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Black Start and Island Operation Capabilities of Wind Power Plants

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Abstract— **Current practice of wind turbines' start-up relies on the electricity available at the network that they are connected. Hence, in case of a long duration of electricity shortage, external auxiliary power supplies are needed for starting and running the wind turbines or at least for powering their internal auxiliary loads. The state of the art wind turbines with power electronics based converters can be equipped with functions such that they can start and run without the need for external auxiliary power supplies; and furthermore wind power plants composed of the state of the art wind turbines can form grid voltage and operate as a stiff voltage source, as long as wind blows. This can help fast and environmental friendly black start solutions by wind turbines for power system restoration and also use of cost effective offshore HVDC converters (e.g. diode rectifier) as well. Additionally, this would help to avoid today's necessity of auxiliary diesel generators for offshore wind power plants, which in turn would increase reliability and decrease cost. In this paper the background and existing solutions for wind turbine and wind power plant (self) start-up and island operation are presented, while the challenges are identified as future focus areas.**

Wind turbine, black start, offshore wind, auxiliary power supply

I. Introduction

Current practice of power system restoration mainly relies on conventional power plants, which can provide black start in case of a black out. The black start capability of conventional power plants, which requires auxiliary units to generate the initial voltage, is characterized by long start-up times due to their slow (for instance thermal) dynamics, and cause extended use of fossil fuels in order to be ready for service. However, wind power plants (WPP) composed of state of the art wind turbines (WT), once equipped with black start capability can provide fast and environmental friendly solutions for power system restoration. The "black start" and "island operation" requirements have been included as optional requirements for (both AC and HVDC connected) wind power plants in the ENTSO-E network codes (RfG and HVDC), where the relevant TSO is allowed to request these functions [1], [2]. Additionally and more importantly, the black start capability can help offshore (AC and HVDC connected) WPPs to be able to start and sustain themselves both for short and long periods in case the offshore transmission line is not operating or in case the offshore HVDC terminal is a passive unit (e.g. diode rectifier). This would also help to avoid today's necessity of auxiliary diesel generators from offshore wind power plants, which in turn would increase reliability and decrease cost.

In this paper, black start and island operation, where the WPP can be supplying a grid with loads or solely the own consumption of idling WTs, will be investigated for type 4, full scale converter, WTs working under a wind power plant controller.

II. Background

An onshore or especially offshore WT might be left out of electricity for very long durations; for example due to an outage at its transmission (AC or HVDC) line connecting to the grid, or due to a local or regional black out in the grid. In general WTs are equipped with internal power supply, which also includes small energy storage, like an uninterruptible power supply (UPS), which can help the WT to supply critical components such as internal lights in the tower and nacelle, aviation obstruction lights, controllers and switchgears for very short durations (e.g. less than an hour). However, in case the WT is out of grid electricity for considerably long durations due to abovementioned reasons, risks arise for the health of the WT. Some of the main concerns are; damage by the moisture (due to low temperatures and rain) in the nacelle and especially in the electronics like converters, icing up of some measurement equipment like anemometer and the blades, vibrations at the natural frequency of the tower due to strong wind and unfavorable orientation in the yaw axis, loss of hydraulic pressure, thus control, due to any slow leakage, deformation in the bearings due to fixed positioning for long durations, not performing lubrication of bearings for long durations. All of these concerns result use of external (/mobile) auxiliary power supplies in order to run the WTs with sufficiently frequent intervals such that all the components including nacelle and rotor are activated or at least auxiliary loads of the WT (e.g. heaters, dryers/dehumidifiers, ventilation, lubrication) are energized periodically. However, as will be explained in this paper, use of the external auxiliary power supplies can be minimized or

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totally avoided since the WTs can produce power to sustain themselves as long as there is wind, which is the case especially for offshore sites.

In an offshore WPP an auxiliary power supply, usually a diesel generator, is located in the offshore (AC or HVDC) substation, which can provide power for the auxiliary components of the substation (e.g. controls, switchgear, climate units), start-up of the substation and also for the WTs for the cases explained above. Similar to the WTs, in case of loss of main grid, the offshore substation might need to be activated (e.g. the climate conditioners) with sufficient intervals, for example to avoid salt accumulation inside. A diesel generator and its fuel consumption in an offshore substation would have negligible cost; however, its existence at all increases the insurance cost considerably. Hence, use of the WTs instead of diesel generator in the substation for the auxiliary supply of the offshore substation would be favored to decrease the cost of offshore substation. As will be mentioned below, this would require harmonized operation of the WTs such that the WPP operates as a voltage source forming the offshore AC grid, on the contrary to their traditional operation as synchronized to the available grid voltage.

In addition to the abovementioned use cases, the WPPs can take over the role of conventional black start units in the power systems once they can operate as stiff voltage source, which can respond to active and reactive power demand with sufficient bandwidth. Owing to the full converter based structure and fast controllers of the state of the art WTs and WPPs, the response of a WPP can be much faster than the conventional power plants, which require long start-up times and perform slow response. Possibly considering the high share of wind power in Europe today, the ENTSO-E has already set requirements as: "*power-generating facility owners shall, at the request of the relevant TSO, provide a quotation for providing black start capability. The relevant TSO may make such a request if it considers system security to be at risk due to a lack of black start capability in its control area*". Hence, there is an interest by the TSOs to have black start capability from the WPPs, as already being considered from HVDC interconnectors today [3]-[5].

Another equally important use of the self-start capability of the WTs is with the passive offshore HVDC converters, such as the diode rectifier or LCC HVDC, which are considered as candidates to decrease the cost of HVDC [6], [7]. Similarly, the black start and islanding capabilities of the WTs/WPPs can be utilized in small (e.g. microgrid) or large island power systems without any conventional generators (i.e. 100% power electronics based power systems). In these cases, the WPP can switch into island operation "on the fly" right after an island is formed due to disconnection from the main grid. It should be noted that the use of the WTs' and WPPs' operation capability as voltage source is not considered here for classical microgrids, where the grid voltage is formed by conventional generators (e.g. diesel) and the WTs would be performing conventional current control operation with droop constants for contribution to microgrid voltage and frequency stability [22]-[24].

III. OBJECTIVES

In this section, the technical objectives to equip the WTs with black start and island operation capabilities are presented. The objectives are classified into three groups as will be explained via Fig. 1 and Fig. 2 below. As mentioned in the previous sections, in relation to the self-start capability of WTs, the first objective is structuring the WTs with internal power supplies, large enough to perform the start-up without any external supply, such that the wind turbine controller and converters are energized, wind speed and direction is measured, yaw mechanism is powered to orient the WT towards wind and pitch system is activated to produce power. Afterwards, the second objective is to be able to continue producing power, whereas the only consumption would be the WT's own as the auxiliary loads (heaters, pumps), which can be around 1 to 5 % of the rated power [8], [11]. In this case the WT has to manage production of minimum and fluctuating power due to fluctuations in the own load, while the wind might be varying as well. Additionally, the WT should be able to respond to step changes in the load (up to 10%), for example when the offshore substation (its auxiliary) is also fed by the WT (or WPP). The third and most important objective is to operate several (more than one and up to few hundreds) of WTs in an harmony to start up as described above and operate as island providing power only to itself and maybe to the substation. In this case, synchronization of individual WTs and sharing the load between the WTs are two of the sub-objectives. The second and third objectives can be extended towards using the WPP for black start of the power system, where the active power controls and sharing (e.g. droop on each WT) become important.

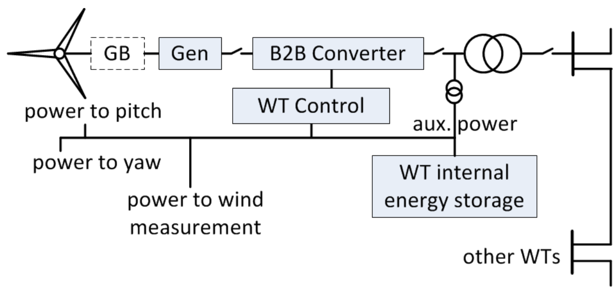

Figure 1. A generic wind turbine structure

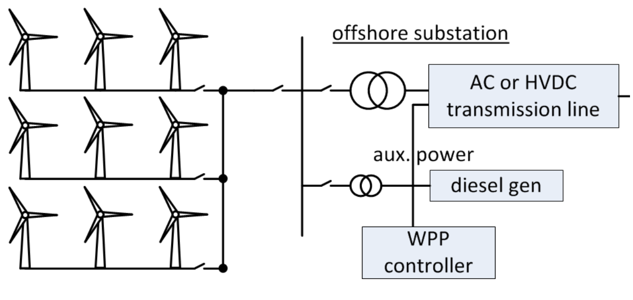

Figure 2. A generic offshore WPP substation

IV. EXISTING SOLUTIONS

In this section existing solutions, related inventions by the industry and research studies, are presented.

In [8], a WPP similar to the one shown in Fig. 2 is proposed to be started via the local power source, e.g. a diesel generator, which can be disconnected afterwards. The method is based on starting only one or a group of WTs and then more or all the WTs one by one or group by group, which is coordinated by a WPP controller based on communication (between the WPP controller and WTs). In addition to operate as an island (disconnected from the external grid and diesel generator), black start provision to the external grid is also proposed. However, any details about parallel operation of WTs during island mode are not given in [8].

In [9], which is a thorough description of a single WT's self-start, details about the WT structure and process for initial internal energization are provided and start-up of the WPP is proposed to be sequentially (similar to [8]) using the first WT. However, any details about parallel operation of WTs during island mode are not given in [9] either.

In [10], a small diesel generator, which will be used for start-up of the WT, is proposed to be located inside one or few of the WTs in the WPP, which will be sequentially started using the WT(s) with a diesel generator inside such that those WT(s) will supply start-up power for the rest of the WTs. Similar to [8] and [9], island operation (as a "stiff voltage source") without any diesel generator or external grid is proposed; however not giving details about WTs' parallel and synchronous operation, whereas the WPP controller in [10] is stated to coordinate and provide voltage phase angle and/or magnitude setpoints for the WTs, without elaborating any details about possibly needed phase angle differences between the WTs (The WPP controller is stated to be able to start based on its own local UPS). Connection to the external grid is mentioned, once the grid is restored, as a smooth transition or stopping and restarting the whole WPP.

In [11], coordinated start-up of a WPP is proposed, based on self-start of single WT(s) as described in [9], relying on the internal energy storage of the WT without any external generator for imitating the grid or for supplying power to the WT.

In [12], start-up of a single wind turbine with an external power supply, similar to [9], and operation as an island without the external supply (i.e. self-sustaining mode) are presented, whereas the start-up is automatized for periodic intervals also taking the wind availability into account, such that the intervals are shortened to avoid long periods without wind.

In [13], a local energy storage in the WT is proposed to be used specifically for pitch activity in order to enter into self-sustaining mode. The energy storage is stated to be electrical battery accompanied by a mechanical spring module or a pressure vessel. It is mentioned that the WT can enter into self-sustaining mode immediately (e.g. 5 seconds) after a grid loss or after a period of no wind period. However, the necessity of power for yaw system in order to align the WT towards wind direction is not mentioned.

In [14], an additional solution based on having a parallel second output directly from the WT generator terminals and then storing this energy for further start-up is proposed, whereas the start-up for the WPP is similar as described in [11].

In [15], a method for operating the WT converters as voltage source is presented such that the WT adjusts its own phase angle based on difference between a fictitious grid phase angle and the desired phase angle. It is stated that preferably only one WT fixes the phase angle and voltage in a WPP and the other WTs synchronizes to that WT. However, sharing the load between the master WT that is creating the voltage and the follower WTs is not explained. The use of this method as black start for restoring a power system is mentioned as well.

In [16], a method to operate the HVDC connected offshore WTs as grid forming units is presented, where the offshore voltage and frequency are settled via droop control at each WT and the generated voltage references are produced by the WT front-end converters. The WTs still perform dq current control; however, details of the synchronization between the parallel operating WTs and initialization are not provided in [16]. In [17], the method in [16] is utilized for island operation of HVDC connected offshore WTs, which is also utilized further for onshore black start. It is assumed that an external auxiliary generator provides power for the WPP. The WT mechanical loads have been analyzed during the island and black start operation. A similar approach for offshore grid forming has been employed for diode rectifier type HVDC connection in [18].

In [19], a method based on the GPS time signal to synchronize the WTs in diode rectifier HVDC connection case is proposed. This control method can possibly be modified and utilized for synchronization of parallel WTs while behaving as a voltage source in self-sustaining mode of a WPP, which is not in the scope of [19] though.

In [20], frequency control methods for a WPP are evaluated when the WPP is employed for black start of a regional grid, while a diesel generator is utilized both for start-up and afterwards.

V. Identified Challenges

In accordance with the technical objectives in section III, technical challenges arise as listed here. In terms of active power control loop of the WT, one of the main challenges is operating the WT at very low generation level corresponding to its own consumption. This would result in excessive use of pitch mechanism in order to reduce the generation down to levels varying between 1% and 5% and have mechanical impact on the drivetrain (e.g. oscillations due to backlash in the gearbox, if exists) and tower. Alternatively, electrical components like larger chopper circuitries, energy storage units in the WT can be utilized, hence additional component cost as a tradeoff to the abovementioned mechanical impact.

Another interesting challenge is the control of WT converter, while operating as a voltage source, in case of step active and reactive power changes (up/down) due to connection/disconnection of auxiliary loads in the WT or WPP substation. In addition to converter control, interaction with the rotor, pitch and generator side of the WT is another impact of these step changes.

One of the main challenges during self-sustaining WPP island operation is synchronized parallel operation of the WTs. It should be noted that the general preference would be to keep the WT and WPP structure as it is today, i.e. running the WPP via relying on the voltage generated from only one WT and synchronizing the others to this WT would be questioned in terms of reliability. Similarly, dependence on advanced and fast communication schemes between WPP controller and WTs and GPS signals should be analyzed in terms of reliability as well.

In order to overcome these challenges, solutions using only the WTs and WPP controller to form the offshore grid voltage, while considering the impact on the generator side, pitch control dynamics and own consumption, are needed.

In relation to the use of WPPs as black start units would require preparation of the market for this purpose, e.g. consideration of wind forecast in the restoration process. As an initial stage, WPPs can be given the duty of statcom to support voltage and reactive power balance during restoration process in a power system.

VI. Conclusion

In this paper, review of literature and industrial inventions on the self-start, self-sustaining, island operation and black start capabilities of state of the art wind turbines, especially in offshore wind power plants, has been performed. It is shown that the industry has prepared solutions for these capabilities and still performing research on “Black startable offshore wind turbines" [21]. The three objectives are identified as; first starting and running the wind turbines with certain intervals for the sake of wind turbine health without relying on external power supplies, secondly utilizing the wind turbines’ island operation for wind power plant’s and HVDC offshore stations’ auxiliary power needs instead of using diesel generators for the sake of wind power plant development costs, and thirdly using the modern and fast wind turbines as black start units for restoration purpose for the sake of future power system with high share of renewables.

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