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Connection of OWPPs to HVDC networks using VSCs and Diode Rectifiers: an Overview

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***Abstract*—This paper provides an overview of two technologies for connecting offshore wind power plants (offshore WPPs, OWPPs) to high-voltage direct current (HVDC) networks: voltage source converters (VSCs) and diode rectifiers (DRs). Current grid code requirements for the connection of such power plants are also addressed, and their implications when using such technologies are discussed.**

***Index Terms*—HVDC, offshore wind power plant, diode rectifier, voltage source converter, grid code requirements**

I. Introduction

In order to unlock the full potential of Europe's offshore wind resources, networks are required, linking the offshore wind power plants (offshore WPPs, OWPPs) to the onshore grids in different countries, providing additional flexibility, efficiency, security and market access. At the end of 2015, the installed wind power capacity had reached 11 GW, most of it installed in the North Sea [1].

To date, most of the installed OWPPs are connected to the onshore grids using traditional high-voltage alternating current (HVAC)—a solution used in most offshore wind plants in the North Sea—or high-voltage direct current (HVDC) technology. The latter is being used in a few projects today, mostly in Germany, but it is widely expected to be used more, as the distance from shore increases.

This paper aims at presenting an overview of the requirements for connecting OWPPs using HVDC technology and discusses their implications when using two offshore power converter technologies: voltage source converters (VSCs) and diode rectifiers (DRs). A diagram depicting the studied technologies for connecting OWPPs to HVDC networks is shown in Figure 1. The paper is organised as follows. Sections II and III present the technologies in question, while Section IV introduces the main requirements for the connection of OWPPs. The final section discusses the main differences between VSC- and DR-HVDC solutions for connecting OWPPs.

II. Voltage Source Converters (VSCs)

The development of insulated-gate bipolar transistors (IGBTs) has enabled the use of VSCs for HVDC power transmission systems, with commercial application since 1999 [2]. Despite having higher costs and losses than the more mature solution using thyristor-based line-commutated converters (LCCs) [3], VSC-HVDC offers advantages such as [2], [4]:

- Compactness
- Black-start capability
- Capability to connect to weak AC networks
- Independent control of active and reactive power
- Fast reversibility of active power flow

By virtue of such advantages, VSCs have enabled the point-to-point connection of remote OWPPs to onshore AC networks. Moreover, they have become the preferred HVDC converter technology: the grid-forming units, upon which most HVDC grid code requirements are based.

III. Diode Rectifiers (DRs)

In quest of lowering the costs of offshore wind energy, new control strategies taking advantage of the type-4 (full-converter) wind turbines' own power converters have been recently shown to enable the use of DRs (instead of the HVDC offshore VSCs) for connecting OWPPs to HVDC networks [5], [6], [7]. Compared to VSCs, DRs offer advantages such as [8], [9]:

- Reduced offshore converter station size
- Reduced losses
- Reduced investment installation and maintenance costs
- Increased reliability

However, they require fundamentally different wind turbine (WT) and WPP controls, changing their control philosophy from grid-following units to grid-forming units [10], [11].

To make up for the DRs' lack of control capabilities, the control of the offshore AC network's voltage and frequency has to be delegated to the WT front-end VSCs, which must also control the power flow [5], [9]. Thus, the WT back-end VSCs have to assume the control of the WT DC link's voltage.

The diagram in Figure 2 shows possible offshore AC network start-up methods for OWPPs connected to HVDC networks using DRs. As the DRs cannot start the offshore AC network by themselves, the OWPPs must take over such role [6]. Nevertheless, auxiliary power is needed to start the OWPPs. Such power can be provided by so-called umbilical cables, which can be connected to onshore AC networks or to neighbouring OWPPs or HVDC offshore VSCs [8]. Alternatively, local auxiliary energy sources can be installed in the OWPPs.

In this paper, VSCs are assumed to be used as the HVDC onshore converters and are simply referred to as *onshore converters*. Moreover, *VSCs* or *DRs* are used to refer directly to the technology choice for the HVDC offshore converters

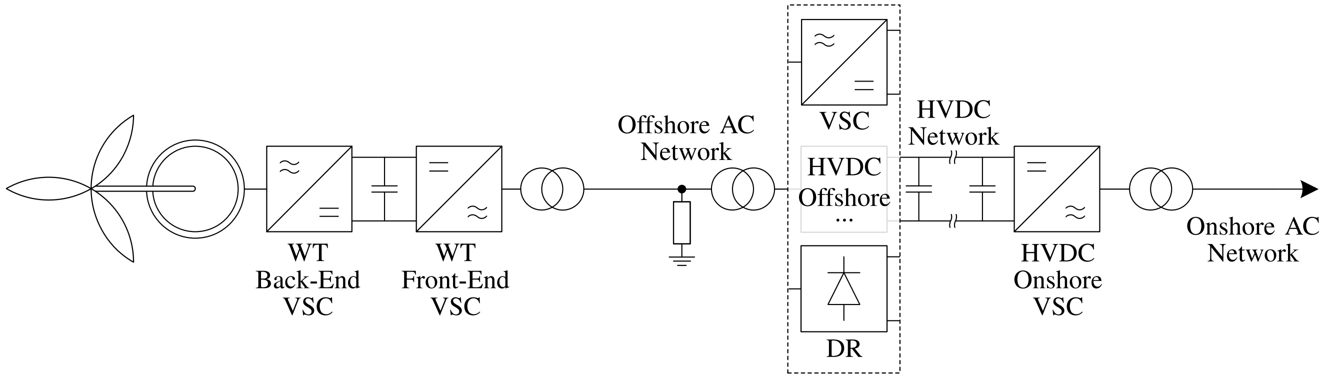

Figure 1. Connection of OWPPs to HVDC networks using VSCs or DRs

to which the OWPPs are connected, unless otherwise noted, and (thyristor-based) LCCs are not considered.

IV. Requirements

One of the main references of requirements for HVDC-connected OWPPs is ENTSO-E's Network Code on HVDC Connections (HVDC Code) [12], which covers also requirements for HVDC power transmission systems' onshore and offshore terminals. This code has been published in the Official Journal of the EU on the 26th of August 2016 and has provided a framework for countries' national grid codes. The technical connection requirements for OWPPs can be classified as: imposed by the onshore AC networks, and imposed by the offshore AC and DC networks.

A. Requirements imposed by the Onshore AC Networks

The requirements imposed by the onshore AC networks are mainly the services that are to be provided to them via the HVDC networks, including [13]: frequency support, active power control, power oscillation damping (POD), AC voltage support, and fault ride-through (FRT).

1) Frequency Support: Onshore converters must be equipped with an independent control to modulate the active power according to the frequency at the connection point in order to maintain stable system frequencies and/or contribute to the frequency control of the AC networks. Each transmission system operator (TSO) provides the detailed operating principle, associated performance parameters and activation criteria of the frequency control, such as:

- Frequency response dead-band
- Upward droop value
- Downward droop value
- Frequency response insensitivity
- Initial delay of activation

HVDC-connected OWPPs can contribute to the regulation of onshore AC network frequency by responding to over- and under-frequency events. The concept of synthetic inertia is mentioned in the ENTSO-E's HVDC Code [12], but such requirement is left to be agreed with each TSO. In case of an over-frequency event, the active power can be considered to be accomplished by the active power control capability mentioned below. However, an under-frequency event imposes a challenge on WPPs, as an increase of active power is required. This might in turn require down-regulated operation to keep reserves, utilising the kinetic energy of the rotating turbines, and/or overloading the WTs beyond their ratings. Similarly, additional active power might also stress the HVDC networks beyond their ratings. This requirement carries also the challenge of mirroring the onshore AC grid frequency to the offshore generation by any means, with or without communication.

2) Active Power Control: The general requirements associated with the active-power control of HVDC networks can be categorised as follows [12], [13].

- Ability to control the active power up to the maximum limit in both directions

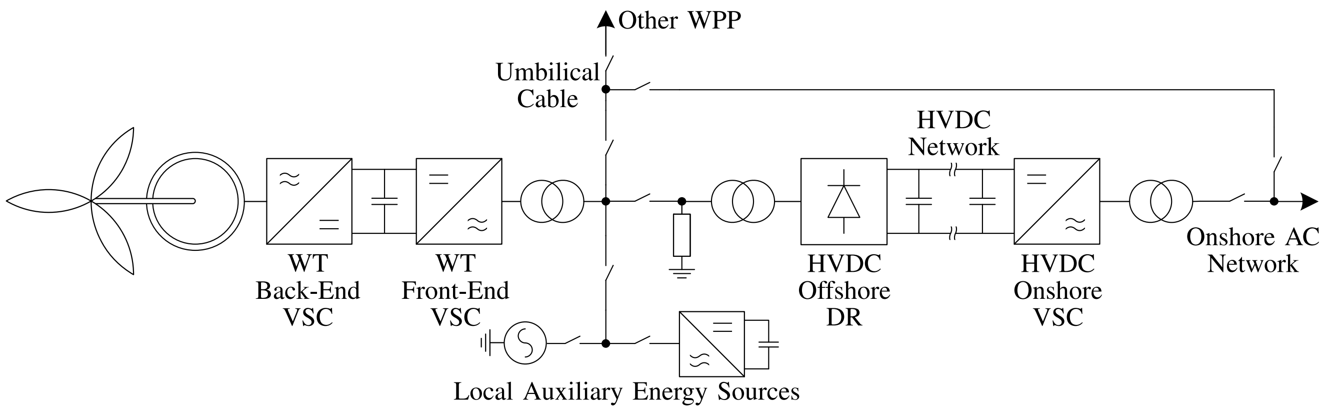

Figure 2. Possible offshore AC network start-up methods for OWPPs connected to HVDC networks using DRs

- Maximum allowed set-point increase or decrease for adjusting the transmitted active power
- Minimum active-power transmission capacity for each direction, below which the active-power transmission capacity is not requested
- Maximum time delay between the reception of a TSO's request and the start of the active-power adjustment
- Adjustment of the ramping rate (the ramping rate does not apply in case of fast power reversal or in case of a disturbance in an AC network)
- Possibility to take remedial actions such as stopping the ramping and blocking the frequency-sensitive mode (FSM), with the triggering criteria to be specified by each TSO
- Fast response in case of disturbance in an AC network, with a maximum allowed delay from the reception of the triggering signal by each relevant TSO
- HVDC networks linking different AC control areas or synchronous areas must be equipped with control functions enabling the relevant TSOs to modify the transmitted active power for the purpose of cross-border balancing
- The control functions of a HVDC network must be capable of taking automatic remedial actions, including stopping the ramping and blocking the frequency control

In the active power control scheme, an active power set point is given to the offshore generation (within the available power level) for down-regulation purposes. This fulfilment of this requirement has been shown in literature using the capabilities of the variable-speed WTs.

3) Power Oscillation Damping: HVDC networks must be capable of contributing to the damping of power oscillations in the connected AC networks [12]. Onshore converters can contribute with POD by manipulating the injection of active and/or reactive power at the connection points with the onshore AC grids. Each connecting TSO must provide the frequency range in which damping is to be provided and has to agree with the final settings for the damping controller. The connection of a HVDC network should not lead to undamped oscillations and should not degrade the damping level in an AC network. To provide POD, the onshore converters require an extra control loop in which a lead-lag compensator (like the one in a power system stabiliser) is normally used [4]. OWPPs can contribute to POD via active power modulation, i.e., the control of offshore generation such that the onshore HVDC terminal helps the onshore AC grid to damp power system oscillations. However, this requirement has the challenge of communicating and synchronising with the oscillation signal.

4) Reactive Power Control and Voltage Support: HVDC networks should be able to maintain the AC voltage at the connection point within a specific range determined by each relevant TSO. The voltage support is implemented by reactive power exchange between the onshore converters and the AC networks, which should not result in a voltage step changes. To provide such reactive power exchange, the onshore converters can be operated in three control modes:

- Voltage control mode
- Reactive power control mode
- Power factor control mode

In voltage control mode, a dead-band around the $1\,\mathrm{p.u.}$ value may be enforced. Each relevant TSO defines time requirements such as the rise time (time required to reach 90% of the reference value) and settling time (time required to settle within a certain tolerance of the reference value). Voltage control must also include the possibility of providing reactive power control according to two set points: one for voltage and one for reactive power. Remote selection of the control mode and associated set points has to be foreseen. Maximum steps in the reference signals should be enforced to limit the disturbances to the grid.

5) Fault Ride-Through: Each TSO specifies a voltage-against-time profile at the connection point, above which the onshore converters must be capable of staying connected and continue stable operation [12]. The pre-fault and post-fault conditions to be used for the low-voltage ride-through (LVRT) capabilities should be provided by each TSO. They may also specify voltages at the connection points under specific network conditions whereby the HVDC systems are allowed to *block* (i.e., remain connected to the network with no active and reactive power contribution). The HVDC networks are required to have the capability of providing fast fault current at a connection point in case of symmetrical three-phase faults, if and as specified by each TSO. The following characteristics are then specified:

- Conditions for activating the fault current contribution
- Characteristics of the fast fault current
- Timing and accuracy of the fast fault current, which may include several stages

Additionally, each relevant TSO must specify the magnitude and time profile of active power recovery that the HVDC systems must be capable of providing to the AC system; and their fault ride-through capabilities in case of asymmetrical faults, e.g., asymmetrical current injection.

B. Requirements imposed by the Offshore AC and DC Networks

The DC-connected power park (i.e., OWPPs) requirements in [12] have been built upon ENTSO-E's Network Code on Requirements for Grid Connection Applicable to all Generators (RfG Code), a binding EU regulation since the 17th of May 2016 [14]. This creates ambiguity as offshore and onshore connection phenomena for WPPs can differ considerably, especially for WPPs connected via DRs. The requirements imposed by the offshore AC and DC networks are mainly the support services to help maintaining their stability. These are listed below.

1) Operational Voltage and Frequency Ranges (including Rates of Change): Offshore HVDC terminals and WPPs must be able to withstand certain voltage, frequency and rate-of-change-of-frequency (ROCOF) deviations without being disconnected.

2) Fault Ride-Through: Offshore HVDC terminals and WPPs must stay connected and inject fault currents to securely cleared offshore symmetrical or asymmetrical AC faults. They can also react to DC network faults in a controlled manner by protecting themselves from the flow of high currents. The response of WPPs to DC faults in meshed offshore DC grids stands as future work.

3) Offshore AC Voltage Generation: Since offshore networks do not include any conventional power plants, the offshore AC grid voltage has to be formed and controlled by either the offshore HVDC terminals (VSC case) or the OWPPs (DRU case). The former is a proven state-of-the-art case, whereas the latter is a new development as part of the PROMOTioN project [13].

V. Discussion

This paper has presented an overview of two technologies for connecting offshore wind power plants (offshore WPPs, OWPPs) to high-voltage direct current (HVDC) networks: voltage source converters (VSCs) and diode rectifiers (DRs). Current requirements for the connection of such power plants have also been addressed.

While DRs offer reduced costs and increased reliability, they lack the control capabilities of VSCs, and their use relies on delegating the corresponding control functions to the (type 4) wind turbine (WT) front-end VSCs in the OWPPs. This requires fundamentally different WT and WPP control schemes and poses new challenges such as their coordination and synchronisation in controlling the offshore AC voltage and frequency.

Because of being mainly based on the requirements for onshore generation, current requirements for HVDC-connected offshore generation can be more stringent than necessary, which can hinder the exploitation of some technologies and corresponding cost reductions. Moreover, the requirements are based on a paradigm in which the HVDC networks' offshore terminals are active, controllable grid-forming units (VSCs) and the power parks (OWPPs) are merely grid-following units. Such paradigm is not compatible with cost-reducing solutions using passive, uncontrollable devices such as DRs at the HVDC network's offshore terminals, which require the OWPPs to become the grid-forming units. However, before requirements specific for OWPPs connected via DRs can be established, more in-depth studies are necessary to determine the specific capabilities of such solutions for contributing to the secure operation of the networks they are to connect to.

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