A Smart Grid Simulation Centre at the Institute for Energy and Transport - Model validation of VSC-MTDC for integration of offshore wind energy

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Abstract— **In this paper the Smart Grid simulation centre facilities of the Institute for Energy and Transport (IET), Joint Research Centre (JRC) of the European Commission's (EC) are presented, providing a specific application of our work. The Smart Grid Simulation Centre is intended to combine electrical power components and communication/control equipment with system simulation tools. In this way the Centre can test grid elements and evaluate different operation scenarios under various conditions. As a specific activity the cooperation in accessing multiterminal grids is described in this paper.**

Keywords-component; *smart grids; interoperability; security of supply; modelling; real-time simulation*

I. Introduction

In order Europe to achieve the de-carbonization of the society and the security of energy supply targets, the contribution of renewable energy sources is of paramount importance. The exploitable offshore wind potential could contribute in this direction. According to the estimations wind farms with a total capacity of 40GW will be installed in Europe by the end of this decade [1]. With the increasing size of the wind parks and the increased distances to shore, HVDC transmission systems will often prevail over HVAC systems. From a certain point HVDC systems are not only more economical compared to HVAC, but also provide more capabilities to control the power flow and to support the AC voltage, both onshore and inside the wind farms. By creating Multi-Terminal DC (MTDC) grids, rather than only point-to-point connections, energy trading can be realized as well as a more efficient usage of the grid. Consequently researchers' interests move towards multi-terminal high voltage DC (HVDC) networks to support different technical problems such as:

- offshore generation (wind, wave and tidal);
- sea or long crossings;
- coupling asynchronous grids;
- reinforcement of /feed-in into weak grids;
- grid reinforcement (e.g. pan-European overlay grid);
- feeding of densely populated urban areas
- isolated loads (e.g. offshore rigs, islands)

Multi-terminal grids have been firstly proposed in 1963 [2] but J. Reeve 17 years later contributed in reviewing the bibliography [3]. The current technology offers two main schemes to develop HVDC multi-terminal grids. The Line-Commuted Converter (LCC-HVDC), which is based on the use of thyristors and the Voltage-Source Converter (VSC-HVDC), which is based on the use of force commutated switches, such as Insulated Gate Bipolar Transistors (IGBT).

Especially for the wind park connection there is a tendency to consider the use of the voltage-source converters (VSC) technology [4], [5] which offers some specific advantages [6]:

- VSC-HVDC can offer ancillary services providing reactive power;

- It does not increase the short circuit current of the AC system;

Another disadvantage is the sensitivity for DC faults A third disadvantage is the higher losses when compared to LCC-CSC.

Also VSCs have their limitations to the AC grid strength

- The filter capacity is much lower compared to other solutions because of the sinusoidal pulse width modulation (PWM) or multi-level topologies.

- Given a fixed DC voltage polarity, VSCs may be linked thus forming a multi-terminal HVDC topology, just as is the case with AC systems. However, power flow control in MTDC is different and more complicated than in AC systems.

The recent research trends [7-15] are focusing in handling stability and protection issues of the equipment using controlling and optimization techniques. Chaudhuri et al. [7] tackle the interaction between multi-machine ac systems and a multi-terminal DC (MTDC) grid and the impact on the overall stability of the combined AC-MTDC system. Chen et al. [8] simulate in PSCAD/EMTDC a model of a five-terminal hybrid MTDC system including a large capacity wind farm, in which the corresponding control strategy is designed. Gomis-Bellmunt et al [9] discuss voltage-current characteristics and equilibrium points for the DC voltages in multi-terminal HVDC systems using voltage source converters. Jovcic et al. [10] studied a hypothetical large offshore wind farm based on centralised power conversion and interconnected to the grid using a multi-terminal parallel HVDC link. Publication [11] studies three configurations of voltage source converter multi-terminal HVDC transmission for large offshore wind farms. Additionally it is addressed the control of multi-terminal voltage-source converters at high-voltage direct current in the context of offshore wind farms [12]. Tang et al. [13] deals with the negative and positive sequence harmonic transfer of the converters. Yang et al. [14] analyzes dc faults, their transients, and the resulting protection issues. Zadkhast et al [15] evaluates the reliability of multi-terminal HVDC systems. The contribution of the current publication is to describe the voltage-source converters applications and to describe the work being carried out in the Smart Electricity Systems laboratory.

In Section II the activities inside the Smart Electricity Systems laboratory are presented. Section III deals with the operational principles of the voltage-source converters and a brief description of multi-terminal grid topologies. Section IV contains an explanation of the experimental PHIL work inside the NSTG project, which is going to be performed jointly by Technical University of Delft, ECN and the JRC. The last section presents a conclusion of the discussed topics.

II. Description of the Smart Electricity Sytems Acton Activities

The Institute for Energy and Transport (IET) of the European Commission's (EC) Joint Research Centre (JRC) provides support to Community policies and technology innovation to ensure sustainable, safe, secure and efficient energy production, distribution and use and to foster sustainable and efficient transport in Europe [16].

Several challenges affect the evolving European energy networks while pursuing the objective of a fully functioning, interconnected and integrated internal energy market. A key concern for policy makers and the energy sector is the increasing risk of supply failure. In this framework the IET's Energy Security Unit (ESU) has been established to support the policy-making processes regarding security of energy supply. This task requires the analysis of different contingencies and scenarios, as well as the assessment of the vulnerability, reliability and resilience of the energy systems.

The Smart Electricity Systems (SES) Action [17], which is one of the projects run by ESU, performs research on smart grids, particularly in the context of the European Strategic Energy Technology (SET) Plan [18] and the Energy Infrastructure Package [19]. This research is aligned with key initiatives on smart grids launched in the framework of the SET-Plan, namely the Smart Grid Joint Programme of the European Energy Research Alliance (EERA) [20] and the European Electricity Grid Initiative (EEGI) [21].

Against this background, the SES Action has already developed offline tools for the visualization and analysis of critical electricity infrastructures [17]. These tools, consisting of map-based applications and advanced power system modeling software, are maintained for the European Commission policy-making services and allow performing detailed analyses to assess criticality and vulnerability of European electricity systems and regions.

In order to better meet its customers' requests and play an active role in smart grids standardization, the SES Action is expanding the computational capabilities and experimental facilities of the recently established JRC Smart Grid Simulation Centre.

The Smart Grid Simulation Centre is intended to combine electrical power components and communication/control equipment with system simulation tools. In this way the Centre can test grid elements and evaluate different operation scenarios under various conditions.

More specifically, the Smart Grid Simulation Centre will expand upon the following facilities:

- Electric power system real-time simulation hardware and software
- Power supply and load equipment
- Power electronics components
- Battery charging stations and related equipment
- "Intelligent" measurement and communication devices

The Smart Grid Simulation Centre will also crucially contribute to the research activities of a new JRC scientific infrastructure: the Electric Vehicle and Smart Grid Interoperability Centre. The latter is the result of a formal cooperation between the JRC and the US Department of Energy (DoE) on e-mobility and smart grids.

III. Description of Multi-terminal Grid Topologies

The bibliography proposes different topology solutions for VSC multiterminal grids [22, 25]. Xu et al [22] analyzed the integration procedure of Doubly Fed Induction Machines (DFIG) for wind farms that are connected to the grid directly (Fig. 1). In this publication a solution for a 300MW wind farm is applied. The wind farm side VSC (WFVSC) directs the wind energy produced to a pair of DC XLPE cables, and then the grid side VSC (GSVSC) injects the energy to the grid. GSVSC is able to provide ancillary services producing reactive power and supporting the voltage which useful to weak connection points with low short circuit ratio (SCR). The authors [22] propose a standard procedure the connection of a high pass filter (HFF) on each side to absorb the high frequency harmonics produced by the converters. In order the VSC transmission system to operate within safe operational limits referring to overvoltages, low losses and low harmonics content and the dc link voltage has to remain stable. GSVSC is assigned to control the dc voltage which is equivalent in ensuring that the energy injected by WFVSC is transmitted to the grid network.

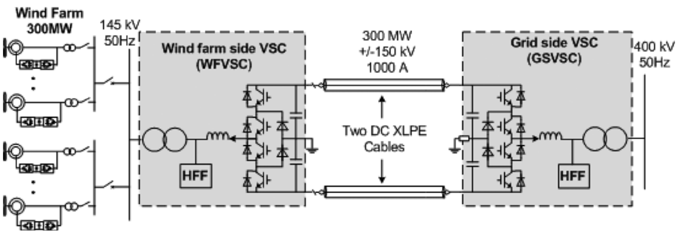

Fig. 1: Single line diagram of wind farm integration using VSC (redrawn from 22)

Jiang et al [23] analyzed the performance of a single line multiterminal grid (Fig. 2). In a multiterminal system of this type, the master control has to constantly maintain the load balance. During abnormal conditions, like DC faults, the structure of the system could change significantly and the master control has to reorganize the control pattern properly. The authors conclude [23] that a multiterminal HVDC system could be a interesting alternative even to a conventional HVAC system in an urban area of a large city.

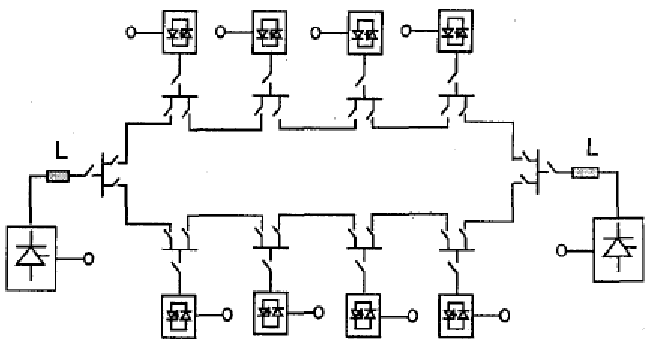

Fig. 2: Single line multiterminal system (redrawn from 23)

Lu et al [24, 25] propose a four terminal wind system focusing in the optimal energy absorption from the low installed power wind turbine point of view (Fig. 3) and a five terminal configuration (Fig. 4). In this paper [25] the VSC-HVDC benefits to power quality are studied. It has been shown that this configuration can contribute significantly to power quality. The authors performed digital simulations [25] and have shown that severe disturbances do not affect the sensitive loads. Concluding it can be claimed that his configuration offers a safe platform for the integration of large amounts of wind energy to the grid.

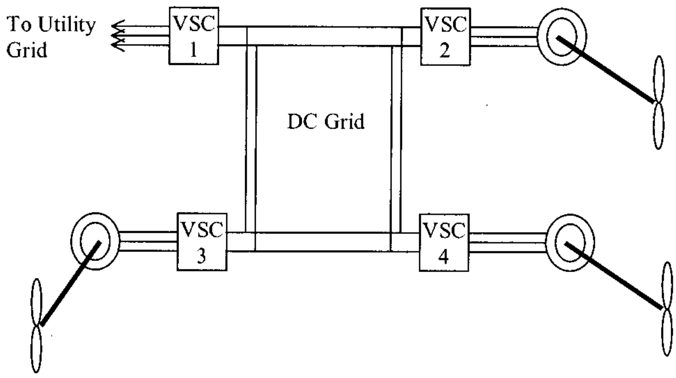

Fig. 3: Four terminal wind system (redrawn from 24)

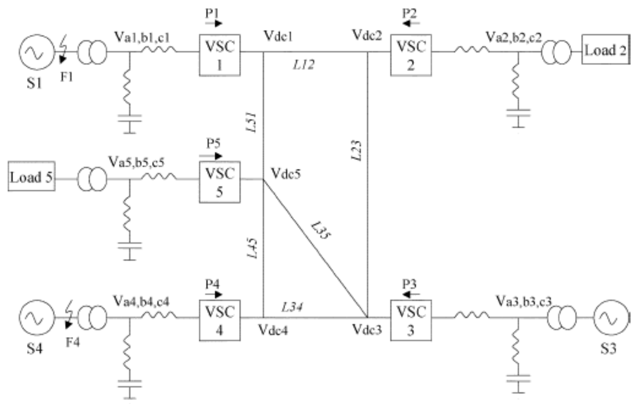

Fig. 4: Five terminal configuration (redrawn from 25)

IV. Description of the NSTG Experimental Setup

In order to achieve the European renewable electricity targets, integration of large amounts of offshore wind energy is foreseen. In that context, the development of transnational grids will play a major role in the integration of large-scale offshore wind power. At the same time, as offshore wind farms are erected with increased distance and installed capacity, HVDC transmission systems will have to be deployed to efficiently and economically bring the generated energy ashore. Therefore, offshore transnational DC grids are a key element for the integration of these future offshore wind farms.

A. The NSTG Project

With the aim to investigate the best ways of integrating large scale offshore wind power by means of a transnational grid in the North Sea, the Energy Research Centre of the Netherlands (ECN) and Technical University of Delft (TU Delft) started, in October 2009, a four year research project, called North Sea Transnational Grid (NSTG). In this project the technical and economical feasibility of different scenarios of the NSTG is studied.

The NSTG project focuses on design, development and operation of offshore grids, as well as on the necessary adjustments to the mainland systems for implementing large-scale offshore wind power [26]. One of the project goals is to develop and validate new control strategies for AC/DC converters operating inside a multi-terminal DC (MTDC) grid.

The NSTG research project is coordinated by ECN. The objectives of the NSTG project are laid down in work packages (WP). These WPs are shown in Fig. 4 together with their interdependencies and projected duration [26]. A brief description of each WP is given below:

- WP1 and WP2 assess the available technologies by performing a literature study and an initial technical-economic evaluation of the different transnational grid configurations. The most promising results will be used as an input for the subsequent WPs.
- WP3 focuses on control and operation of multi-terminal DC networks. The main goal is the development of a control strategy capable of operating multi-terminal DC networks composed of VSC-HVDC regardless of the network topology and size.
- The results and control strategies developed in WP3 will be simulated and tested by scaled-down experiments on a real-time simulator in WP4. This work package will be carried out in collaboration with JRC-IET.
- The fifth WP consists of a genetic algorithm multi-objective optimization of the NSTG topologies (WP2).
- Grid integration aspects to the different national AC networks of the NSTG are addressed in WP6 which – together with WP3 and WP4 – is used as input for the detailed multi-objective optimization (WP5).
- WP7 deals with market, policies, regulatory and organizational aspects of the NSTG using the most promising results and scenarios from the previous WPs.

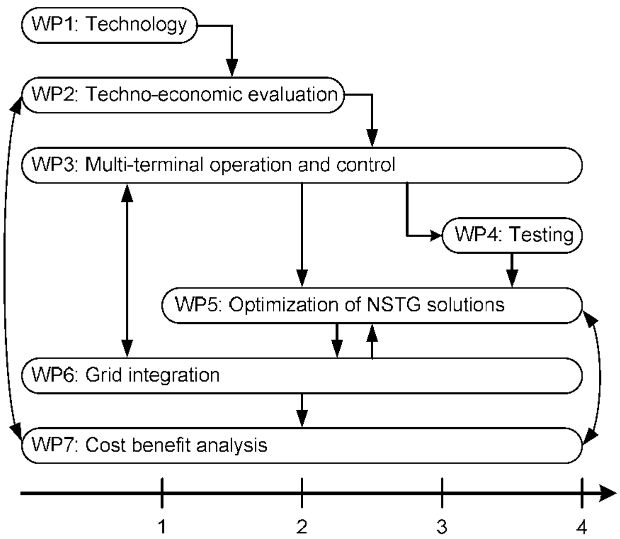

Fig. 5: NSTG-project work packages: duration (in years) and interdependencies between the work packages.

B. *WP4: Multi-terminal DC Network Testing*

For the validation of the models and controls developed on NSTG WP3, a scaled-down MTDC grid will be built and tested in co-operation with JRC-IET.

For the testing phase, the Electrical Power Processing (EPP) Group of TU Delft, in partnership with ECN and the JRC, has acquired 3 voltage-source converters from Triphase Systems®, each rated at 5 kVA. With the Triphase® VSCs, it is possible to use PC-based controller models, directly developed in Matlab Simulink™, together with the actual power hardware. Fig. 6 displays two of the three acquired VSCs installed in the EPP group laboratory at TU Delft.

The acquired VSCs provide a very straight-forward platform for obtaining practical results from the developed control strategies in WP3, i.e. the simulation phase. In addition, the JRC has available an OPAL-RT® real-time digital simulator for the study and analysis of power system and power electronics phenomena. The advantage of using a real-time simulator in this scenario lies in the fact that it becomes possible to exchange signals with external devices, such as the VSCs, and use them in real-time, making this a valuable setup for PHIL (power-hardware-in-the-loop) testing.

Fig. 6: Two of the three 5kVA AC/DC converters sitting on the laboratory of TU Delft EPP group.

C. *MTDC Network Testing*

The testing phase of NSTG WP4 will be divided into several steps, which will permit the final scaled-down setup to organically grow with time, much as the future offshore MTDC network will probably grow from simple topologies, with four or five terminals, into more intricate meshed designs.

In the very first phase, which is currently in place, a single VSC was connected to the AC grid of the EPP laboratory. In this phase the goal is to gain knowledge on the operation of a single cabinet and to start porting the control blocks and other models developed in WP3.

In this phase the following components of the VSC-HVDC simulation models are being ported to one of the cabinets for testing:

- the Phase-Locked Loop (PLL) block, which synchronizes the VSC to the AC network;
- the reactive power and DC voltage outer controllers, which provide the VSC its current reference;
- the inner current controller, which receives the VSC current references from the outer controllers and sends the voltage references to the modulator block;
- and the modulator block, which uses space-vector PWM to switch the cabinet IGBTs.

During the first phase, since just one VSC is connected to the AC network, it is only possible to exchange reactive power between the converter and the grid. In order to test the VSC ability to exchange reactive power with the laboratory AC network, the converter is controlled to vary step-wise its d-current reference (reactive component), as shown in the first graphic of Fig. 7.

When the converter current in the d-axis is positive, it means it is absorbing reactive power from the AC network, whereas when the d-axis current is negative, the converter is supplying reactive power to the AC grid. The second graphic of Fig. 7 shows the active power (blue), the reactive power (green) and the apparent power (red) as seen from the AC grid. It is possible to notice the influence of the VSC LCL-filter capacitance on the reactive power exchange when the converter is absorbing and injecting reactive current in the AC grid. The last graphic of Fig. 7 shows the capability of the DC voltage controller. At simulation t = 5 s, the VSC IGBTs are unblocked and the DC voltage controller rapidly brings the DC voltage to 1 pu, i.e. 700 V. Then, between t = 25 s and t = 40 s, the DC voltage was varied with a ramp from 700 V to 640 V and back, in order to test the controller ability to track changes in the DC voltage operating point reference.

D. NSTG WP4 Future Work

On the first phase only one VSC cabinet was connected to the AC network. On the subsequent phases the other cabinets will be interconnected through their DC sides.

On the second phase, two of the small VSC cabinets will be connected in back-to-back, thus making it possible to exchange not only reactive power with the AC network but also active power between the two converters. On the third phase, after two cabinets where connect in back-to-back, the third cabinet will be added already forming a small MTDC Network.

The scaling down of the MTDC grid will be done in such a way that the dynamic properties are comparable to a full-scale MTDC grid allowing for a meaningful validation of the developed control strategies. When all three converters will be connected and operational, the MTDC grid configuration will be implemented via lumped components which will serve to emulate the behavior of the high voltage DC cables. The lumped components values have, therefore, to be carefully selected in order to preserve the same dynamic characteristics as it would be expected from a high-voltage MTDC grid.

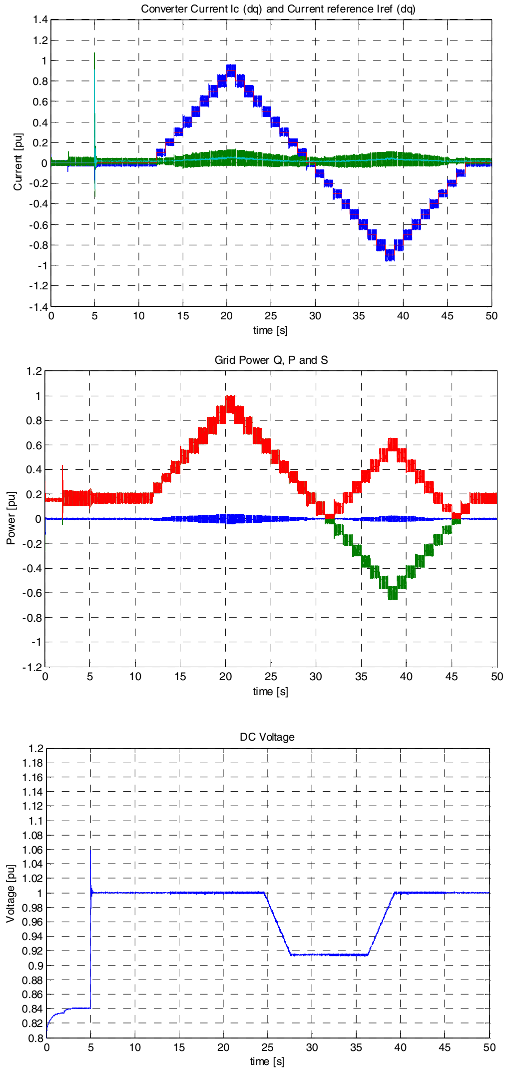

Fig. 7: Resulting converter currents (in the dq frame), power and DC Voltage during a test of a single VSC in the EPP laboratory.

Hence, the first three phases of WP4 consist in a stand-alone configuration comprising only the three small VSC cabinets.

On a later fourth phase, a real-time digital simulator will be added to the setup. The real-time digital simulator will be connected to perform testing of the small VSC cabinets and its controls, interactively with the MTDC grid model. Inside the real-time simulator a combination of different models (e.g. wind farm models and large AC networks), and control strategies previously developed in the NSTG project will be validated in real time.

An initial simple setup that would allow getting start with PHIL type of simulations is depicted below in Fig. 8. It depicts a point-to-point VSC-HVDC transmission system, where a model – which can either be an average or switching model – of the VSC sits inside the simulator, while the second VSC is constituted by one of the real physical VSC cabinets. The goal in this phase is to establish the connection between the real-time simulator and one the VSC cabinet.

On the fifth and final stage, all three VSCs will be connected to the real-time simulator forming a multi-terminal DC network environment comprising real converters, while the offshore wind farms will be simulated by the OPAL-RT. The configuration of the desired final stage is displayed in Fig. 9.

In conclusion, the laboratory work for the NSTG project will be composed of five phases:

- Phase 1: Single connection of one VSC cabinet for stand-alone measurements and VSC model validation;
- Phases 2 and 3: Setting up the small scale multi-terminal network system in the laboratory to test the developed operation and control strategies;
- Phases 4 and 5: Connection of the OPAL-RT real-time digital simulator to the VSC, forming a setup configuration where testing of the MTDC operation and developed control strategies can be tested with wind farm models running in real time.

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