

Novel Energisation Method for Offshore Wind Farms Connected to HVdc via Diode Rectifiers

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Abstract

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Abstract—Recently put forward as a feasible alternative for connecting OWFs to HVdc networks, diode rectifiers (DRs) have elicited growing interest from both academia and industry. Energisation of such OWFs is, however, not straightforward. The present study constitutes a proof of concept for the application of a novel energisation method to the case of an OWF connected to HVdc via DRs. The proposed method provides a robust and reliable alternative with minimal additional hardware, i.e. short additional dc cables connecting the dc bus bar of the *energising* WT to the HVdc link, and corresponding dc disconnectors at the cable terminals and at the DR dc terminals. This can be easily extended to more WTs in the OWF, increasing reliability by providing redundancy. The simulation results indicate that the proposed method is a suitable alternative for energising OWFs connected to HVdc via DRs.

Index Terms—Diode-rectifier-based HVdc transmission, energisation, grid-forming wind turbine control, offshore wind energy integration

I. INTRODUCTION

Further exploitation of Europe’s offshore wind resources entails the development of electrical infrastructure interconnecting offshore wind farms (OWFs) and onshore networks. Thus far, most OWFs are connected via HVac, and only a few export their production through HVdc [1]. The amount of HVdc-connected OWFs, however, is widely expected to increase, as the distance from shore and OWF size increase and the associated costs decrease [2], [3].

Since first presented in 1997 [4], HVdc transmission technology making use of voltage source (forced-/self-commutated) converters (VSCs), based on insulated-gate bipolar transistors, has experienced great development. Such HVdc transmission solutions still have higher losses and overall costs than the more common, mature ones employing (phase-controlled) line-commutated converters, based on thyristors (in a current source converter topology), which are largely used for bulk power transmission [3], [5]. However, VSC-based HVdc transmission (VSC-HVdc) offers advantages such as independent control of active and reactive power, smaller footprints, fast reversibility of active power flow, and the (grid-forming) capability to form ac networks, i.e. to control their ac-side voltage magnitude and frequency (which allows them to operate without the need of a strong AC grid) [4]. Because of such advantages, the use of VSC-based offshore HVdc terminals has enabled the development of HVdc-connected OWFs with

the prevailing grid-following approach to controlling wind turbines (WTs), in which WTs rely on other (grid-forming) units (e.g. VSC-based offshore HVdc terminals) forming their ac network [6].

Recently put forward as a feasible alternative for connecting OWFs to HVdc networks, (uncontrolled, line-commutated) diode rectifiers (DRs) have elicited growing interest from both academia and industry [7]–[14]. DR-based offshore HVdc terminals offer advantages such as lower costs, smaller footprints, higher efficiency and higher reliability [9], [13]. As passive devices, however, they are inherently devoid of the grid-forming capability of VSCs. As a consequence, WTs have been suggested as viable candidates to take over such duty. This entails fundamentally different WT and WF controls, changing their control principle from that of grid-following units to that of grid-forming units [7], [12].

A. Wind Farm Energisation

WTs and WFs have auxiliary systems (loads) that need electricity most of the time, even when the WTs are not generating electricity. Such loads can consist of pitch and yaw motors, oil pumps, air conditioning, dehumidifiers, navigation lights, and measurement, control, protection, communication and safety systems, among others. When WTs generate electricity, a portion of their output is used to supply the energy required by the WF auxiliary loads and offshore ac network. Auxiliary power must otherwise be supplied from local auxiliary energy sources, e.g. batteries or diesel generators or from the networks connected to the WFs [1]. This is the case, for example, when there is no aerodynamic power available from the wind, i.e. the wind speed is below the cut-in wind speed or above the cut-out wind speed of the WTs.

The use of VSC-based offshore HVdc terminals allows remote OWFs to draw the required auxiliary power from the HVdc networks connected to them. This, however, is not possible for OWFs connected to HVdc via DRs or thyristor-based LCCs, as power flows through the former only towards the shore and the latter require a strong (energised) ac network connected to them. Such OWFs thus need to be energised by other means. This is also the case for OWFs connected to HVdc networks via VSCs, when such offshore converters are not operational.

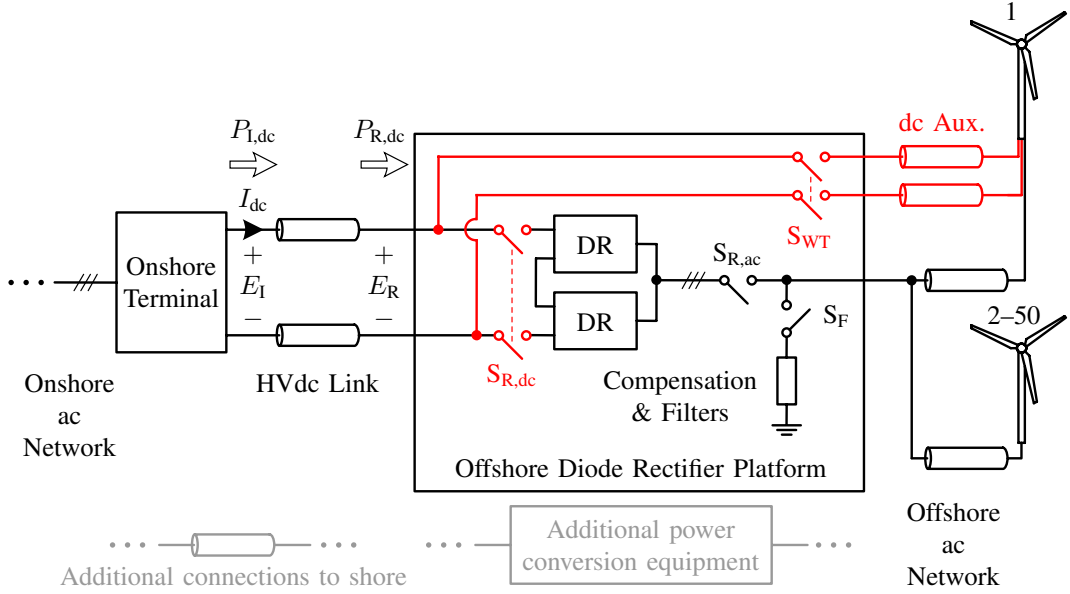


Fig. 1. Overview of the studied system; red: additional equipment introduced by the proposed energisation method, grey: alternatives in literature for providing the auxiliary power from onshore ac networks

Different solutions have been proposed for energising OWFs connected to HVdc via DRs [10], [11], [14]. Solutions for providing the auxiliary power from onshore ac networks are represented in gray in Fig. 1. The use of local auxiliary energy sources or the connection to neighbouring energised offshore ac networks, e.g. other OWFs, have been proposed in [11]. The latter has been considered in several subsequent studies [15], [16].

Additional connections between the OWFs and the onshore ac networks have also been considered. The use of an additional LVdc link has been proposed in [11], which requires additional VSC-based power conversion terminals. Moreover, an additional MVac *umbilical* cable interconnecting the onshore and offshore ac networks have been introduced in [11]–[14]. Such umbilical cables have been considered in several subsequent studies [15], [17]–[21], and have been assumed to be disconnected during normal operation, i.e. their use has been restricted to the energisation of the corresponding OWFs. Other solutions avoid the need for additional long submarine cables by introducing additional power conversion equipment offshore to effectively bypass the DRs during energisation [10], [11].

In quest of increasing reliability and lowering costs and environmental impact, a new energisation method has been proposed in [22] for OWFs connected to dc networks. The present study constitutes a proof of concept for the application of such method [22] to the case of an OWF connected to an onshore ac network through an HVdc link having a DR-based offshore terminal and a full-bridge-VSC-based onshore terminal. During energisation, the auxiliary power is provided by the onshore ac network through the dc bus bar of one of the WTs. The method only requires short additional dc cables connecting such *energising* WT dc bus bar to the HVdc link,

and corresponding dc disconnectors at the cable terminals and at the DR dc terminals, highlighted in red in Figs. 1 and 2.

The rest of the paper is organised as follows. In Section II, the investigated system is described and the main control algorithms are detailed. In Section III, the considered case is described, and corresponding simulation results are presented and discussed. Finally, concluding remarks are made in Section IV.

II. MODELLING AND CONTROL

Fig. 1 shows an overview of the studied system. The system is based on that described in [15], [18] and consists of one of three 400 MW OWFs connected to an onshore ac network by means of a 200 km long 1200 MW ± 320 kV monopolar HVdc link. Balanced/symmetric operation is assumed. The offshore HVdc terminal: one of three diode rectifier platforms (one per OWF), depicted in Fig. 1, consists of two (uncontrolled, line-commutated) diode-based 12-pulse rectifiers (DRs) connected in series, with corresponding reactive power compensation and filter bank on their ac side.

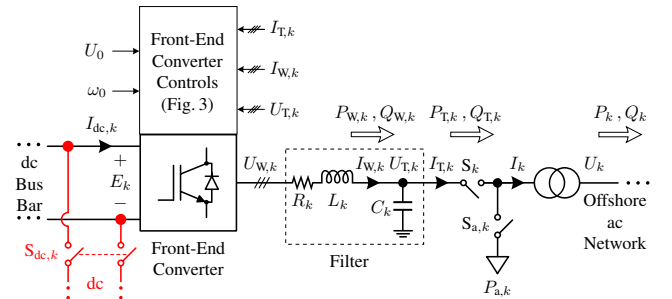
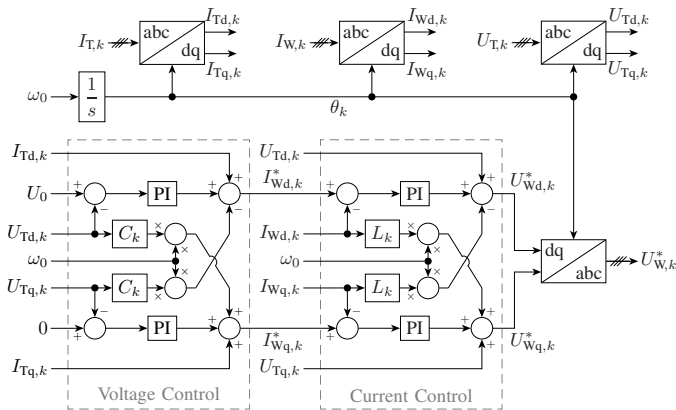


Fig. 2. k th wind turbine front-end (line-side) network; red: additional equipment introduced by the proposed energisation method

Fig. 3. k th wind turbine front-end (line-side) converter controls

The OWF has 50 type-4 (full-converter) 8 MW WTs. The WT converter nominal ac voltage is 3.3 kV. Fig. 2 illustrates the front-end (line-side) network of the k th wind turbine(s), WT $_k$. The auxiliary loads are represented within each (equivalent) WT by a constant active power load, $P_{a,k}$, corresponding to 0.2 % of the nominal power (800 kW in total for the whole WF).

WT₁ is chosen as the energising WT: its dc auxiliary supply terminal is connected to that of the DR platform by means of additional dc cables. Additional dc disconnectors are also introduced at the corresponding terminals, S_{dc,1}, S_{WT}, and at the DR dc terminals, S_{R,dc}. The additional equipment introduced by the method is shown in Figs. 1 and 2, highlighted in red. The HVdc link dynamics are assumed to dominate in the energisation path. The influence of the other elements, e.g. dc cables, effectively interconnecting the HVdc link and the WT₁ dc auxiliary supply terminals (when S_{WT} is closed) is thus neglected, i.e. $E_1 \approx E_R$. The other 49 WTs are aggregated into an equivalent 392 MW WT, WT_{2–50}, and corresponding cable equivalent π circuit using the method proposed in [23].

The WT front-end (line-side) converter (FEC) controls, shown in Fig. 3, are based on those proposed in [24] and consist of cascaded voltage and current control loops, implemented on a rotating reference frame (RRF) with angular speed given by the offshore ac network (angular) frequency set point, ω_0 . The d axis and q axis components of the filter capacitor voltage, $U_{T,k}$, are regulated by the FEC controls to follow the corresponding references, $U_{Td,k}^*$, $U_{Tq,k}^*$, respectively. The RRF is oriented on $U_{T,k}$ by setting $U_{Tq,k}^* = 0$, whereas $U_{Td,k}^* = U_0$ corresponds to the offshore ac network voltage set point.

WT rotor and back-end (generator-side) network dynamics are not considered, as they are not relevant to the case in question. Pulse-width modulation (PWM) is assumed to be done in the linear range, switching effects and any delay due to implementation of the PWM are neglected, and average value models are used to represent the WT FECs. Focus is given to dynamics not faster than the WT FEC (inner/lower) current control loops, which are designed to have a bandwidth of 200 Hz.

The full-bridge-VSC-based onshore HVdc terminal manipulates its dc terminal voltage, E_I , according to the open-loop control scheme described by (1), in which the estimated voltage drop on the HVdc link is added to the offshore terminal direct voltage set point, E_R^* . The voltage drop on the HVdc link is calculated using the onshore terminal current measurement, I_{dc} , and the estimated HVdc link resistance, \tilde{R}_{dc} .

$$E_{\text{I}} = E_{\text{R}}^* + I_{\text{dc}} \tilde{R}_{\text{dc}} \quad (1)$$

III. SIMULATION RESULTS

Results of the dynamic simulations performed in PSCAD are presented in Fig. 4. Both (equivalent) WT front-end networks and corresponding converter controls have the same parameter per-unit (pu) values. Moreover, $\omega_0 = 1$ pu for both of them. Fig. 4a depicts the voltage at the onshore and offshore ends of the HVdc link, E_I and E_R , respectively, whereas the HVdc link current, I_{dc} , is shown in Fig. 4b.

Fig. 4c portrays the rms voltage at the ac terminals of the energising and non-energising (equivalent) WTs, U_1 and U_{2-50} , respectively, at the ac terminals of the energising WT FEC, $U_{W,1}$, and at its filter capacitor, $U_{T,1}$. The output rms currents of the energising WT, I_1 , and of its FEC filter, $I_{T,1}$ are presented in Fig. 4d, together with the active and reactive components of the latter, $I_{Td,1}$ and $-I_{Tq,1}$. Fig. 4e portrays the offshore ac network frequency, f .

Fig. 4f depicts the active power flowing out of the onshore terminal, P_{Ldc} , into the offshore diode rectifier platform, P_{Rdc} , out of the energising WT, P_1 , and into the non-energising (equivalent) WT, $-P_{2-50}$. Finally, the reactive power flowing out of the energising WT FEC, $Q_{\text{W},1}$, out of the energising WT FEC filter, $Q_{\text{T},1}$, out of the energising WT, Q_1 , and into the non-energising (equivalent) WT, $-Q_{2-50}$, are shown in Fig. 4g. Table I summarises the simulation sequence of events, which are discussed in the following.

TABLE I
ENERGISATION SEQUENCE

Stage	Time [s]	Events
0	< 0	WTs, offshore ac network and HVdc link de-energised; voltage set points, E_R^* , U_0 , set to 0; offshore ac network (angular) frequency set point, ω_0 , set to 1 pu; all ac circuit breakers and dc disconnectors open
1	0	dc disconnectors S_{WT} and $S_{dc,1}$ closed: WT_1 dc bus bar effectively connected to the HVdc link, $E_1 \approx E_R$
	1 – 6.39	direct voltage set point, E_R^* , increased from 0 to the WT dc bus bar nominal voltage: onshore terminal energises the HVdc link and WT_1 dc bus bar
2	9	WT_1 main ac circuit breaker, S_1 , closed
	10 – 11	offshore ac network voltage set point, U_0 , increased from 0 to 1 pu: WT_1 energises the offshore ac network, establishing its voltage and frequency
3	15	ac circuit breakers $S_{a,1}$ and $S_{a,2-50}$ closed: auxiliary loads energised

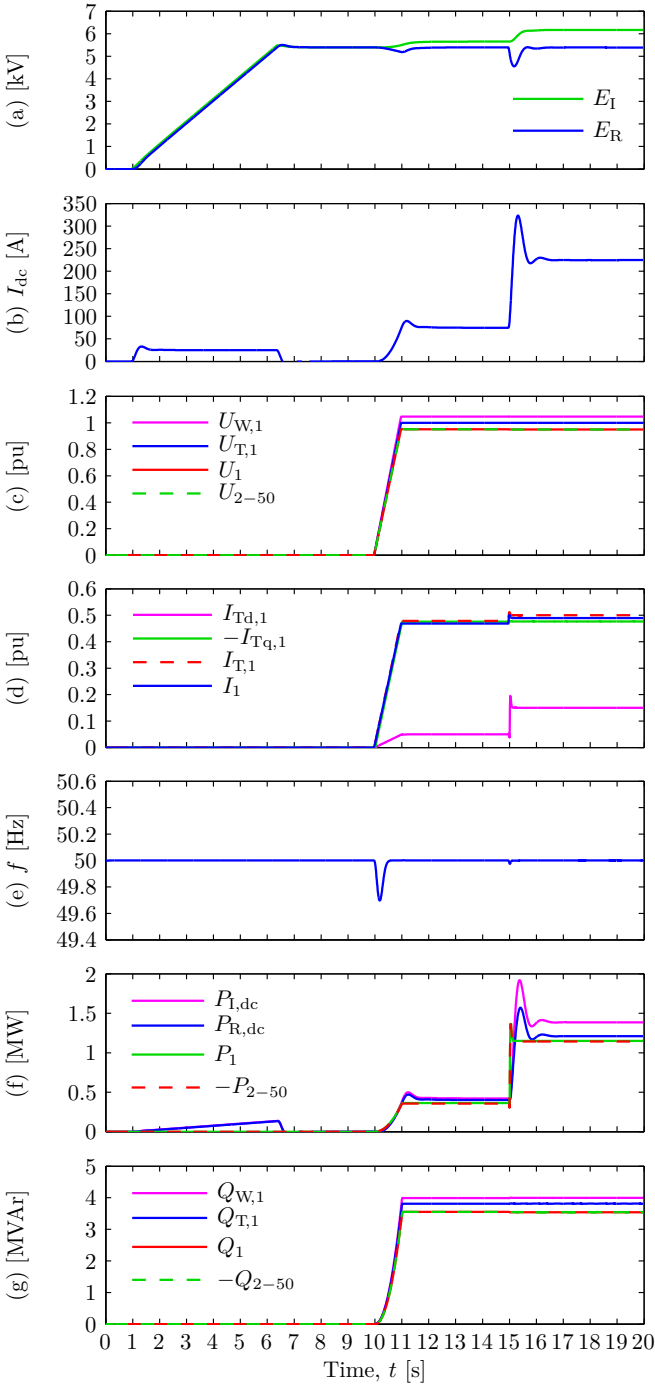


Fig. 4. Simulation results: (a) voltage at the onshore and offshore ends of the HVdc link, E_1 and E_R , respectively; (b) HVdc link current; (c) rms voltage at the ac terminals of the energising and non-energising (equivalent) WTs, U_1 and U_{2-50} , respectively, at the ac terminals of the energising WT FEC, $U_{W,1}$, and at its filter capacitor, $U_{T,1}$; (d) output rms currents of the energising WT, I_1 , and of its FEC filter, $I_{T,1}$, and active and reactive components of the latter, $I_{Td,1}$ and $-I_{Tq,1}$, respectively; (e) offshore ac network frequency; (f) active power flowing out of the onshore terminal, $P_{1,dc}$, into the offshore diode rectifier platform, $P_{R,dc}$, out of the energising WT, P_1 , and into the non-energising (equivalent) WT, $-P_{2-50}$; (g) reactive power flowing out of the energising WT FEC, $Q_{W,1}$, out of the energising WT FEC filter, $Q_{T,1}$, out of the energising WT, Q_1 , and into the non-energising (equivalent) WT, $-Q_{2-50}$.

A. Stage 0: Initial Conditions

Initially, the WTs, offshore ac network and HVdc link are de-energised, the voltage set points, E_R^* , U_0 , are set to 0, and all ac circuit breakers and dc disconnectors shown in Figs. 1 and 2 are open.

B. Stage 1: WT dc Bus Bar Energisation

At $t = 0$ s, the dc disconnectors S_{WT} and $S_{dc,1}$ are closed, effectively connecting the WT_1 dc bus bar to the HVdc link, $E_1 \approx E_R$. Between $t = 1$ s and $t = 6.39$ s, the onshore terminal energises the HVdc link and WT_1 dc bus bar as the direct voltage set point, E_R^* , is increased from 0 to the WT dc bus bar nominal voltage (approximately 5.39 kV), as shown in Fig. 4a. Such rate of increase in the direct voltage (i.e. 1 kV/s) requires a temporary charging current of up to 33.1 A, as depicted in Fig. 4b.

C. Stage 2: Offshore ac Network Energisation

WT_1 main ac circuit breaker, S_1 , is closed at $t = 9$ s, and the corresponding FEC then energises the offshore ac network, establishing its voltage and frequency, as the offshore ac network voltage set point, U_0 , is increased from 0 to 1 pu between $t = 10$ s and $t = 11$ s, as illustrated by Figs. 4c and 4e. In doing so, it draws about 422 kW from the onshore terminal, as depicted by Fig. 4f, which stands for the no-load losses of the studied system. As shown in Figs. 4a and 4b, the corresponding increase in dc current causes a temporary drop in the WT_1 dc bus bar voltage, $E_1 \approx E_R$, of about 205 V, i.e. 3.80 % of its nominal value. Moreover, it causes a voltage drop in the HVdc link of about 259 V \approx 4.58 % in steady state.

D. Stage 3: Auxiliary Load Energisation

Finally, ac circuit breakers $S_{a,1}$ and $S_{a,2-50}$ are closed at $t = 15$ s, and the auxiliary loads are energised, as shown most notably in Fig. 4f. As depicted by Figs. 4a and 4b, the corresponding increase in dc current causes a temporary drop in $E_1 \approx E_R$, of about 840 V, i.e. 15.6 % of its nominal value. Furthermore, it causes a voltage drop in the HVdc link of about 780 V \approx 12.7 % in steady state.

E. Further Comments

As illustrated by Figs. 4d, 4f and 4g, reactive (output) current, $-I_{Tq,1}$, constitutes most of the energising WT FEC filter output current, $I_{T,1}$, in steady state. The corresponding 3.81 MVar are needed mainly to energise the (equivalent) WT transformers. The active (output) current, $I_{Td,1}$, is required to cover the OWF auxiliary loads and active power losses, which constitute 10 % and 5.11 %, respectively, of the energising WT's nominal power.

The onshore terminal controller calculates the voltage drop in the HVdc link using the measured I_{dc} and estimated HVdc link resistance, \tilde{R}_{dc} , and compensates for it by increasing E_1 accordingly, maintaining E_R close to its reference value, as depicted in Figs. 4a and 4b. WT_1 FEC grid-forming controls

maintain f at 50 Hz ($\omega_0 = 1$ pu) and regulate U_{T1} to follow U_0 , as depicted by Figs. 4c and 4e.

As illustrated by Fig. 4d, less than half of the energising WT's nominal rms current is needed to energise the studied OWF with the proposed method. Moreover, it requires an HVdc link current of less than 225 A, i.e. less than 12 % of its nominal current, as shown in Fig. 4b, leaving enough HVdc link current capacity to energise the other two 400 MW OWFs in the same way. In the studied system, such current constitutes the necessary capacity of the additional dc auxiliary supply cables, introduced in the proposed energisation method to interconnect the (also introduced) dc auxiliary supply terminals of the energising WT and of the DR platform. Such capacity can in turn determine the current limit for the corresponding protections.

IV. CONCLUSIONS

The simulation results indicate that the proposed method is a suitable alternative for energising OWFs connected to HVdc via DRs. With the considered WT converter voltage level, the necessary auxiliary power can be provided to the studied OWF while leaving enough HVdc link current capacity to energise the other OWFs in the same way. The method provides a robust and reliable alternative with minimal additional hardware, i.e. short additional dc cables connecting the dc bus bar of the *energising* WT to the HVdc link, and corresponding dc disconnectors at the cable terminals and at the DR dc terminals. This can be easily extended to more WTs in the OWF, increasing reliability by providing redundancy.

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