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Challenges and Solutions in Integrating Black Start into Offshore Wind Farms

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Abstract—**Power systems are currently experiencing a transition towards decarbonisation of electrical generation through large-scale deployment of renewable energy sources. These are gradually replacing conventional thermal power plants. Consequently, in case of a total/partial blackout, conventional black-start resources are not ready for operation. Offshore wind farms, with their large capacity and fast controllers, show potential as innovative black-start units. This introduces the need of a new design for the wind power system. In this paper, challenges and possible solutions in integrating black start service into offshore wind farm will be presented. A first challenge is represented by the implementation of a black-start unit. The black-start unit should be capable of forming the wind farm power island, withstanding transient phenomena due to energisation. There could be several different solutions, e.g. the integration of grid-forming converters in the wind farm design. These could be battery energy storage systems (BESSs) and/or new generation grid-forming wind turbines. The selected challenges are analysed using simulation on a wind farm, and the proposed solutions discussed. It can be concluded that a system comprised of BESS, grid-forming wind turbines and STATCOM, in combination with novel technologies such as virtual synchronous machine, soft-charging, harmonic active filtering, etc. represent a good proposal for the integration of black start into offshore wind farms.**

Keywords—black start, power system restoration, offshore wind farms, power system resiliency, grid-forming, island operation, soft-charge, virtual inertia, harmonic filtering

I. INTRODUCTION

Power systems are currently experiencing a transition towards decarbonisation of electrical generation through large-scale deployment of renewable energy sources. Industries are now facing a major re-thinking of strategies in order to cut emissions faster and further since global warming has to be limited 1.5°C by reaching net-zero emissions in 2050, as per the Paris Agreement. Therefore, conventional power plants which run on fossil fuels are more and more often taken out of operation to accommodate higher shares of renewable energy. However, this weakens the resiliency of the modern power system after a blackout, as there are no black start (BS) sources ready to re-energise the grid in this scenario. At the same time, it is not convenient to maintain conventional power plant systems in stand-by only for the possible risk of a blackout scenario [1]. Consequently, economic considerations also point towards the integration of new types of BS service providers. Integrating BS service into non-conventional technologies to participate in the BS market could introduce financial gain to consumers, such as lower costs and increased competition [1]. Therefore, the integration of a large volume of renewable energy sources as BS providers offers new opportunities in power system restoration planning. Accordingly, a part of this major re-thinking of strategies needs to consider BS service providers.

High attention has recently been given to BS as it represents a crucial counteraction to the emergency state introduced by a blackout [2]. The occurrence of a massive power outage that includes the complete loss of generation, load and the transmission network serving the system loads, requires the use of selected generating stations with self-starting capability, i.e. BS sources, to get the system back into operation [3]. Power system blackouts are rare, but depending on how fast the power is restored, these may have great impact on the economy and society. Hence, a fast and reliable restoration scheme is a major concern to minimize the losses. Important organizations such as ENTSO-E [4], CIGRÉ [5] as well as the EU Commission [6] addressed this concern.

Among renewable energy sources, wind energy is the fastest growing, thanks to its abundance and cleanliness [7]. In particular, offshore wind farms (OWFs) represent an attractive solution at global [7], European [8] and both Danish [9] and British level [10]. In this context, OWFs, with their large capacity and fast controllers, show potential as innovative renewable-based BS units. Since the restoration time reduces exponentially with the availability of BS units, integrating BS capability into OWFs could significantly reduce the extent, intensity and duration, and thus the overall impact of blackout events [1]. Therefore, it is important that OWFs gain the ability to participate in the restoration strategy as BS units. Furthermore, BS is a crucial and extra service that is agreed separately from ancillary services. Thus, it is additionally paid, enhancing the revenue in operating OWFs.

The practical feasibility of successfully providing BS capability from an OWF still has to be proven, as no OWF is able to restore a black grid yet. Therefore, more research needs to be developed. Some literature around the main topic can be found in [11, 12, 13, 14]. However, no research is found which shows the challenges that BS functionality introduces in OWFs and illustrates possible solutions to take into consideration and implement. Innovative power electronic solutions in combination with modern storage can enable this [15]. The increase and diversification of novel power-electronic-based devices, such as wind turbines (WTs), high-voltage direct-current (HVDC) transmission, STATCOMs and battery energy storage systems (BESSs) in particular, creates many opportunities for extended functionalities and innovation in power systems. This introduces the need of a new design for OWFs with integrated BS capability.

The rest of this paper is organised as follows: the analysis of BS functionality in OWFs and transmission systems is given in Section II, where the different stages identified in the

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implementation of BS procedure by OWFs are outlined. Then, the selected challenges and possible solutions for OWFs as BS service providers are presented in Section III. These are classified and justified according to their different nature. Simulation analysis on an OWF system and discussion are presented in section IV. Finally, concluding remarks are given in Section V.

II. BLACK START FUNCTIONALITY ANALYSIS

BS comprises of different stages, which start from a state of no power to get to a state of restored normal operation for the power system. The OWF operating as a BS unit needs to respect a certain set of requirements, i.e. the BS requirements. As shown in [11], these requirements do not apply to OWFs currently as they are not conventional power plants. Nevertheless, an extended set of requirements has been proposed by some transmission system operators (TSOs), e.g. in the United Kingdom (UK), and it is considered here [16]. In having an OWF as BS source, the first stage represents the energisation of the wind farm in island operation, i.e. working as a wind farm power island. Once the island is energised and stable, the energisation of the onshore transmission grid and the energising block loads can start and thus forming a BS power island. This is also a challenging operation, as the transmission grid itself consists of many transmission lines and large loads such as substations and induction motor loads which have to be energised. After that the energisation of the part of the system instructed by the TSO is completed, the synchronisation with other power islands in the system has to take place until the full system is synchronised and restored. These stages are shown in Figure 1. As they have different characteristics, these will be analysed separately.

A. Wind Farm Power Island

After a total shutdown, the electrical circuits of the OWF are found in a state of no power, with all WTs disconnected. The first operation happening instructs the OWF operator that a BS operation needs to take place. This will have a required time to connect to the onshore grid, e.g. two hours for the UK [16], where the BS unit needs to be ready to energise the onshore transmission grid and block loads. The OWF has to have a unit able to self-start which can deliver the first energisation power. This self-starter will have to energise the system, i.e. the export and array cables, WTs, substations and other parts of the system that are needed for the BS. This procedure can be challenging due to the different devices present, i.e. reactive components and power electronic converters, and switching operations involved. The charging of the reactive components can trigger transient phenomena, e.g. inrush currents, which are problematic for power-electronic-based generation sources.

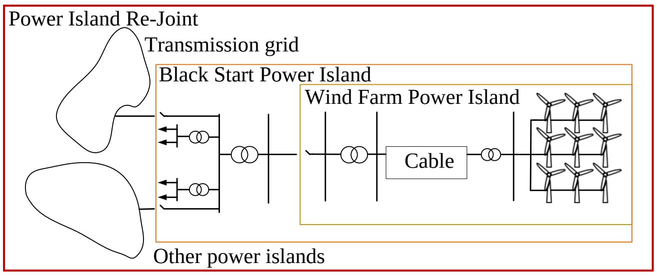

Fig. 1. Stages of the black start procedure implemented by an offshore wind farm.

Thus, the island itself represents a dead system which is ultimately a weak grid. Therefore, the location of the self-starters as well as the energisation strategy are fundamental for a resilient BS strategy. At this stage, the OWF is working as a wind farm power island, as it is not connected to the grid, i.e. working as an islanded power system balancing local loads and generation. Once the system is stable and ready, the connection and energisation of the dead transmission grid can take place.

B. Black Start Power Island

This stage is the first one when an actual system restoration is occurring. At this stage, the OWF acting as BS source will have to energise both passive components of the transmission and distribution network, as well as block loads. There are specific requirements on both, and they are different according to the specific country. In the UK, the reactive capability of the BS unit needs to be at least 100 Mvar exported from the OWF and the block loading capability is set for a minimum of 20 MW. Due to the variability of the transmission network configuration, the OWF as BS unit needs to be prepared for different scenarios and flexible in accommodating them. The challenge to solve at this stage consists mainly in the performance of the OWF, and all its power-electronic based sources, during the energisation of the system where phenomena like large inrush currents, resonances and loss of synchronism could jeopardise the BS power island stability. Once part of the onshore network is restored the OWF is working as BS power island as the OWF will be exporting power to the transmission grid while controlling the frequency of the island. The actual number of block loads will depend on the TSO requested service and the OWF power available at the moment of block loading. Furthermore, the considerations need to account for the OWF power availability for a minimum of three days, according to UK BS grid codes according to the TSO’s needs in the overall system restoration.

After this stage, the joining with other power islands will occur to complete the restoration of the network.

C. Power Island Re-Joint

Initially, the OWF is controlling power consumption and frequency of the BS power island. When the TSO is ready for the islands to re-join in one synchronous grid, the OWF operator has to initiate the grid synchronisation processes. The transition from islanded to grid connected needs to be seamless, therefore the controller settings need to easily pass from islanded to grid-synchronisation.

III. CHALLENGES AND POSSIBLE SOLUTIONS IN INTEGRATION OF BLACK START INTO OFFSHORE WIND FARMS

The main challenge posed by the integration of BS capabilities into OWFs is the fact that OWFs are usually 100% power-electronic-based systems whose source of power is variable, in contrast to conventional BS sources that are mainly synchronous generators. Therefore, different challenges arise as presented in [11]. Following this example, these challenges and their proposed solutions will be now analysed.

A. *Self-Start Capability*

Firstly, power electronic converters present in usual OWF design are grid-following (GFL) converters, which do not have self-start capability. This is because normally OWFs do not contribute to restoration strategies, and they are typically energised by the transmission grid. In contrast, to integrate BS capabilities, there is the fundamental need to introduce a device with self-start capabilities.

There are different alternatives and different configurations that are possible [11]. The use of new generation power electronic converters with grid-forming (GFM) control is highly relevant. These converters in the OWF could be storage-interfaced units or GFM WTs. Another option is represented by the use of a conventional unit as a synchronous generator, which could be fuelled by diesel or, more recently proposed, by biomass [1], or even green hydrogen. Nevertheless, more and more research is focused on the application of novel GFM control strategies to BS, instead of synchronous generators. This current trend is mainly due to the fact that many companies are trying to support sustainable goals, by implementing carbon neutral solutions in their operations and supply chain [17, 18], and therefore want to avoid the use of fossil fuels, such as diesel, as much as possible. Furthermore, biomass-powered synchronous generators are typically available on a much smaller scale than conventional units [1]. Thus, this affects their capability and so this must be considered when setting technical requirements and levels of service.

The use of GFM converters is interesting, however, the self-starter needs to overcome many challenges, such as working with complex system dynamics and transient phenomena in a weak grid system, where physical inertia is not present and stability issues may arise.

B. *Service Availability*

Secondly, the availability problem is of high concern. As wind is the source of power of an OWF, the BS service availability highly depend on the wind variability. For the UK, the BS availability requirement is 90%, which is the same established for conventional BS sources. As presented in [21], the average amount of procured wind capacity to secure a sustained 500 MW of power for 24 hours for 90th percentile is higher than 10 GW. This is certainly an extreme number and it is also stated that very large diversity could be found also in two wind farms with very similar total capacity, and this is due to their geographical location. Nevertheless, the challenge posed by the service availability requirement is understood. This would surely need to be examined thoroughly by the OWF system operator. Therefore, combining energy storage with OWFs could be a potentially attractive way to boost the contribution that this generation could make. Generally, the integration of energy storage can contribute to a more efficient and stable power system. The choice of adequate energy storage is based on various parameters, such as accurate technical and economic evaluation of deployed energy storage and geographical considerations. In [22], an overview of all existing energy storage systems is carried out.

Out of various types of energy storage systems, BESSs are recently considered as the most suitable technology due to numerous advantages. Their scalability, response time and ability to absorb and deliver power to the system is making them a great option for smoothening wind power output and increasing power system stability. Moreover, the cost of this type of technology is in a constant decrease and it is expected that the trend will continue in the future [23].

Lately, numerous projects involving BESS technology are announced, under construction or ongoing worldwide. Most recent one involved installation of 150 MW/189 MWh, recently expanded, Li-ion BESS called Hornsdale Power Reserve, co-located with the Hornsdale Wind Farm [24]. It is considered the largest Li-ion BESS in the world and its purpose is to provide power system stability services in South Australia. Moreover, the Dalrymple BESS, also known as ESCRI-SA project, is a 30 MVA/8 MWh GFM BESS with microgrid automation, controlled with virtual a synchronous machine (VSM) algorithm. This BESS is able to store excess generation from Wattle Point Wind Farm in order to charge and perform the necessary services [25].

As presented in [26] by the IBESS project, the combination of OWF and integrated BESS and STATCOM can deliver BS with high level of availability [27]. Nevertheless, this depends on the OWF capacity and availability level required. Analytical results show that a partially energised OWF in combination with BESS is able to provide BS with a level of availability higher than 80%. While, availability higher than 90% are found with large BESS and fully energised OWF, which are costly and depend on wind conditions. As a consequence, it can be understood that adequate competition in the BS market to enable renewable energy sources to participate in this new service depends on the selected technical requirement. A lower level of required availability could ensure adequate competition, allowing more renewables to contribute in a BS scenario.

C. *Inertia Provision*

Inertia provision has clearly been added as a BS requirement. This is challenging for conventional OWFs as they are 100% power electronic based systems. Nevertheless, this requirement can be fulfilled either by real or virtual inertia. As virtual inertia, the requirement can be achieved by implementing inertia emulation in the converter control. More specifically, the WTs and/or BESS in the OWF can be controlled as VSM and deliver inertia emulation when needed. Both GFL and GFM control can emulate inertia and examples are [28, 29]. Practical applications of VSM GFM in power electronics can be found in BESSs [24, 25] and WTs [30, 31].

Furthermore, also VSM algorithms have been proposed in order for STATCOMs to emulate inertia. In this context, STATCOMs could behave as synchronous condensers [32]. Innovative types of STATCOMs can support the system with more than only dynamic voltage regulation. One example is the SVC PLUS® with power intensive energy storage, which is a combined STATCOM with supercapacitors able to provide both voltage and frequency support [33]. These capabilities could be exploited and used for inertia emulation as well.

D. *Control, Stability and Interoperability*

With a whole new service to provide, the control and interoperability of the system also add as a challenge. Depending on the numbers of self-starters, there will be the need to coordinate the interoperability, for both during energisation and system operations. In particular, the challenge gets tougher as the system represents a weak grid, compared to the onshore transmission grid which is usually the reference for the power electronic control. Therefore, issues such as energisation sequence and island frequency control are of main importance. In this regard, the possibility to combine a GFM BESS together with GFM WTs has the potential to ensure stable operation also in weak grid conditions. The GFM unit/units will have to firstly coordinate the response, which could be primarily assigned to the BESS, in order to avoid relying on wind conditions, and then be shared with the WTs. During operation, the interoperability could be guaranteed keeping the system coordinated by a high-level control which applies communication, or by droop strategies for example. Moreover, as the system parts get energised, the need of an adaptive control may emerge in between these settings. Hence, the complexity of the proposed solution is increased.

BESSs are considered as one of the prominent solutions in stability maintenance in a renewable energy system [23]. Thus, their use is expected to be relevant in OWF BS.

There are many different types of GFM control strategies that have been presented in the state-of-the-art literature and could be applied for OWF BS [34]. In between these strategies, VSM type of GFM control has achieved successful application, e.g. in test fields for GFM WTs [30, 31] and Dalrymple BESS working in combination with Wattle Point Wind Farm in South Australia [25].

E. *Transient Behaviour*

Transient phenomena are involved in every energisation operation related to OWF BS. Due to the switching operations, transients can be challenging for the system to survive. Transient overvoltages (TOVs) can lead to equipment failure or damage that may hinder the successful implementation of the restoration plan. Energising equipment during BS conditions can result in higher overvoltages than during times of normal operation [3]. These TOVs originate from energising operations and equipment non-linearity, e.g. transformer saturation. A first challenge is represented by the wind farm power island energisation. To contain the energisation transients novel energisation methods such as soft charging can be applied if GFM units are used. After that, another challenge is the energisation of the transmission system and block loads. If the load has been de-energised for several hours, the inrush current upon re-energising the load can be as high as eight to ten times normal [3]. Hence, a detailed BS strategy and simulation plan will have to confirm that the OWF system will be able to cope with the BS.

F. *Harmonic Performance*

The combination of different power converters, long cables and other passive elements introduces also issues for the harmonic performance of the system. This is due to the fact that power system resonances may be excited during the restoration procedure, potentially leading the system to instability conditions. Therefore, the analysis of the BS strategy needs to consider this challenge to mitigate the possible effects of harmonic distortion.

The main solution to this challenge can be harmonic active filtering, which is adaptive to topology changes and system loadings [35]. This represents a flexible harmonic mitigation measure and can be successfully applied to the OWF during BS.

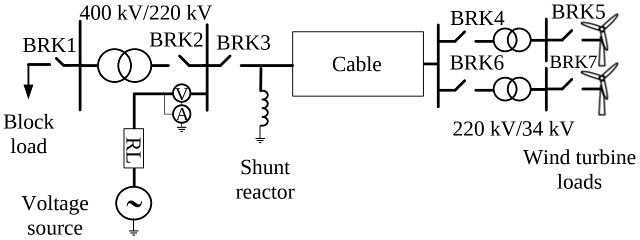

Fig. 2. Simplified benchmark with self-start unit for preliminary system studies.

G. *Automation and Communication Settings*

Automation of the process and communication systems could also represent a challenge in the design of OWFs with BS capabilities. The right automatization settings will give faster response, with less work from the operator and thus, reducing the possibility of human errors. As BS procedure is initiated after a blackout, part of the system may be damaged. A first automatization already available is the use of the state reporting by the equipment. However, not all pieces of equipment in the OWF are able to send this status signal. Thus, more complete tools need to be developed. Once the state of the system can be reliably checked, the sequencing process during the wind farm power island operation can be initiated. A possible solution is the implementation of a state machine diagram to be applied for the OWF BS. In this way, the BS procedure could be semi-automatized, gaining higher resiliency and faster operations.

IV. ANALYSIS AND DISCUSSION

In a real BS scenario where the main unit would be a BESS, a general strategy needs to be implemented. As the integration of BESS together with WTs represents a hybrid generation system, the main role as master could be given to the BESS. Therefore, the BESS could be the lead to the BS procedure. In this way, the BESS is the first element to self-start once the command of BS is instructed by the TSO, and energise the OWF, forming the wind farm power island.

According to this procedure, the BESS supplies the initial power, while the WTs will then charge the BESS to maintain an optimal state of charge. Forming the black start power island, i.e. energising 20 MW block loads, the BESS will also be the one providing the initial energy, which will then be passed to the WTs. This procedure has the possibility to ensure high resiliency as the main power supply is accounted on one single element, which energy storage is controlled, and then is backed up by a large OWF.

Some of these presented challenges can be illustrated by a simplified OWF system. Time-domain simulations of the BS system have been developed in PSCAD/EMTDC. The analysed system is shown in Figure 2. The system is comprised of a voltage source connected onshore at the 220 kV level to represent a BESS in order to evaluate the expected performance in a simplified way. The BESS is connected onshore at the 220-kV level as usually, the offshore substation of an OWF does not allow for big equipment such as a BESS. The size could be lowered in order to make it feasible to install offshore, however this may probably be too low for an effective BS procedure. Furthermore, the resiliency of the system is higher when having the BESS onshore, as the maintenance and reparations can be faster due to the easy access to the location.

In the model, the OWF is consisting of the aforementioned voltage source, connected at the 220 kV level of the submarine cable which exports the power from offshore stations for this preliminary study. This is a 55-km long Cu XLPE 1600 mm2, 220-kV HVAC cable. This is represented with frequency-dependent model, as it is useful for studies wherever the transient or harmonic behaviour of the cable is important. A shunt reactor is used for reactive power compensation purposes of the cables and this is here modelled as a 120 Mvar saturable shunt reactor. The offshore end of the cable is connected to an offshore 220 kV, which in turn is connected to 220/34 kV, 240 MVA transformers. The WTs arrays are connected to the transformers via 34 kV busbars. As a simplification, WTs are modelled as PQ loads to take into consideration their internal loads when these are first energised. The total load is equal to 6-MW and considers the internal loads of for the WT energisation as heaters, dehumidifiers, lights, and no-load losses in WT transformers for WTs are PQ loads to take into consideration their internal loads when these are first energised. The total load is equal to 6 MVA and considers the energisation loads of WTs such as heaters, dehumidifiers, lights, and no-load losses in WT transformers for a cluster of 55 new-generation offshore WTs, thus representing 1% circa of rated power, which is considered as 440 MW. At the onshore end of the cable the 400/220 kV, 475 MVA onshore transformer is connected. This connects the OWF to the onshore grid, which is only considering a 20 MW block load for simplification. In this way, it is possible to simulate first the wind farm power island and later the black start power island and its impact on the self-starter, in the intention to consider a BESS for this application. The saturation characteristics are considered in all the implemented transformers.

In the simulations, the energisation time is reduced, in fact the total simulation time is 2.5 seconds. Obviously, it would take much longer in real life due to the physical time constraints involved, in the range of tens of minutes. The voltage source is set to ramp up in 0.1 s. Subsequently, the first breaker is closed at 0.15 s energising the cable and shunt reactor. Figure 3 shows the current waveform from the voltage source point of connection. As shown in Figure 3, the major inrush is seen at this point, having the current reaching a peak of 2 kA. This is due to the fact that the source is energising the 55-km long cable and shunt reactor, and due to their inductive and capacitive components a high current is flowing through the system. A better zoom of this transient is seen in Figure 4.

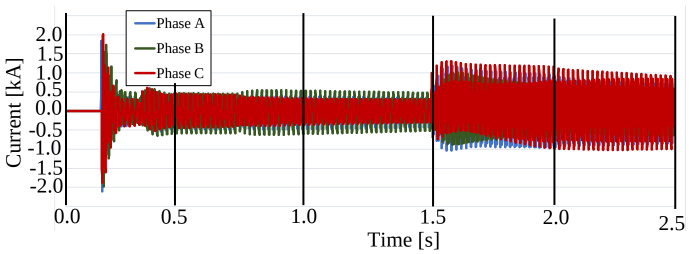

Fig. 3. Current waveforms during the sequential energisation of the offshore wind farm black start procedure and block load.

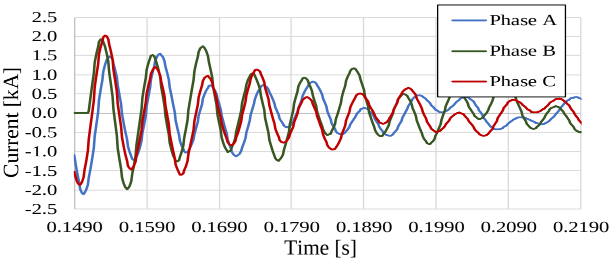

Fig. 4. Zoom of the transient of the current when energising the cable and shunt reactor.

The energisation of cable and shunt reactor during BS can be challenging for a BESS, as phenomena like zero missing (to avoid protection malfunctions) and/or the Ferranti effect (to avoid equipment damage) have to be prevented. In sequence, the first and afterwards second offshore branch with WT loads. After also the WT loads are energised, the onshore transformer is energised at 1.1 s. In all switching operations, single pole operation of the breakers is considered in order to minimise the transients, via implementation of point of wave (POW) switching. At 1.5 s, the block load of 20 MW is energised and it can be seen that the current level is increased thereby. This is an important aspect to consider when implementing systems with BESSs as the current capabilities of this type of devices are crucial during a BS scenario. The most important thing to consider is that the BESS does not exceed its current rate and collapses both in charging and discharging state. For this, the analysis of different types of BESS and different BS strategies have to be compared. The voltage waveforms are shown in Figure 5. It can be seen that the cable and shunt reactor energisation give also the highest overvoltage, which is around 1.07 pu at maximum. The requirements specify also voltage and frequency control to be respected during BS, and for example for the UK the voltage requirements relate to ±10%.

From this simple analysis, it is easy to understand that a dynamic procedure as BS has to be thoroughly investigated to make sure that the outcome has high resiliency and success rate. It is not currently implemented nor already proven that OWFs with a combination of BESS, GFM WTs and STATCOM controlled as VSM constitute a resilient BS service provider. However, analytical simulations and hardware-in-the-loop type of demonstrations can be a valuable solution for proof of concept of the system before actual implementation.

V. CONCLUSION

More research pointing towards this novel type of service in OWFs needs to be conducted. The possible solutions discussed are to be applied and thoroughly analysed. In this way, they can be considered valid and worth to be tested. Nowadays, different implementations may allow a successful BS provision by OWFs. Different solutions have been explored and proposed, also based on existing systems with similar purposes of BS applications.

The investigated system, even if extremely simple, shows the challenges which need to be overcome before implementing this system in real life. It is found particularly

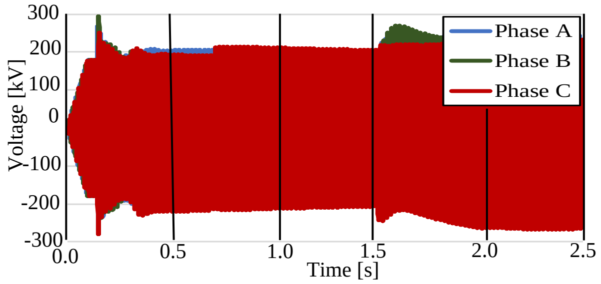

Fig. 5. Voltage waveforms during the sequential energisation of the offshore wind farm black start procedure and block load.

interesting to implement the discussed solutions, i.e. GFM control, VSM, soft-charging, active harmonic filtering, etc.

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