wind energy generation. This estimate equals a total of 44GW of installed offshore capacity throughout Europe by the end of this decade. Figure 1 shows the currently online accumulated installed capacity in Europe in the last decade.

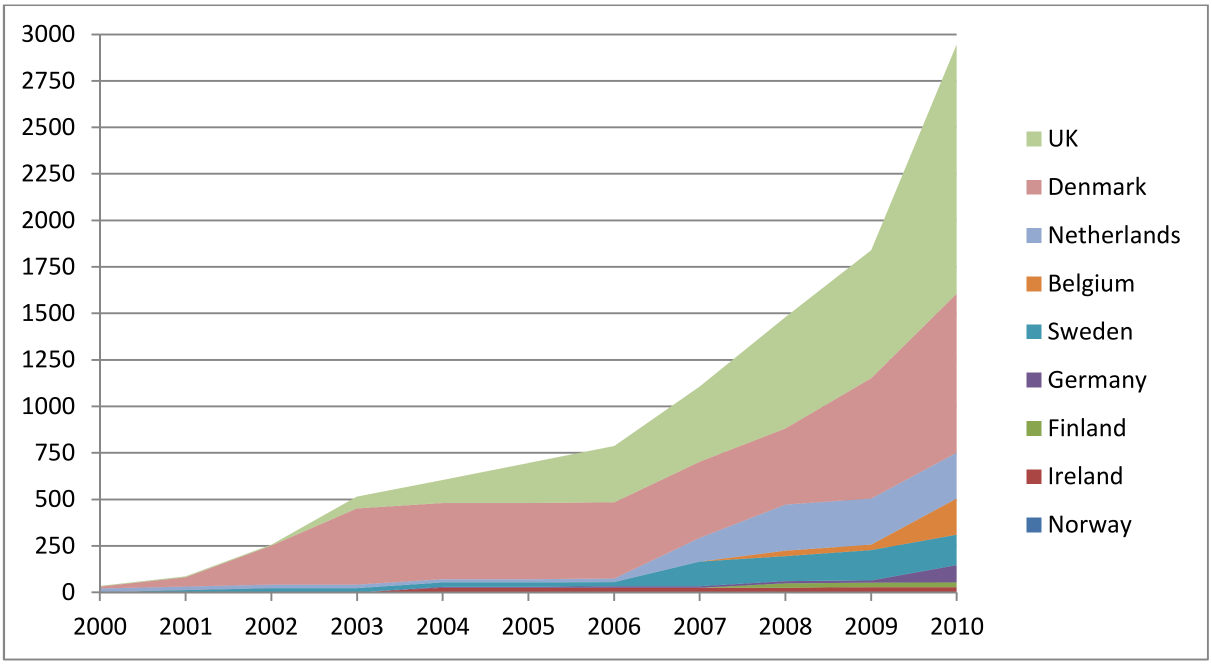


Figure 1 – Offshore wind energy accumulated installed capacity in Europe in the last decade [4].

As shown in Figure 1, currently only nine European countries have wind turbines installed offshore and the top two countries – UK and Denmark – account together for 75% of the whole 2.95 GW installed capacity. If Europe is to meet the prediction of having 44 GW installed offshore by 2020, it will be necessary to install an average of 4.1 GW of offshore wind power every year for the next ten years.

Since most of the offshore energy in Europe is to be installed in the Baltic or North Sea, the integration aspects of this offshore power to the different national electricity grids constitute a very important challenge for the power industry.

Building offshore wind farms is a very challenging engineering task, hence, getting the generated electricity efficiently to shore is essential. Several European studies, e.g. Tradewind and OffshoreGrid, have shown that electricity networks in Europe will require major reinforcements in order to proper integrate the predicted amount of offshore wind energy into the aging European grids.

Nevertheless, additionally to important onshore grid reinforcements, there will be also the need to develop an offshore grid infrastructure to efficiently integrate the large amounts of offshore wind into the different European countries' transmission networks and promote trade between these countries.

The first step towards an European offshore grid network was taken on 7 December 2009, at the EU Energy Council in Brussels when nine European countries – Belgium, Denmark, France, Germany, Ireland, Luxembourg, the Netherlands, Sweden and the United Kingdom – signed a political declaration for joint cooperation on the development of a transnational electricity infrastructure in the North Sea [5].

On December 3rd 2010, the EU countries taking part at The North Sea Countries Offshore Grid Initiative signed a memorandum of understanding where they agreed to make available, by 2012, a series of deliverables on grid configuration and integration; market and regulatory issues; planning and authorization procedures for the construction of the transnational offshore grid [6].

Inside this vision of Europe's future grid, the North Sea Transnational Grid project (NSTG) aims to identify and study the technical and economic aspects with regard to the development of the transnational electricity network in the North Sea for the connection of offshore wind power and trade between countries [7]. The project is jointly executed by the Energy Research Centre of the Netherlands (ECN) and the Delft University of Technology; it was started in October 2009 and will continue for a duration of 4 years.

2. Transmission Technology for the NSTG

Regarding the transmission technology for the connection of offshore wind farms to the ashore networks, there are two transmission technologies available, viz. high-voltage AC (HVAC) and high-voltage DC (HVDC). Depending on the location where the offshore wind farms are to be installed and on technical aspects, which are project dependent, the choice of which transmission technology to use will be based on its efficiency and economic viability.

In comparison with HVDC systems, HVAC transmission systems have a wider dissemination, are more straightforward to install and present a lower footprint when installed offshore [8]. Hitherto, all of the operational offshore wind farms in Europe have been connected through an HVAC transmission system to shore. The main reasons for choosing this technology are given the fact that currently only a few offshore wind farms have power ratings above 200 MW and almost all of them are located within less than 30 km to shore [4].

However, it is not always economically viable (or technically possible) to realize the transmission system through cables carrying alternating current. The German offshore wind farm BARD Offshore 1 (or BorWin1), scheduled to be in operation in 2012, is going to be connected to shore using an HVDC transmission system. This offshore wind farm will have 400 MW of installed capacity and will be located 130 km away from the German shore, justifying the choice for a DC transmission system to shore.

To cross long distances by means of submarine cables (≥ ~ 60-100 km), the HVDC solution starts to be preferable in comparison with traditional HVAC lines, since these have higher losses (due to skin effect and leakage capacitive current) and will demand additional equipment to provide reactive power compensation [9]. In the other hand, DC cables do not suffer from leakage current of capacitive nature and thus, in steady state, the transmission of the electricity is only limited by the cable resistance, i.e. the Joule losses.

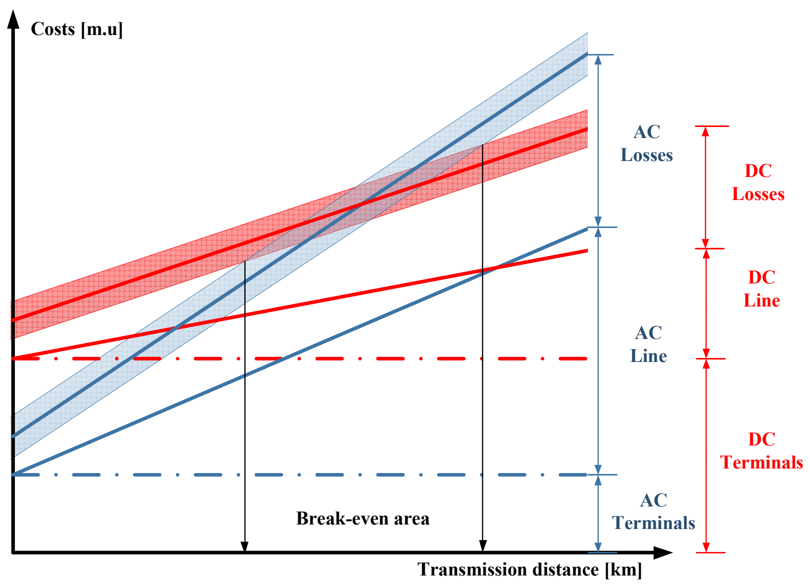


Figure 2 – Cost Comparison between HVAC and HVDC transmission systems.

Selecting AC transmission for the connection of offshore wind farms brings some disadvantages, namely [10]:

- Long submarine AC cables produce large amounts of capacitive reactive power;
- There is need to provide reactive power compensation (from STATCOMs or SVCs);
- Transmission capability decreases sharply as a function of distance given the reactive power production and high dielectric losses through the cable.

The current carrying capacity of a cable depends on its rated power, voltage, length, isolation method, burying depth, soil type and electrical losses. As previously mentioned, AC cables must carry, in addition to the load current, the reactive current required by the cable capacitance, which reduces the transmittable active power through the cable.

The capacitive current in the cable can be obtained as, $I_C = 2\pi fVCl$; where *f* is the system frequency, *C* is the capacitance per km (usually 0.1–0.3 mF/km for submarine cables), *V* is the cable voltage and *l* is the cable length in km. Table 1 shows some parameters and a comparison between AC and DC submarine transmission cables [11] [12].

Table 1 – AC and DC submarine cable parameters.

Voltage	**AC 132 kV**		**AC 220 kV**		**DC +- 80 kV**		**DC +- 150 kV**	
Cross-Section [mm²]	630	1000	630	1000	300	1200	300	1200
Rated Power [MVA] or [MW]	187	217	308	360	102	200	191	376
Capacitance per phase [µF/km]	0.209	0.238	0.151	0.177	N/A	N/A	N/A	N/A
Reactive Power [pu] @50 km	30,59%	30,05%	37,27%	37,39%	N/D	N/D	N/D	N/D
Reactive Power [pu] @100 km	61,18%	60,09%	74,55%	74,78%	N/D	N/D	N/D	N/D
Available Power [pu] @50 km	95,19%	95,39%	92,79%	92,78%	94,12%	95,50%	95,29%	96,01%
Available Power [pu] @100 km	79,14%	79,95%	66,66%	66,39%	91,18%	94,25%	93,72%	95,21%

* N/A – Data not available; N/D – Field not defined.

Based on Table 1, for the 220 kV AC cable with a cross-section of 1000 mm², at a distance of 100 km, the produced reactive power would be of 269 MVar, leaving only 239 MW of active power — or 66% from the original 360 MVA – left possible of being transmitted at full-load current.

Meanwhile, the AC industry is trying to improve the voltage rating of submarine underground cables and voltages up to 400 kV AC are being investigated [13]. While it is true that increasing the voltage augments the cable rated power, the cable reactive power generation grows with the square of the voltage, thus the problem of high losses persists.

Figure 3 shows the maximum transmittable power in relationship with the transmission distance considering the receiving voltage constant and equal to the rated value of the cable for the AC and DC options in per unit of the cable power rating.

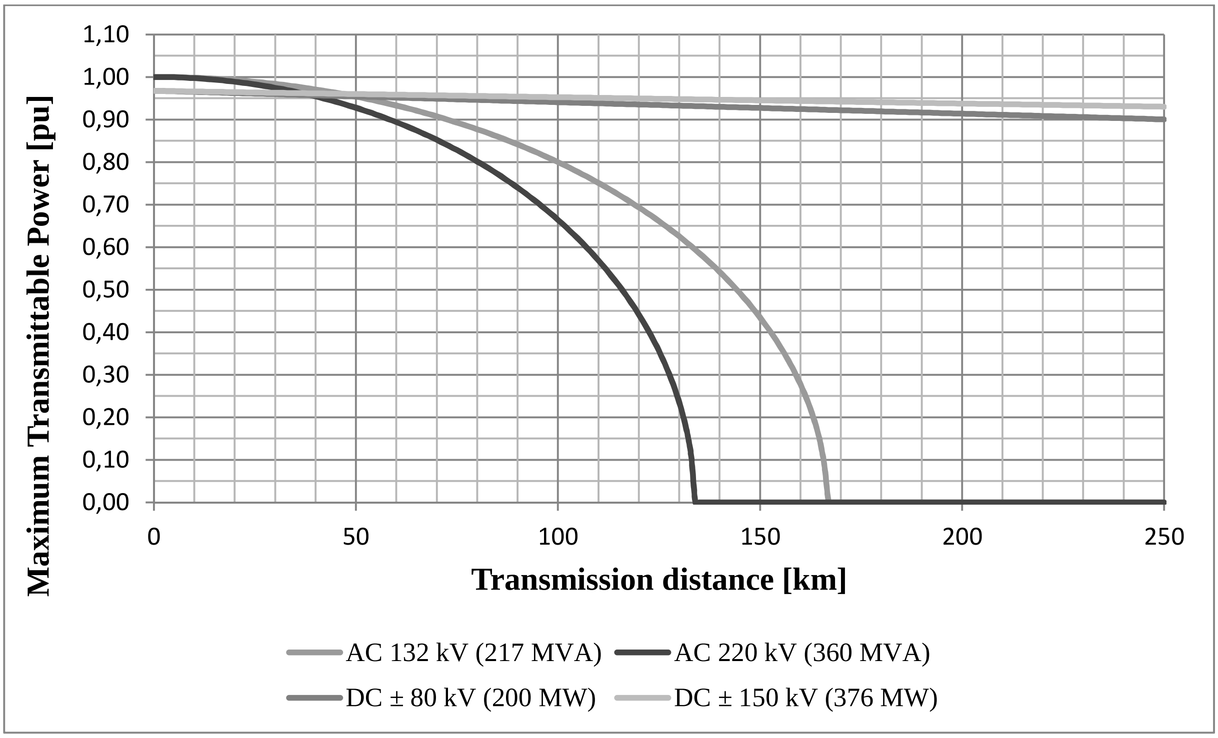


Figure 3 - Maximum transferrable power as a function of transmission distance for AC and DC submarine cables.

From the above graphic it is possible to conclude that with the state-of-the-art technology and without providing reactive power compensation – which adds to the total transmission costs – for offshore wind farms with power ratings above approximately 200 MW and for transmission distances higher than circa 50 km, AC transmission starts to be less competitive than HVDC option.

As future planned offshore wind farms tend to be build further away from the shore and become ever bigger in size, HVDC transmission becomes a better option and it will be increasingly difficult to keep using HVAC transmission systems for the connection of offshore wind farms.

Hence, when the distances and power involved are high, the use of HVDC transmission lines becomes justifiable, even though they present a higher capital expenditure cost for its implementation.

3. The Role of Modularity

The North Sea Transnational Grid project, with its intention of interconnecting around 60 GW of offshore wind power between several countries in the North Sea up to 2030, is a very ambitious initiative. For projects of such dimension and complexity, choosing the most suitable construction architecture is extremely important right from the start. The NSTG will have to organically grow with time from its initial phase; inherently simple, to its desired final form, expected to have a much more complex topology.

System Architecture

It is possible to define system architecture in several ways. One possible way is to verify the way on which the operative elements of a system are arranged into blocks and how these blocks interact. Ulrich defines system architecture as [14]: "*System architecture is the scheme by which the function of a system is allocated to physical components*".

Hence, system architecture is related to the way how components inside a system interact and interface with each other. Usually two distinctive types of system architecture are recognized: integral (or closed) and modular (or open) system architectures.

A system employing an integrated architecture is usually designed to maximize a particular performance measure. Modifications to one feature or component are not straightforward and may affect the design of the whole system. In addition, functionalities inside the system may be distributed across multiple components and eventually boundaries between these components may be difficult to identify or may not even exist.

Analysing the complexity involved in the development of a system such as the NSTG, it is somehow immediate that an integrated architecture is evidently not the most convenient choice for the construction and expansion of the system. Modifications to features and/or components are likely to occur regularly during the initial and growing phases. Nevertheless, there should be little redesign of the whole system given technical difficulties and large costs involved.

For complex systems such as the NSTG, one potential solution is to adopt, already from early stages of development, a modular architecture approach. A module is usually defined as a part of a system that is not so strongly coupled to other elements inside the system. According to Carliss [15]: "*Modularity is the practice of building complex systems or processes from smaller subsystems that can be designed independently yet function together as a whole*".

In a modular-architecture system, each module may be designed practically independent from each other, which allows changes to be made to one module without generally affecting the other modules. Therefore, it becomes important to be able to distinguish clearly which are the objectives and primary functions of each system's modules and what are the possible interactions between them. The task of establishing the modules functionalities inside the system can be accomplished by the design hierarchy and standardisation.

Design Hierarchy & Standardisation

Design hierarchy and standardisation are two important concepts for complex systems such as the NSTG, since more than one stakeholder will be involved and needed for funding and development of the whole system.

In the modularization process of a complex system, the first task is to establish which are the parts of the system that can be considered modules or subsystems. For instance, in an offshore transmission grid; wind farms, HVDC converter stations, DC transmission cables and potential protective systems, naturally constitute the basic building blocks or modules.

In a modular system, the design engineers are the ones responsible for establishing a set of design rules which accounts for:

- System components: what are the system's modules and their roles;
- Interfaces: description of how the modules inside the system are connected and interact with each other;
- Test procedures: procedures that set the performance levels of a certain subsystem and allow for comparison between different versions of the same subsystem.

Therefore, in a modular system, the design hierarchy is composed of levels. The global design rules are at the highest level. At the next level are the modules interfaces, system integration and communication. Finally, at the lower levels, there are the design parameters that concern only the modules themselves. An example of how a system design hierarchy for the NSTG could resemble is shown below.

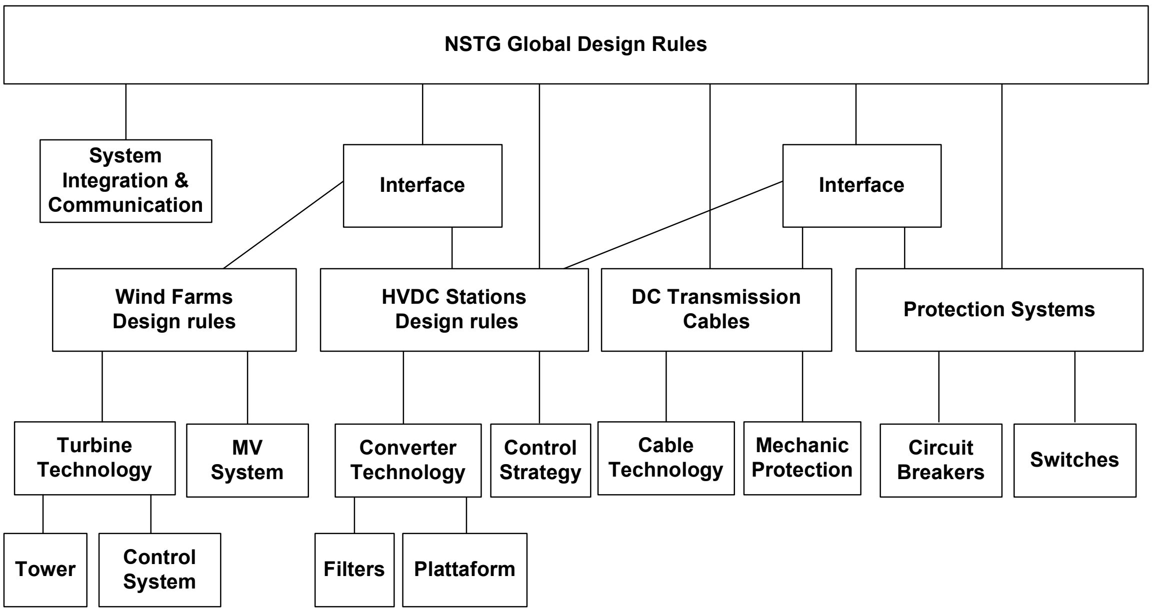


Figure 4 - A possible design hierarchy for the NSTG system with four modules.

From the system design hierarchy displayed above, it is possible to see different levels of information access. In this case for example, the global design rules are directly visible to the

HVDC Stations and to the Protection System modules but indirectly visible to Wind Farm modules.

This means that Wind Farm system engineers need only to take into account their local interface, i.e. the HVDC Stations modules, whilst engineers working on the latter have to take the system global design rules into consideration in addition to their local interfaces.

Offshore DC networks will require rules in a similar way in which AC grids operate with regard to the transmission system operator grid code. During early development stages, the design rules might appear simple or not complete. However, as the characteristics of the NSTG and the modules inside it become better understood, the design rules will also tend to be further developed.

The NSTG global design rules, i.e. the design parameters in the top level of the diagram, must be established first due to the fact that they directly affect all the modules that are part of the system. Examples of global design rules inside the NSTG could include, but are not limited to, the DC voltage level – nominal, steady-state and transient range – in the offshore grid, the size and topology of each HVDC station, multi-terminal DC protection philosophy, multi-terminal DC control and the power transfer capability of the DC cables.

The crucial point is that changes made in the global design rules will have large implications on all system modules, and are thus expected to be expensive and difficult to perform. In comparison, modifications of features inside a module in the lower levels of the diagram have limited extension and should be then easier and cheaper to perform [15].

For instance, changing the DC voltage level of the MTDC system would be one of this far reaching modifications that are bound to be costly and technically difficult [16]. Thus, once the DC level inside the NSTG system is establish, there will be very little room to change it.

System engineers must carefully establish and take global design rules into consideration before systems like the North Sea Transnational Grid can be developed and built. Proper development of the system global design rules can lead to DC grids standards which could allow for costs reduction by having a single common design, allowing systems to be built incrementally and by different equipment suppliers, thus supporting incremental investment plans.

In this way, large pan-European DC grids would be developed “organically”. First by the construction of a few small independent DC grids (four to six terminals) that, in a later stage, would be combined to form together a larger offshore network with a much more complex topology, such as a meshed multi-terminal DC network.

4. Multi-Terminal DC Networks

Multi-terminal HVDC (MTDC) transmission systems are characterized by more than two HVDC converter stations somehow interconnected on the DC side of the transmission system, i.e. multiple HVDC converters linking different AC power networks through a DC transmission network.

The MTDC configurations can be classified according to the type of HVDC technology implemented at the converter stations, viz.: line-commutated current-source converters (CSC) or forced-commutated voltage-source converters (VSC):

- CSC-MTDC: all the converter stations use the line commutated current-source converter HVDC technology;
- VSC-MTDC: all the converter stations use the forced-commutated voltage-source converter HVDC technology;
- Hybrid-MTDC: when both HVDC technologies (CSC and VSC) are used together.

Even though there are over one hundred HVDC transmission systems installed all over the world, only three have more than two terminals: The Hydro-Québec/New England scheme, in Canada; the SACOI-2 scheme, between Italy and France [17]; and a back-to-back scheme using VSC technology at the Shin-Shimano substation, in Japan [18].

To form a multi-terminal transmission system, the converters stations can be either connected in series or in parallel. When connected in series all the converter stations share the same current whilst for the parallel connection the converters share the same DC transmission voltage.

Given all the previously discussed characteristics, one possible way of classifying MTDC transmission systems would be according to the HVDC technology used and also according to the MTDC transmission system network topology.

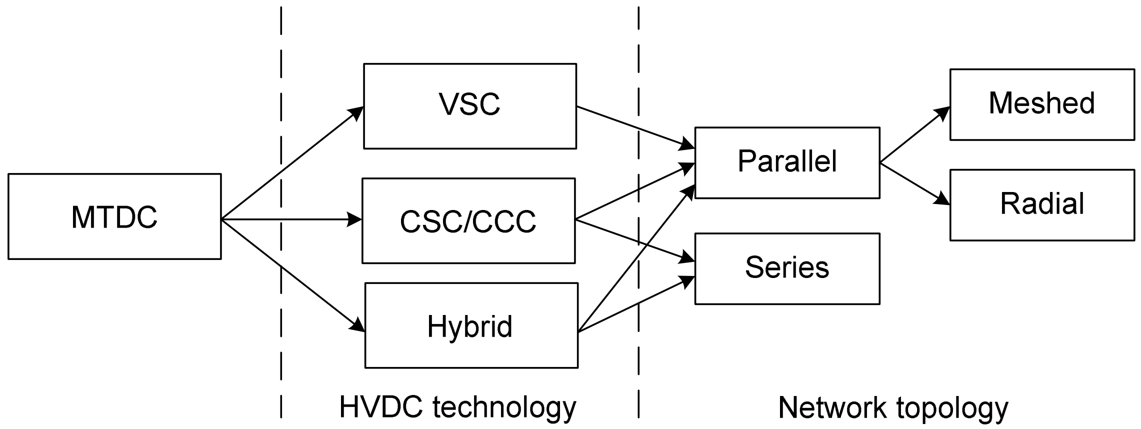


Figure 5 - MTDC Network classification scheme

Due to its the physical characteristics, VSC-HVDC transmission systems, will most probably be the technology initially chosen for the connection of offshore wind farms, since in offshore projects converter station footprint is a critical variable.

Modern state-of-the-art voltage-source converters for transmission purposes make use of modulation schemes or multilevel topologies, which allow them to have smaller space requirements than current-source converters. In addition, in VSC-HVDC stations there is no need for bulky special transformers, able to block DC voltages, as is the case for CSC-HVDC stations [8].

Figure 6 shows an example of a radially connected VSC-MTDC network with 6 nodes and four terminals. The example displays the AC networks, AC/DC converter stations and HVDC cables. However, it does not encompass other components that might be present in an MTDC network such as VSC-HVDC protection, dump resistors, DC/DC converters and DC breakers.

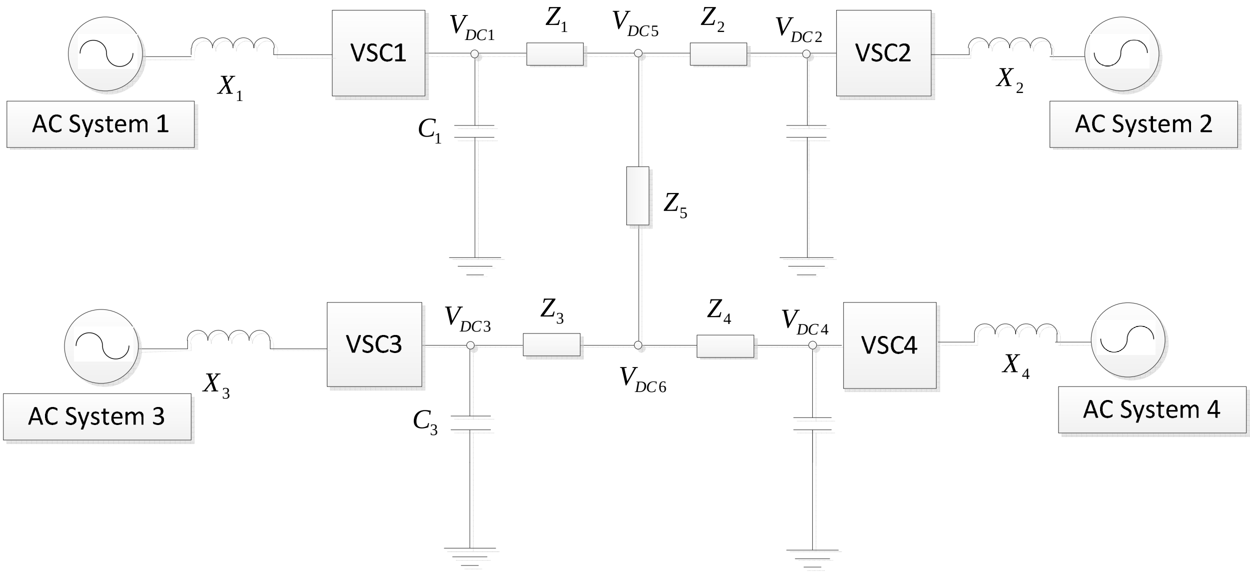


Figure 6 - Example of a radially-connected VSC-HVDC MTDC network with four terminals.

5. DC Load Flow Study Case

A possible layout for the North Sea Transnational Grid, where the five European countries with the highest expected installed offshore capacity – i.e. UK, Denmark, Germany, Netherlands and Belgium - are interconnected via the DC transmission network, is displayed below in Figure 7. As it can be seen, this layout is already very complex, with 19 DC nodes and 19 DC transmission lines. Since performing dynamic simulations for such a grid consisting of 19 VSC-HVDC stations would be time consuming, the chosen approach is to study the effectiveness of the global design rules and the DC voltage control strategy with a load flow analysis.

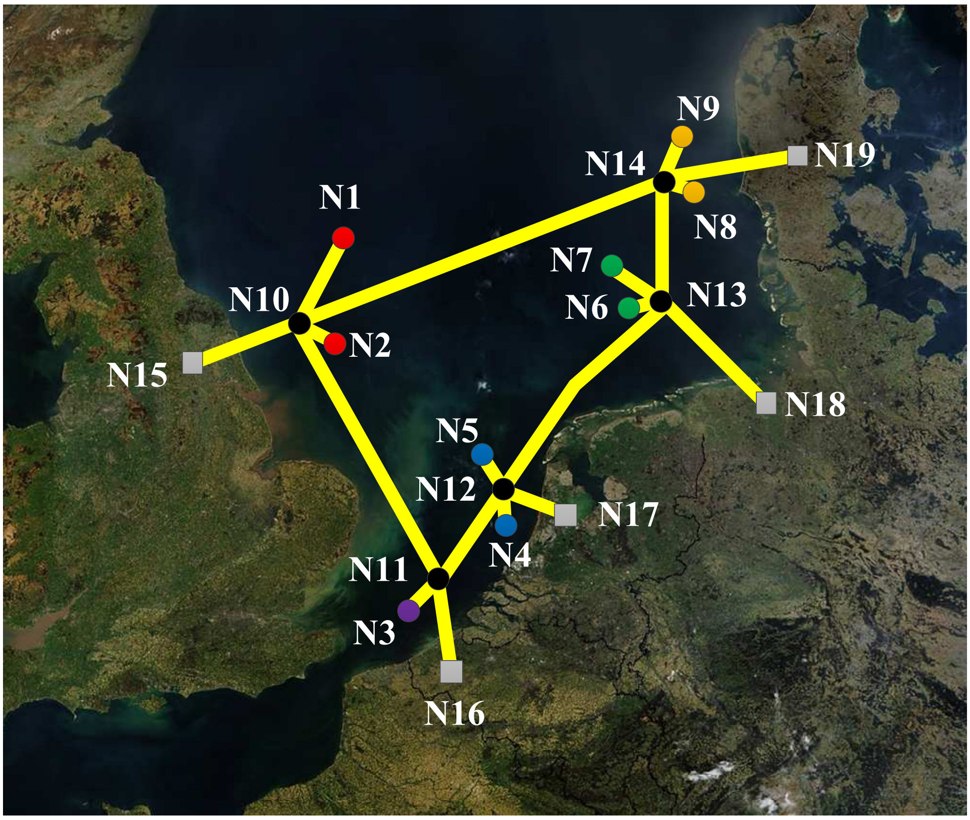


Figure 7 - NTSG layout for load flow study with five EU countries.

System Data for the Load Flow Example

With regard to Figure 7, the most important parameters for the load flow analysis of the proposed layout are displayed in Table 2. The unit length resistances of all the transmission lines have been assumed equal to 0,023 ohm/km, as contained in the latest report of UK Round 3 offshore wind farms [19]. For the DC load flow calculations, the base DC voltage is assumed to be ± 150 kV and the assumed base power is 500 MW.

Table 3 shows the size of the wind farms of each participating country in the load flow example. The location and sizes of the considered wind farms is taken from actual offshore development plans of each participating country, even though the locations displayed on the map are only approximate.

Table 2 – DC Lines Data.

Line Name	Nodes	Length (km)	Line Name	Nodes	Length (km)
L01	N01-N10	100	**L11**	N12-N13	250
L02	N02-N10	40	**L12**	N06-N13	40
L03	N10-N15	120	**L13**	N07-N13	70
L04	N10-N11	300	**L14**	N13-N18	150
L05	N03-N11	50	**L15**	N13-N14	120
L06	N11-N16	100	**L16**	N08-N14	40
L07	N11-N12	120	**L17**	N09-N14	50
L08	N04-N12	100	**L18**	N14-N19	150
L09	N05-N12	40	**L19**	N10-N14	380
L10	N12-N17	70			

Table 3 – Wind Farms Data (1 pu = 500 MW).

Wind Farm	Country	Node	Size (pu)	Wind Farm	Country	Node	Size (pu)
Doggersbank	UK	01	3	**Hochsee Sud**	Germany	06	2
Hornsea	UK	02	2	**Hochsee Nord**	Germany	07	2
Thorntonbank	Belgium	03	1	**Horns Rev**	Denmark	08	1
IJmuiden	Netherlands	04	2	**Ringkobing**	Denmark	09	1
Eemshaven	Netherlands	05	1				

Simplified DC load flow

The classic AC load flow iteration process can be written as:

$$\mathbf{x}(k+1)=\mathbf{x}(k)+\Delta\mathbf{x}(k) \;\; with \;\; \Delta\mathbf{x}(k)=-\mathbf{J}(k)^{-1}\cdot\mathbf{F}(\mathbf{x}(k))$$

In the above equation, $\mathbf{x}=\left[\delta_i,...,\delta_{N-1},V_i,...,V_{N-1}\right]^T$, are the state variables (node phase angles and nodal voltages) and the slack is considered to be the last node (N-th node) of the network. The vector $\mathbf{F}(\mathbf{x}(k))=\left[f_{P_1},...,f_{P_{N-1}},f_{Q_1},...,f_{Q_{N-1}}\right]^T$ holds the mismatch equations, which contains the load-flow equations, calculated as:

$$\begin{cases} f_{P_i}=P_{Gi}-P_{Li}-\sum\limits_{j\neq i}V_iV_j\,y_{ij}\cos(\delta_i-\delta_j-\varphi_{ij})-g_{ii}V_i^2 \\ f_{Q_i}=Q_{Gi}-Q_{Li}-\sum\limits_{j\neq i}V_iV_j\,y_{ij}\sin(\delta_i-\delta_j-\varphi_{ij})-b_{ii}V_i^2 \end{cases}$$

Since in DC networks it makes no sense to talk about phase angle, the state variables are simplified as $\mathbf{x}=\left[V_i,...,V_{N-1}\right]^T$, with the slack still considered to be the last node (N-th node) of the DC network. The vector that holds the mismatch equation is also simplified, since there is no need to write equations for the reactive power flowing in the DC network, thus $\mathbf{F}(\mathbf{x}(k))=\left[\,f_{P_1},...,\,f_{P_{N-1}}\,\right]^T$. Finally, since during steady state in DC networks only the resistive part of the transmission cables plays a role the load-flow equations become:

$$f_{P_i}=P_{Gi}-P_{Li}-\sum_{j\neq i}V_i V_j Y_{ij}-Y_{ii}V_i^2$$

Therefore, the simplified Jacobian matrix $\mathbf{J}$, defined as the variation of the mismatch equations with respect to the state variables, yields:

$$\mathbf{J}(k)=\frac{\partial \mathbf{F}_P}{\partial \mathbf{V}}=\begin{pmatrix} \frac{\partial f_{P_1}}{\partial V_1} & \cdots & \frac{\partial f_{P_1}}{\partial V_{N-1}} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_{P_{N-1}}}{\partial V_1} & \cdots & \frac{\partial f_{P_{N-1}}}{\partial V_{N-1}} \end{pmatrix}$$

$$or\;\; \frac{\partial f_{Pi}}{\partial V_k}=\begin{cases} -Y_{ik}V_i & for\; k\neq i \\ -\sum_{j\neq i}V_j Y_{ij}-2Y_{ii}V_i & for\; k=i \end{cases}$$

After computing the Jacobian matrix for the simplified DC load flow the difference between two load flow iterations can be written as:

$$\Delta\mathbf{V}(k+1)=-\mathbf{J}(k)^{-1}\cdot\mathbf{F}_P(\mathbf{V}(k))$$

In the simplified DC load flow the $\mathbf{Y_{bus}}$ matrix can be calculated as the product of the incidence matrix $\mathbf{I_M}$ and the primitive $\mathbf{Y}$ matrix:

$$\mathbf{Y}_{bus}=\left(\mathbf{I_M}\right)^t\cdot\mathbf{Y}\cdot\mathbf{I_M}$$

$$where\; Y_{ii}=\frac{1}{R_{DC\,line\,i}}\; and\; Y_{ij}=0$$

If L is the number of lines in the system and B is the number of buses (or nodes), the $\mathbf{Y_{bus}}$ is a B x B matrix, $\mathbf{Y}$ is an L x L matrix and $\mathbf{I_M}$ is an L x B matrix.

Load-Flow Results

The idea behind the load-flow analysis is to show that a configuration where all the HVDC stations onshore function as DC voltage regulators is superior to the case where only one or a couple of HVDC stations are left with the task of balancing the power within the network, in other words, functioning as slack nodes. This means that during the load-flow, these nodes (slacks) will have their DC voltage assigned to a pre-defined value (e.g. 1 pu).

In the analysis, all the wind farms were considered to be producing 75% of their nominal power and the power produced shipped to the country where it was produced, with exception made for the slack node, where that country will be instead controlling the DC voltage at its node.

The load-flow was performed for 3 different scenarios. In the first scenario, displayed below in Figure 8, only UK is working as a slack node, since it is the node with the highest installed capacity. In the second scenario, depicted in Figure 9, the three countries with the highest installed capacity – UK, Germany and The Netherlands – function as slack nodes. Lastly, in the third scenario (Figure 10), all the countries function as slack nodes, controlling their DC voltage.

In each of the scenarios there are 6 cases: the normal load-flow case and also five N-1 cases, where one particular country is faulted and not anymore being able to exchange power with the other countries through the MTDC network. In the graphics, the name of the case correspond to that country not being able to support the HVDC voltage due to a fault.

For the scenario with only 1 slack node (Figure 8), if a fault occur in a node with a larger power rating than the other nodes (e.g. UK or Germany) the voltage profile of several nodes, in steady-state, become over 1.1 pu, with some node voltages in a few cases having over-voltages of 20%.

The results for the scenario with all the countries working as slack nodes with a DC voltage of 1 pu is shown in Figure 10. As it can be seen, in this scenario the voltage profile within the NSTG network is much more flat than in the other scenarios, with almost all the nodes having voltages levels which are in the range of 1.05 pu, even in the N-1 faulted cases.

It derives from the graphic analysis that as the number of countries functioning as slack nodes increases, the voltage variation at the MTDC nodes for the N-1 cases becomes lower. Nevertheless, the marginal gain of increasing the number of slacks decreases as the number of HVDC stations controlling the DC voltage increases.

Figure 11 displays the losses inside the NSTG network for the different scenarios and cases. During normal operation, the losses difference is not very significant, still the first scenario have 4,5% less losses than in the first scenario and 1,8% less than the second one.

In the other hand, the difference can be quite significant for the cases where one node of the network is faulted or unavailable. In those cases the losses can be significantly different and be of economic concern when calculated over the lifetime of the MTDC network.

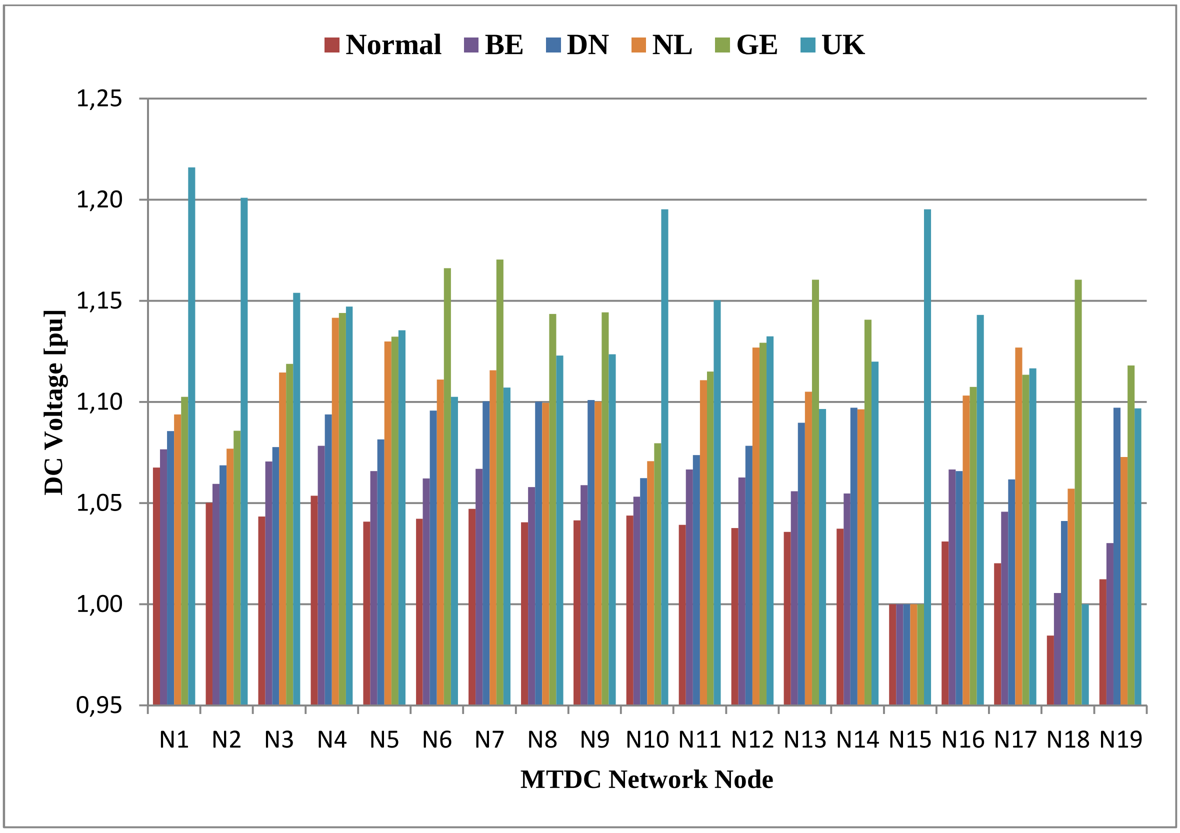


Figure 8 – Voltage profiles for the 1st scenario: 1 slack node (UK).

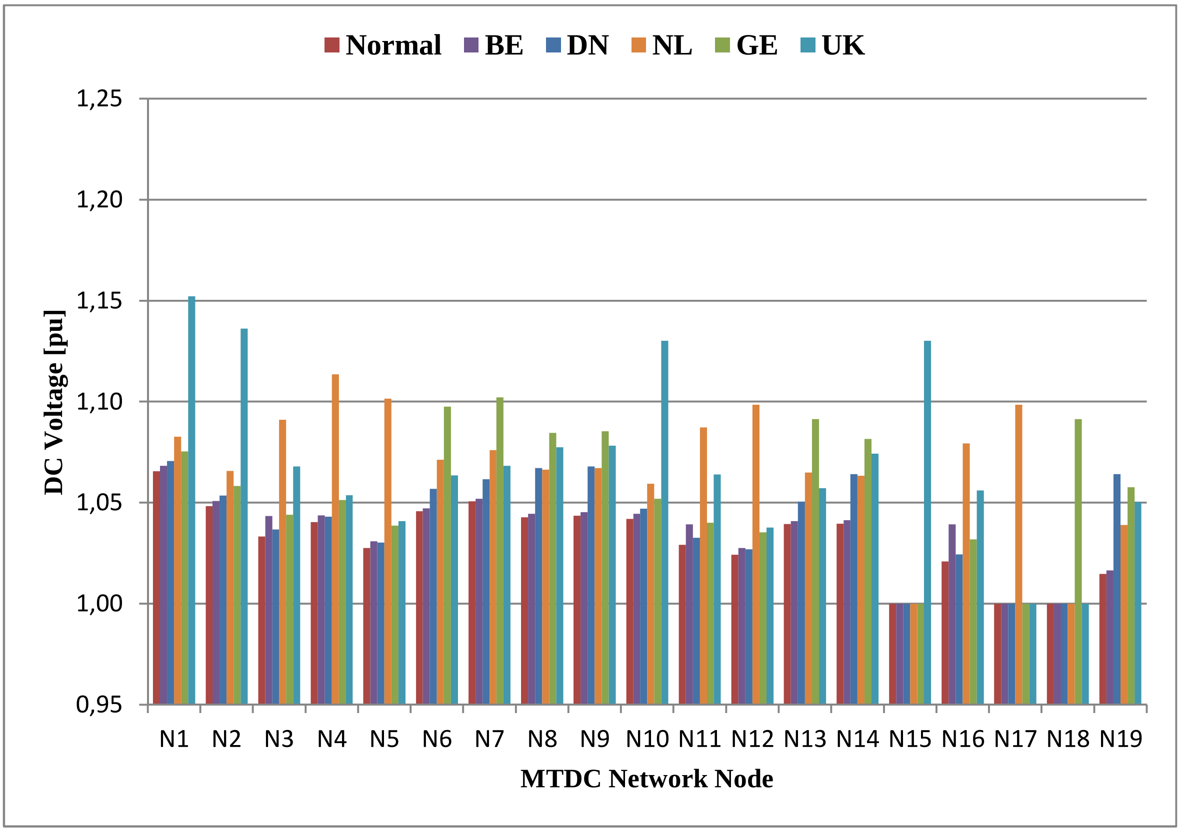


Figure 9 – Voltage profiles for the 2nd scenario: 3 slack nodes (UK, GE and NL).

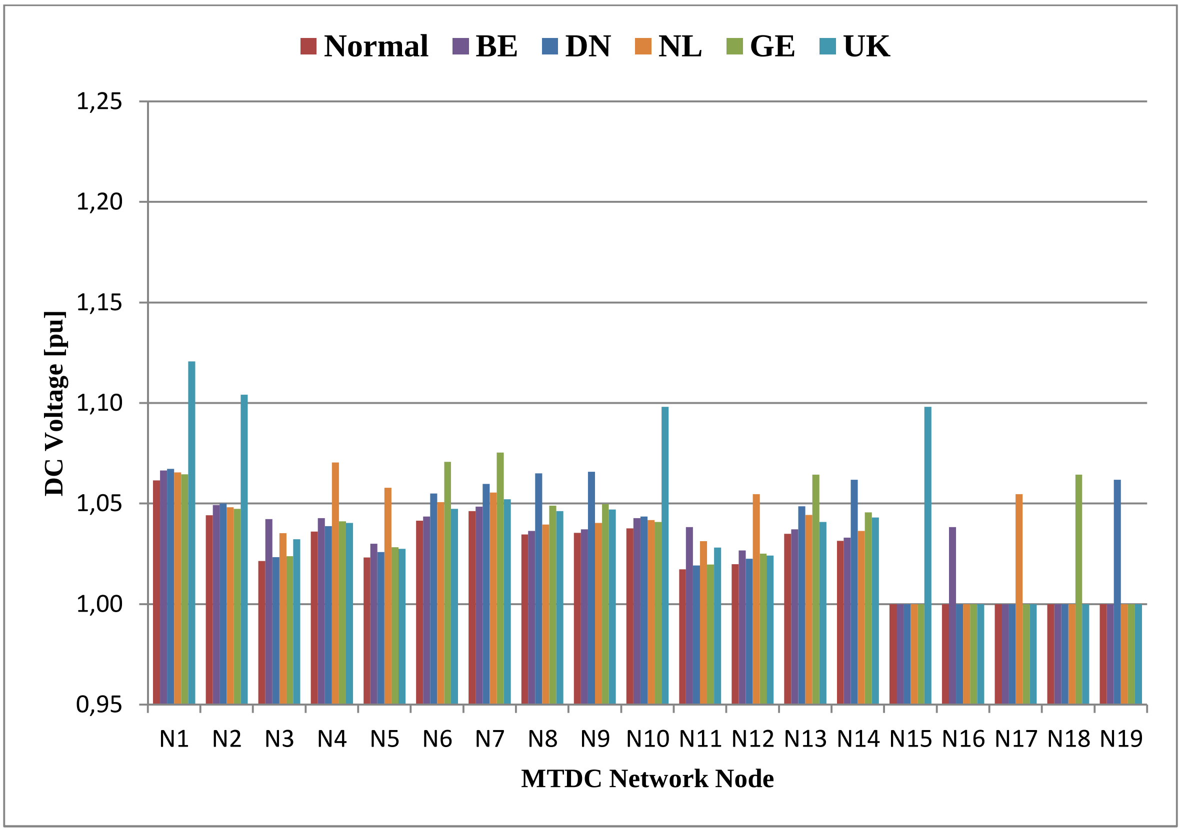
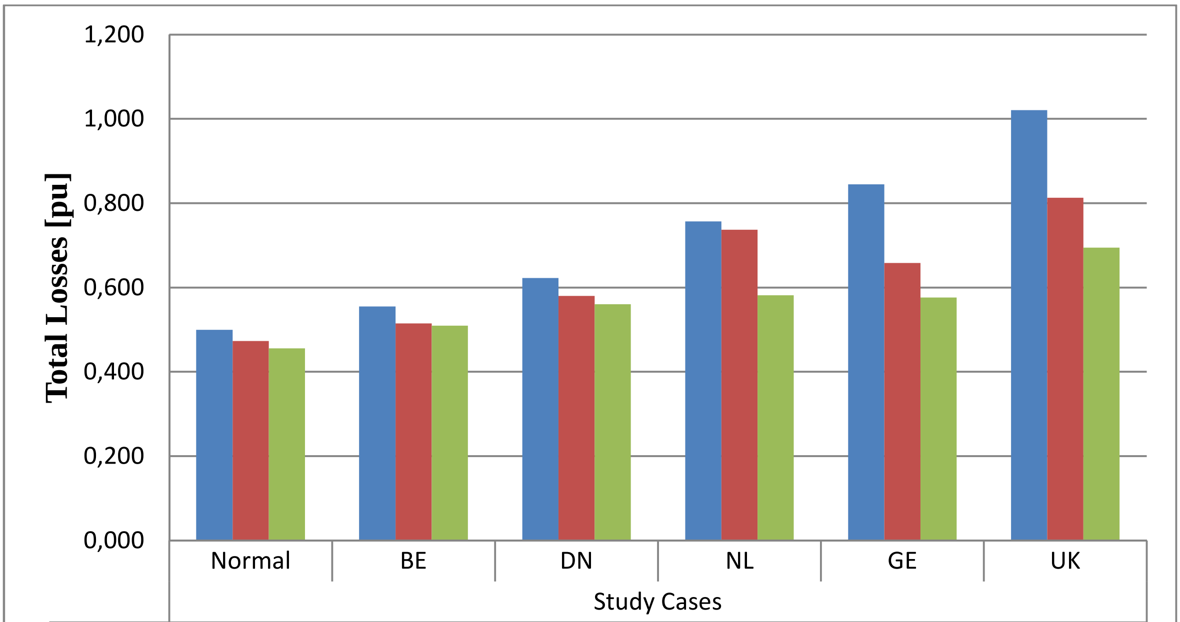


Figure 10 – Voltage profiles with all 5 countries as slack nodes.



	Normal	BE	DN	NL	GE	UK
1 slack	0,500	0,555	0,622	0,757	0,844	1,021
3 slacks	0,473	0,515	0,580	0,737	0,658	0,813
5 slacks	0,455	0,510	0,560	0,582	0,576	0,694

Figure 11 – Losses on the MTDC network for the different analysed scenarios in dependency of the number of slack nodes.

6. Conclusions

Modularity and standardization will most definitely play very important roles in the construction and development of multi-terminal DC networks for integration of large-scale offshore wind energy. To allow offshore networks to grow organically with time, the global design rules of such systems will have to be carefully discussed between all the involved stakeholders in order to avoid large changes in later development stages, which are expected to be expensive and difficult to perform.

In this work, a DC load-flow analysis was performed for a possible NSTG layout involving the countries with the highest expected offshore installed capacity. It was shown that a control strategy where more than one node is controlling the DC voltage inside the MTDC network – thus working as slack nodes – is superior when compared to a strategy in which only one node is given that task. The superiority was find both regarding N-1 contingencies and the overall losses in the transmission system.

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Biographies

Rodrigo Teixeira Pinto was born in *São Paulo*, Brazil, on November 3rd 1983. In 2003 he joined the *Escola Politécnica da Universidade de São Paulo* for a bachelor in Electrical Engineering at the Electrical Energy and Automation (PEA) department. In 2006 he started his MSc. in Electrical Engineering at the *Politecnico di Torino*, in Turin, Italy. From May to November 2008 he was with Siemens PTI, in Erlangen, Germany, working towards his MSc. as a *Diplomand* on the Network Dynamics Studies department. On December 2008 he received his MSc. (cum laude) from the *Politecnico di Torino*. Since December 2009 he is working as a PhD researcher on the North Sea Transnational Grid research project at the Electrical Power Processing group (EPP) of TU Delft.

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