Symposium Aalborg, Denmark
4th-7th June 2019

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Techno-economic Feasibility of a STATCOM with Battery Energy Storage for the Offshore Wind Power Plants

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SUMMARY

An integrated power converter and battery energy storage system (BESS) has been proposed to meet multi-functional requirements for active and reactive power control and harmonic filtering in large wind power plants (WPPs).

In this paper, first a high-voltage, high MVA static synchronous compensator (STATCOM) based on modular multilevel converters (MMCs) with an integrated BESS system is analyzed from the techno-economic feasibility point of view. Economic benefits of the additional functionalities are quantified based on available market data (and trends) for ancillary services or the least cost option for the mandatory compliance with the relevant Grid Code. Afterwards, its efficacy in achieving different ancillary services to the WPP and to the grid is qualitatively discussed. Their significance to the operation and control of offshore WPPs and their relevance for the market and the grid are evaluated.

KEYWORDS

Ancillary services, Battery energy storage system (BESS), Black start, Frequency regulation, Harmonic compliance, STATCOM, Voltage regulation, Wind power plant (WPP)

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1. INTRODUCTION

Wind power plants (WPPs) are widely used for producing renewable and sustainable energy. There are certain inherent challenges in the large-scale integration and operation of WPPs in the power systems. There is a growing inclination towards large offshore WPPs, spread over a large area due to the relatively small wind turbine unit size, which is less than 10 MW at present. Typically, the WTs are connected by medium voltage (MV) cables and the collected power is exported to the onshore grid using high voltage (HV) alternating current (AC) cables. Thus, there are a lot of MV and HV cables in between the WTs and the onshore grid, which are problematic for the reactive power management, and hence, voltage regulation as well as from the point of view of harmonic compliance and damping of resonances. Moreover, the wind power output is dependent upon the instantaneous wind conditions, and it is normal to operate the plant at the maximum available power for the prevalent wind conditions (i.e. maximum power point tracking, MPPT). These factors lead to a variable power generation from WPPs.

Power generation and consumption must be balanced in a power system to achieve a stable system frequency. Any excess power must be stored or dissipated. Battery energy storage system (BESS) is one of the mature energy storage solutions, nowadays, that can provide fast and efficient control of power. Moreover, the variable generation affects the voltage regulation at the point of connection (POC) and there is a need for proper reactive power control. A static synchronous compensator (STATCOM) can be used to improve the voltage regulation. In addition, well-designed passive and/or active harmonic filters are usually needed to limit the incremental harmonic voltage distortion due to the grid connection of a WPP.

A modular multilevel converter (MMC) with a high control bandwidth can provide both reactive power control and harmonic filtering [1]. A BESS can be integrated with the MMC [2],[3] to compensate for any imbalance between electric power generation and load. In view of the increasing size of offshore WPPs and their penetration level in the power systems, which could eventually replace the conventional fossil-fuel based power generation systems, an effective BESS embedded in a large STATCOM [4] can be a convenient means to enable offshore WPPs to operate like modern power plants with controllable generation and reactive power services exceeding what conventional power plants can offer to the grid.

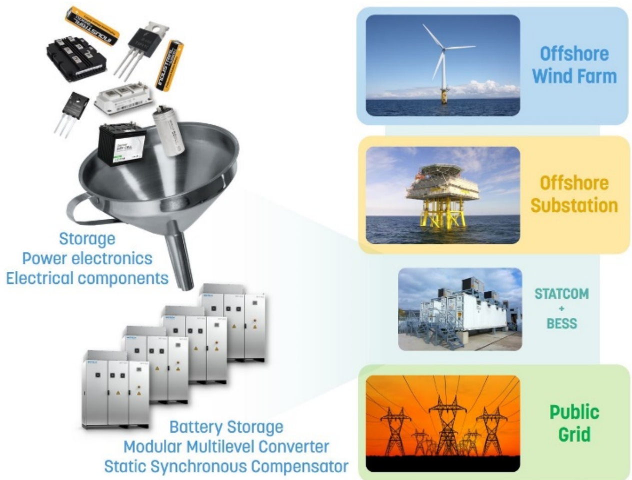

Figure 1 Simplified representation of a WPP setup with a BESS unit and MMC STATCOM onshore.

There is a big potential for the wide application of power electronic-based embedded converter systems, viz. a STATCOM, a BESS, an active power filter (APF), etc. Thus, the revenue streams can be maximized, thereby, reducing the cost of electricity (CoE) by employing the active and reactive power control and harmonic filtering capabilities of an integrated power electronic converter system with BESS. The MMC is a relatively new converter topology suitable for HV and high-power applications. It overcomes many of the limitations of the 2-level or 3-level converters, which have been quite popular in low voltage (LV) and MV applications. They are usually targeted to accomplish one predefined functionality (e.g. dynamic voltage control) due to their need for higher switching frequency which results in high switching losses. Integration of MMC STATCOMs and BESSs directly at the transmission level in WPPs can fully utilize the hardware potential and further optimize the WPP design as well as operation (see Figure 1).

2. ANCILLARY SERVICES FOR GRID OR WPP ITSELF

An optimized integration of BESS in an MMC STATCOM along with the active power filter capability can provide extensive functionalities, which can contribute to the following ancillary services:

- Black start capability
  - Soft-charging of cables / inductive components
  - WPP auxiliary supply
  - Island frequency control
  - Synchronization
  - Synthetic inertia
  - Black start service
- Short-circuit infeed
- Grid frequency response
  - Inertial response
  - Primary/secondary frequency response
- Intra-day balancing and arbitrage services
- Active filtering
- Voltage regulation

A short summary of the ancillary services investigated for the grid or internal application in the WPP is presented in Table 1. It is further elaborated in the subsequent sections.

Table 1 List of investigated services and their integration with the WPP electrical infrastructure.

Service / Capability	Battery size	Capability
SOFT-CHARGING	2x5 MWh	Energize the WPP cable network with voltage ramp-up to provide plant black start and auxiliary supply when the grid is shut-down.
SHORT-CIRCUIT INFEED	2x5 MWh	Use energy stored in the BESS to create additional fault current within the islanded WPP network.
WIND POWER PLANT AUXILIARY SUPPLY	2x25 MWh	Provide auxiliary power to WPP in the event of a grid outage or commissioning and avoid deploying auxiliary diesel generator offshore.
BLACK START	2x150 MWh	WPP capability to operate in an island mode, be able to charge local transmission system and accept 50 MW block loads.
ISLAND FREQUENCY RESPONSE	2x25 MWh	Provide and balance frequency control as well as load / demand during block loading in case of island and black start operation.
SYNTHETIC INERTIA	2x5 MWh	Use energy stored energy in the BESS to create synthetic inertia within the WPP islanded network and during the black start.
GRID FREQUENCY RESPONSE	2x25 MWh	High- and low-frequency response capability to support the grid during normal operation without need to partly deload wind turbines.
INTRA-DAY BALANCING	2x150 MWh	The BESS can provide additional capacity to compensate / balance wind forecast error as well as the "duck curve" caused by solar generation.
ACTIVE FILTERING	2x5 MWh	Filter, extract and store the energy associated with system harmonics and improve the quality of power by active harmonic filtering.

The proposed system comprises of two redundant combined STATCOM and BESS units, each implementing a converter capability for example 50 MW and ±150 MVAr output (~160 MVA). Three sizes of battery storage viz. 2x5 MWh, 2x25 MWh and 2x150 MWh, depending on service requirements as shown in Table 1, can be considered. The BESS should be located at the onshore substation of the

WPP adjacent to the transmission connection to ease maintenance and lower installation costs. Several services are prioritized and selected for further investigation, however, the relative effort for each of the selected services will be defined later.

2.1. Black start capability

2.1.1. Soft-charging

Since an offshore WPP is equipped with long HVAC power cables, there is a large demand for charging current from an external power source or BESS during the re-energization of the offshore grid after a shutdown. The energization is further complicated by the presence of low-frequency resonances and low damping. It is challenging to maintain the electrical characteristics within the boundaries specified in Grid Codes. Energization also entails noticeable inrush currents when the large transformers are energized [5] . Using soft-charging, the inrush current demands can be reduced. The integrated BESS and STATCOM system should be able to energize, maintain nominal voltage and frequency, and build up the islanded network by gradual restoration.

2.1.2. WPP auxiliary supply

There is a potential lack of power supply within the offshore electrical infrastructure in case of a prolonged grid outage and during the wind power plant commissioning period. Lack of power for the offshore auxiliary loads can affect the system performance (e.g. longer start-up time), wear on components due to wind misalignment or even malfunction (e.g. blades fatigue development as there is no yawing capability, failure of subsystems due to increased levels of moisture and salinity, etc.).

Emergency power supply can be provided using power electronic equipment together with battery storage units. A grid forming converter unit, which can be the integrated STATCOM and BESS at the onshore substation, can provide voltage and frequency references to form an autonomous asynchronous system to deliver active power to offshore auxiliary loads.

2.1.3. Island frequency response

During the islanded mode of offshore WPP operation, the voltage and frequency reference in the WPP is provided by the grid forming unit. The grid forming unit needs to be supported by WTs, providing power to the islanded network, to optimize the battery size which is used to form the grid and response swiftly to sudden frequency variations. This feature is needed during the black start process to assure frequency control coordination during island mode and block loading. Continuous frequency control coordination is needed in multi-converter systems.

2.1.4. Synthetic inertia

The synthetic inertia function is expected to be provided as a standard feature in WPPs with black start capability. Moreover, this function can be also continuously used during WPP normal operation to support a low inertia grid.

During islanded operation of offshore WPPs and BESS, the system stability is vulnerable to connection of big blocks of load, which is the case during the black start and system restoration. Hence, synthetic inertia is necessary to (i) maintain the synchronous frequency within the specified limits, (ii) reduce rate of change of frequency, and (iii) minimize frequency nadir during island operation and block loading.

Furthermore, WTs connected within the islanded WPP can support the integrated battery unit to further reduce sudden frequency variations.

2.1.5. Black start service

Renewable asynchronous generation is gradually replacing fossil-fuel based synchronous generation. Therefore, system operators are asking for black-start capability from renewable generation sources like offshore WPPs to provide this essential service [6].

In a black start situation after a total shutdown, the offshore WPP grid will have to be re-energized without external grid supplies. The wind turbines will need to be able to reconnect to the collector grid and the frequency within the isolated cable network must be controlled. The WPP island so formed will then need to energize the local grid system with the help of the BESS and accept block loads of demand up to 50MW in size whilst ensuring the frequency does not violate emergency Grid Code limits (which in UK are between 47 Hz and 52 Hz), and then be able to maintain a stable frequency.

2.2. Short-circuit infeed

In the event of short-circuit faults in the offshore grid while the offshore WPP is operating in the islanded mode and the offshore grid is formed by the BESS and STATCOM, the short circuit current has to be provided by the STATCOM. However, the maximum current is limited by the maximum current limit of the power converters, which is rarely over-dimensioned. This creates challenges with respect to protecting the islanded system against faults. Short-circuit infeed by power converters equipped with a battery can facilitate the protection of the system by detecting and discriminating the fault and allow to use the same protection settings for the asynchronous islanded network as well as offshore WPP connected to the main synchronous system.

2.3. Grid frequency response

2.3.1. Inertial response

The capability of traditional frequency response from wind power, without prior de-loading, is limited to reduction in output power. Wind turbine technology allows to provide inertial response where the kinetic energy from the moving parts is used as a short burst of additional power generation. Inertial response can alleviate the nadir and rate of change of frequency (ROCOF), but at a cost of subsequent generation reduction from the WPP. A combination of BESS and wind turbine inertial response can provide a fast burst of additional energy from wind power while utilizing battery capacity to counteract the recovery period in a controlled manner. The combined service of inertial response and battery must be synchronized to efficiently counteract the negative aspects of the service. The function can (i) lessen frequency nadir at critical events, (ii) lessen RoCoF, and (iii) enable wind power to partake in upwards frequency response.

The value of inertia response is already clear to some transmission system operators (TSOs) and combining it with a BESS could enhance the service value in low inertia systems where loss of generation can be detrimental to the system stability, and the secondary dip is dangerous for system recovery.

2.3.2. Primary/secondary frequency response

General frequency response (primary/secondary) is valued highly in European markets and is already a requirement in many Grid Codes. With active power control from the BESS, the provisioned frequency response services can be increased in terms of speed and magnitude, and without incurring any additional capital expenditures (CAPEX). Thus, BESS creates value for both the TSO and the WPP operator. BESS should support the offshore WPP to provide the primary frequency response as stipulated by the TSO. In addition, the BESS may enable the offshore WPP to contribute to the secondary frequency response and short time operating reserves (STOR).

2.4. Intra-day balancing and arbitrage services

To provide intra-day balancing and arbitrage services a WPP requires the capability to store energy and discharge energy in response to real-time energy prices caused by the discrepancy between generation and demand. The control functionality needs to factor in round-trip efficiency and the operational limits of the battery.

2.5. Active filtering

WPPs use power electronic converters in WTs, whose wide timescale control dynamics may interact with other electrical components, e.g. power cables, transformers, and STATCOMs, etc., leading to abnormal harmonics or resonances across a wide frequency range [7]. The highly non-linear dynamics of the power and grid-synchronization control may bring in sideband harmonics around the grid fundamental frequency, which may trigger the low-frequency resonances of the power cable, while fast current control of WTs tend to interact with each other, resulting in harmonic instability [8] unless carefully managed in the design.

A high harmonic distortion within the WPP can increase the component stress and lead to malfunction. The potential Grid Code non-compliance can further lead to power curtailment or even disconnection. Moreover, unstable converters (e.g. WTs, STATCOMs) can trip and lead to loss of production, Grid Code non-compliance and a reduction of power transmission capability.

There is, thus, a growing demand for converters with active filtering functionality for tackling abnormal harmonics and instability in WPPs. However, besides the characteristic harmonics caused by the inherent nonlinear operations of WTs, e.g. dead-time, the abnormal harmonics and resonances that may result from control interactions of WTs and other WPP electrical infrastructure have to be considered in the active filtering function. Consequently, both the harmonic detection and the analysis of harmonic interactions in WPPs become essential to realize the active filtering function [7]. On the other hand, active filtering can be deactivated in case of abnormal conditions where the system safety and resilience have higher priority than the power quality.

2.6. Voltage regulation

Grid Code regulations require that the offshore WPP does not create any undue voltage deviation. Voltage rise due to grid connection of an offshore WPP should be limited to within 3% as stipulated in the Danish Grid Code [9]. In addition to the maximum allowed limit values for short-term and long-term flicker levels, the Grid Code also defines the operating capability for the reactive power injection as functions of the generated active power and terminal voltage level. During normal operation, the continuously varying power generation of the offshore WPP affects the voltage regulation at the point of connection (POC). Therefore, reactive power control using the STATCOM may be necessary depending on the grid strength and the location of the point of common coupling (PCC). For example, in the UK, the PCC is at the HV bus onshore, and hence a STATCOM is usually necessary to provide the required dynamic reactive power regulation.

3. HARDWARE CONSIDERATION FOR INTEGRATED BESS

3.1. MMC STATCOM with BESS

The proposed solution of integrating BESS into the offshore WPP electrical infrastructure is based upon a HV STATCOM with a high MVA rating for the connection at the transmission voltage level. Several converter topologies have been introduced to the market. The purpose of this analysis is also to propose which topology would be the most relevant for the integrated BESS solution.

Cascaded H-bridge topologies were presented in the 1990's [10]-[12]. These used full-bridge cells (referred to here as bridge cells) connected in star or delta configuration. The modular multilevel converter (MMC) using half-bridge cells (referred to here as chopper cells) was introduced for HVDC applications by Marquardt in 2003 [13]. The different MMC topologies for STATCOMs can be classified as (i) Double star chopper cell (DSCC), (ii) Double star bridge cell (DSBC),(iii) Single star bridge cell (SSBC) and (iv) Single delta bridge cell (SDBC) [14]. According to Cupertino et. al., though SDBC requires less energy storage in comparison to the DSCC topology, the latter offers superior performance during asymmetric grid conditions when negative sequence current has to be injected. On the other hand, the DSBC topology requires many components, while topologically it is equivalent to two units of SSBC in parallel. The SSBC and SDBC topologies and their controllability is presented in [15]. For the balancing of the capacitors in the bridge cells, zero sequence current is used in the case of delta connection and zeros sequence voltage is used in the case of star connection.

Nowadays, dynamic reactive power compensation and voltage control are the primary functions of the STATCOM. Moreover, there is an interest in integrating basic STATCOM functionality with active harmonic filtering. Reference [16] describes the reduction of the 3rd and 7th harmonic voltage distortion by the active filtering units from the 100 MVAr STATCOM units installed in the Hornsea Project One offshore WPP.

Commercial MMC based STATCOMs are available under different names like chain-link converters, cascaded H-bridge, SVC-Light, SVC-Plus, etc.

3.2. Battery energy storage system (BESS)

A BESS can be installed as a large centralized unit onshore along with the converter for STATCOM or as several distributed units along with the existing converters in the WT units. The centralized storage unit can directly contribute to the onshore grid services as it can be installed at the POC to the onshore grid. Furthermore, the onshore installation is favorable for maintenance. On the other hand, the distributed offshore units have inherent redundancy and hence increased redundancy, and they are closer to the WPP auxiliary loads. However, offshore installation is fraught with challenges in maintenance, additional increase in weight and volume along with the harsh offshore environment. With WTs capable of compensating the reactive power generation of the cable system independently, providing large scale services such as reactive power balancing at the POC at a substantial electrical distance impacts HV cable design and costs to allow for the additional current. Hence, the centralized battery solution appears to be the most attractive choice for offshore WPP electrical infrastructure optimization.

The integration of BESS with a STATCOM was first proposed in [17] stating that the BESS improves the power oscillation damping capability of the STATCOM. Spahic et al. [4] describes the benefits of energy storage in MMC STATCOM in providing the fast frequency and voltage support to the transmission grid. Vasiladiotis [18] describes the split cell implementation of the battery units in the sub-modules of the SSBC and SDBC as well as DSCC based converter units. A tuned filer is used between the bridge cell and the battery unit to block the second harmonic current. Purakin et. al. claim that the low frequency harmonic content affect the life-cycle of the battery and that it should be filtered [19]. A hybrid energy storage system comprising of super-capacitors in some cells and battery units in other cells is proposed in [20].

4. MARKET ASPECTS

The need for STATCOM and filtering of harmonics is usually guided by the Grid Code requirements regarding voltage regulation and harmonic limits. Energy storage in offshore WPP is a relatively new concept and is being explored in some countries to ensure that the services offered by the conventional power plants are also available from WPPs as well. The BESS specification in an offshore WPP is based upon its participation in the energy intensive services like primary and secondary frequency regulation, and participation in reserves and arbitrage markets.

In the last five years the average cost of battery units has decreased by 60 % from 500 USD/kWh to 200 USD/kWh [21]. At the same time, several revenue streams like fast frequency response (FFR), triad services, short time operating reserve (STOR) and black start services are available in markets like in the UK [21]. In December 2017, the 100 MW, 129 MWh battery installation in the Hornsdale WPP in Australia proved to be a savior when it responded within a few milliseconds to stabilize the frequency of the electricity grid after a 560 MW coal-fired unit tripped in Victoria [22]. Since then, a number of BESS units have been installed to support the growth of renewable energy in the weak grid in Southern Australia.

Since actual market data is not available, and many of the services do not exist at the moment, a qualitative analysis has been performed and summarized in Table 2. The decision matrix method, i.e. the Pugh method, has been selected to rank the investigated services based on selected criteria. It indicates that the black-start service would have the top priority for offshore WPPs; followed by grid frequency response and synthetic inertia. Though soft-charging and WPP auxiliary supply are at the bottom ranks, they are essential to the black start of WPP to provide a high-quality service to the grid. The low ranking is applicable only when these are considered separately.

Table 2 The application of qualitative Pugh method to select the most attractive services.

Criteria	Description	Soft-charging	Short-circuit infeed	WPP auxiliary supply	Black start	Island frequency response	Synthetic inertia	Grid frequency response	Intra-day balancing	Active filtering
Market Availability	How many countries are considering the service or where it is already available.	−	0	−	+	−	+	+	+	0
Market Maturity	If the services are already defined or only considered.	−	0	−	+	−	0	+	+	0
Cost Impact	What is the capital and operational expenditure to provide the service.	+	0	0	−	0	0	−	−	+
Service Utilization	How often the service is needed.	−	−	0	−	0	0	+	+	+
Service Impact	How the service is critical w.r.t. to the system stability and its social impact.	−	+	0	++	0	0	+	−	−
Mandatory or Optional	Is the service required or optional to enable additional revenue stream.	+	0	0	+	0	0	0	0	+
Supporting or Stand-alone	Is the service supporting other or can be provided to the markets as a stand-alone.	−	0	−	+	0	+	+	+	+
Service Values	What is expected service value.	−	0	0	++	0	+	+	+	0
Critical for Other Services	Is this service needed to functionally support other.	+	+	+	−	+	−	−	−	−
	TOTALS	-3	1	-2	5	-1	2	4	2	2
	RANK	9	6	8	1	7	3	2	5	4

Symbols	Relationship	Value
++	Much better than baseline	2
+	Better than baseline	1
0	Same as baseline	0
−	Worse than baseline	-1

5. SUMMARY

The paper first presents the key services required for the operation of an offshore WPP as a modern power generation unit in renewable-power-based systems. While the voltage regulation can be provided by STATCOM units, active filtering will need multilevel converters so as to attain the high control bandwidth. Even though these services do not generate a direct revenue, they are critical from electrical infrastructure optimization and grid code compliance point of view to assure electromagnetic compatibility, system stability, avoid undue power curtailment and assure CoE reduction.

Other services like black start, frequency and reserve services are energy intensive and hence they require energy storage system. BESS technology is available for grid level applications. Technically it is possible to be integrated with MMC; and that creates the possibility of integrating the BESS and the STATCOM in a single converter system. While black start service appears to be the most promising from the offshore WPP perspective, other services might also be included depending upon the grid operating conditions, grid strength, penetration of renewable energy and prevalent market opportunities as well as system requirements.

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