North Sea Wind Power Hub concept

Simulation requirements for de-risking of the NSWPH concept

TENNET

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1. Introduction

North Sea Wind Power Hub (NSWPH) is a consortium of Tennet, Energinet and Gasunie to develop required infrastructure in the North Sea for the integration of large-scale offshore wind energy from the North Sea into the northern European power systems. The NSWPH approach is based on “hub-and-spoke” concept where the power generated from multiple wind farms are collected at a power hub and then transmitted to multiple receiving power systems utilizing HVDC. Compared to the traditional approach, the hub-and-spoke approach reduces the cost of integration and provides additional flexibility in power trade among the participating networks.

The NSWPH project is expected to be realized in four phases: feasibility, specification, implementation and operation. At the feasibility phase the needs of the project, environmental impacts, available alternatives etc. are studied. Then at the specification phase preliminary design studies are performed and technical requirements of the system are determined. Once the suppliers are selected and contracts are signed the implementation phase starts where the manufacturers design, test and install the system. Finally, the operation phase starts by commissioning the system and delivery to the TSO. During the operation phase system may be expanded or modified. Figure 1 shows an illustration of the phases as envisioned for the NSWPH project.

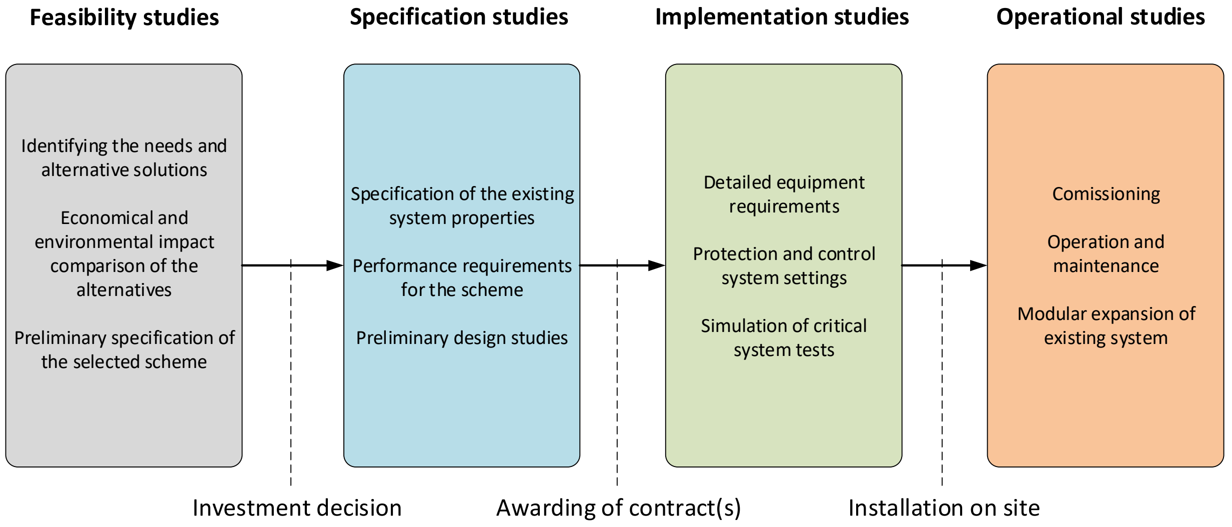

Figure 1 - Development phases for NSWPH

Two configurations have been proposed for the offshore power hub: the AC connected hub and the DC connected hub. In the AC connected hub a number of wind farms are connected and feed a small AC network (or busbar) which is defined as an AC hub. Two or more HVDC links transmit power from this AC hub to various onshore networks. As the offshore power generation expands multiple offshore AC hubs can be built. Two (or more) of such AC hubs can be connected to each other via an HVDC link. Figure 2 shows the principal concept of two AC hubs connected to via an HVDC link.

In a DC connected hub each cluster of wind farms is connected to the onshore grid via an HVDC link, similar to the conventional offshore wind integration. However, two or more HVDC links are connected to each other at the rectifier end through submarine DC cables to form a power hub. In principle this is a multi-terminal (MT) HVDC system, with the inverter stations (onshore) located in separate receiving networks. As the system expands other hubs can be established and connected to each other via DC cables. Figure 3 shows the principal concept of such DC connected hub.

The power hub is a novel concept and need to be carefully analysed before its implementation. An important aspect of the analysis is to identify and address the potential issues (risks) related to the control and protection of the system. The objective of this report is to identify and discuss the risks and propose the studies necessary to address them. For each study the responsible party (TSO, manufacturer,…) is identified. . Further, the tools required to conduct the study are also identified. This means for each of the studies it is identified whether to perform it offline or utilizing Hardware in the Loop (HIL) arrangement. The report also addresses the advantages and disadvantages of performing HIL simulation.

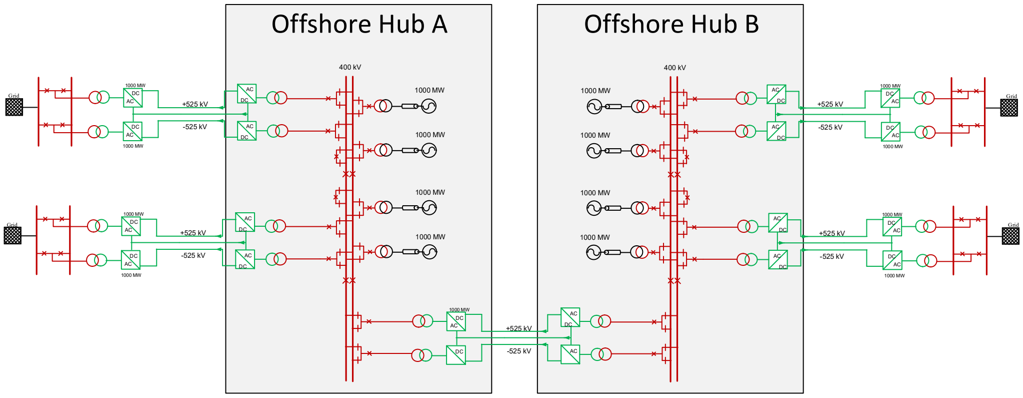

Figure 2 – AC connected hub concept

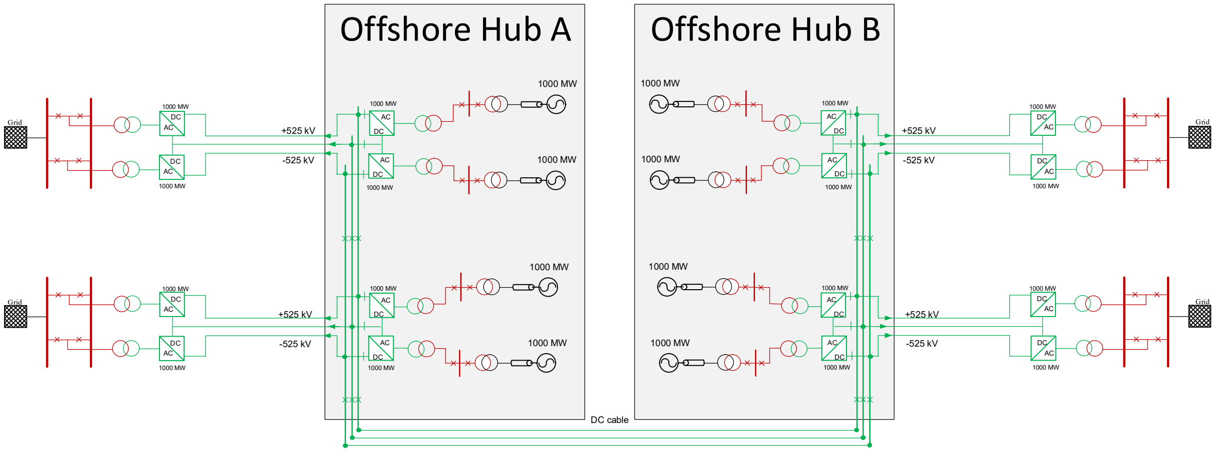

Figure 3 - DC connected hub concept

2. Control and Protection Studies

The NSWPH concept of hub-and-spoke is the first of its kind. To ensure the safe and stable operation of the system a number of studies must be performed at various stages of the project. This section provides a summary of the main potential issues related to the control and protection of the system as well as the necessary studies to minimize the associated risks.

2.1 AC Connected Hub

In the AC connected hub (Figure 2) multiple wind farms and HVDC systems are connected to the same offshore AC busbar. There are also potentially large offshore loads (hydrogen plants) possibly fed from the same offshore AC bus. There are challenges in the power flow and dynamic control as well as the protection of this system as discussed in the following sections.

2.1.1 Power flow control

In steady state the offshore HVDC controllers must maintain the power flows near their set points while allowing the fluctuations in wind power to be shared among HVDC links. In the event of a wind farm, converter or DC cable outage the controller must be able to bring the system to a new stable operating point where the power flows into the onshore terminals are as close as possible to their pre-event levels. The controller must also maintain the offshore frequency within acceptable limits at all times. There shall be no oscillatory interaction between HVDC converters, wind farms, loads and any other component within the hub. To achieve these goals the HVDC links connecting to the onshore grid need to operate in grid forming mode. Achieving a stable and robust power flow control scheme under all operating conditions (i.e. system intact, during and post faults) is an identified risk. This risk is addressed through the following studies:

Steady state power flow study

This study is performed first at the *feasibility stage* to develop the concept. At the *design stage* of each wind farm and the HVDC integration a more detailed study is performed. Further, at *operation stage* as new wind farms, HVDC or major loads are added to the hub, a power flow study has to be performed to ensure the power flow in the new system with the additional components is still satisfactory. The study determines:

- Operating ranges and droop settings of the HVDC and windfarms under system intact and contingency conditions
- The need for special protection schemes such as automatic tripping of windfarms when an HVDC outage occurs (cross tripping)
- The need of short-term power flow stabilization devices such as AC choppers.

The study at the feasibility and operation stages is normally *performed by the TSO*. At the design stage the study is *performed by the manufacturer*.

The steady state analysis is typically performed *offline*.

Offshore frequency/angle stability study

It is very important to maintain the frequency stability of the offshore grid. The HVDC terminals may operate in grid forming mode and there is a possibility of having some wind farms in grid forming mode as well. Therefore, it is very important to maintain power balance between the multiple grid forming converters in parallel during the system intact and contingency conditions. Such condition of multiple grid forming converters in parallel is not common in existing offshore grids or onshore grids. Therefore, there is a significant risk associated with the power-frequency/angle stability.

The power-frequency stability can be evaluated as part of the transient stability analysis and/or the dynamic performance studies (EMT). The studies usually involve the HVDC controls (outer loops and grid forming controls) and the power plant and turbine controls of the wind farms. If there is a master controller regulating the offshore frequency, this needs to be modeled as well during these studies. At the specification phase the study will determine the signals exchanged between the master controller and each HVDC or windfarm and the functions provided by the master controller.

If accurate models of the controllers involved are available, the studies can be performed *offline*. Otherwise, real time HIL simulations would be required utilizing the actual control hardware. Obviously, this means having access to the actual control hardware. Ideally for the HIL simulation control hardware from both HVDC and windfarms are required.

Similar to steady state analysis, this study needs to be repeated at the three stages of development by TSO and Manufacturer.

Small signal stability study

When multiple parallel converters operating in grid forming mode, there is a possibility of having power swings similar to the electromechanical oscillations of conventional generators. In addition to these, different controllers may exhibit oscillatory behaviours. Therefore, it is very important to evaluate any offshore grid oscillations and the damping associated with them. There are two possible study methodologies:

- The oscillations can be evaluated using detailed EMT models of the controllers and applying small perturbations such as step changes. This method is a trial-and-error based method. However, there is a risk not to identify some oscillations that can appear under certain operating conditions (system conditions). Therefore, it is important to consider a large number of operating points and small signal disturbances. The study is usually performed at the *design stage by the manufacturer*. The studies can be done *offline* (with detailed controller models) or *real time (HIL)*.
- The oscillations can be evaluated using Eigen analysis [7]. This is the preferred method. The oscillations and damping associated with the entire system can be evaluated at a particular operating point by looking at the Eigen values of the linearized model of the system. The devices and controllers can be identified by evaluating the Eigen properties such as participation factors, mode shapes and residues. Therefore, this method gives a better insight into the oscillatory behaviour. The method can also be used to develop the mitigation measures such as damping controllers. However, the main challenge here is to get the detailed linearized models of the HVDC systems and the wind farms from the manufacturers. This offline study is usually done at the *design stage by the manufacturers*. So, it is obvious there will have to be an exchange of information between the HVDC and wind turbine vendors.

2.1.2 Reactive power Control

The reactive power coordination of the offshore grid is very important. The offshore grid voltage is usually controlled by HVDC and the wind farms can be operated in constant reactive power control. However, there is a possibility of getting more active power control flexibility for grid forming HVDC converters by operating at zero reactive current control. In this case, the wind farms need to be used for the voltage control. Furthermore, offshore grid reactive power generation and consumption depends on the loading of the offshore AC cables. Therefore, it is important to identify the offshore grid reactive power requirements and control possibilities.

The reactive power control requirements are evaluated using steady state analysis and small signal stability analysis described in the above sections and transient stability and dynamic performance studies described in the following sections. At the feasibility stage the reactive power requirements (steady state and dynamic) of the HVDC and windfarms need to be defined by the TSOs. The steady state and transient stability studies are adequate for this purpose (offline simulation). The reactive power coordination between the windfarms and the HVDCs should be determined by the TSOs and the relevant information should be included in the specifications. At the design stage these requirements need to be revisited by the manufacturers. At this stage the study can be performed either offline or HIL.

2.1.3 AC Resonances

Electrical resonances have been reported in existing offshore systems connected to a single HVDC symmetrical monopole [8]. The HVDC controllers may adversely affect the damping of the electrical resonances. Now it is a requirement of most of the European grid codes to have active damping controls in the offshore HVDC converters to control the electrical resonances.

When the HVDC converters are tightly coupled at the AC hubs, the issue of electrical resonances is more complicated. There might be a possibility of having multiple resonances and the electrical components (e.g. transformers and phase reactors) of multiple HVDC converters can contribute to the resonances. The identification of the resonances and designing the damping controllers is much more complicated for an AC hub with multiple HVDC links (compared to DC hub). The active damping controllers tuned considering only one HVDC link may not be effective when more HVDC links are connected into the AC hub. Therefore, the electrical resonances are recognized as a major risk in the case of AC hubs.

Offshore network resonance study

A refined study procedure would be required to identify the electrical resonances and damping associated with the offshore grid.

Impedance based methods [9] can be used to identify the resonances in the offshore grid. The frequency dependent impedance (i.e. transfer functions) of the HVDC converters and the wind farms need to be obtained for the required frequency range (up to about 3000 Hz) using current injection methods (EMT simulations). It is very important to include the detailed controllers and the finalized parameter values in order to obtain the correct impedance profile. The device impedances are combined with the electrical network impedances to obtain the system impedance profile to evaluate the electrical resonances. It is necessary to consider all possible operating conditions (outages of wind farms, cables, HVDC converters) to identify the possibilities of having resonance conditions. The impedance-based resonance study is performed offline.

The Eigen analysis of the linearized models (similar to small signal stability analysis described above) can also be used to identify the resonances and the damping. However, the electrical network needs to be modeled using dynamic phasors with frequency dependent characteristics. This study is performed offline.

The electrical resonances need to be evaluated by the manufacturers at the design stages using the offline simulations. The TSOs need to provide the correct input data such as AC cable parameters, Wind farm and other HVDC system impedances (obtained from the other manufacturers). The study needs to be repeated every time when the AC hub is changed (adding HVDC converters, windfarms, cables, etc.).

Damping Control Design and Demonstration

The active damping controls associated with HVDC links need to be tuned to have adequate damping for all the resonances identified. It is necessary for manufacturers to demonstrate the system performance with and without tuned active damping controls. This is usually done using real time simulations (HIL) by the manufacturer. It is also necessary to evaluate the same conditions using offline EMT simulations (in order to evaluate the accuracy of the offline EMT models in terms of electrical resonances).

2.1.4 Controller interactions

The controller interactions are major concern when multiple power electronic devices are connected together. There are few possibilities:

- Interactions between the AC voltage/reactive power controllers of different HVDC converters
- Interactions between the frequency/active power controllers of different HVDC converters
- Interactions between different windfarm controllers (turbine & Powe Plant Controller)
- Interactions between the transient current controllers
- Controller instabilities (a badly tuned controller producing oscillations)

Interaction study

A comprehensive interaction study needs to be performed in order to identify the degree of controller interactions in the offshore grid. Both steady state (small signal) and transient interactions need to be evaluated.

The steady state interactions can be evaluated using small signal stability assessment techniques described in Section 2.1.1.

The transient interactions are evaluated during the transient stability assessment and dynamic performance studies described in Sections 2.1.5 and 2.1.6 respectively.

2.1.5 Transient stability

The transient stability assessment of the offshore AC hub would be much more complex than a single HVDC symmetrical monopole connected to the wind farms which is used in the existing HVDC links integrating windfarms.

Transient stability study

The transient stability assessment is usually done using RMS simulation tools. Considering the complexity of the offshore grid, it would be difficult to model them accurately in RMS tools. This system is relatively small (than large system models used in RMS simulations), the transient stability studies can be performed using the EMT simulations.

These studies are done at feasibility stage by TSOs (using generic representations of the part of the system being designed) and at the design stage by the manufacturers (using detailed models). The studies need to be repeated when a new component is added to the offshore grid (operational studies). The studies can be done using offline tools.

2.1.6 Dynamic performance

The dynamic performance studies of the HVDC systems and wind farms are very important for proper design of the devices and to avoid any interactions between the devices. The dynamic performance evaluation becomes much more complex when there are multiple power electronic devices connected to each other.

Dynamic performance study

The dynamic performance study is usually done by the manufacturer at the design stage using the detailed models. These studies are usually done using offline EMT and real time simulations. It is very important to use the detailed models of the other devices in the system (Wind farms and HVDC) for the studies. The windfarms are usually aggregated into several turbine models (e.g. one model pre string) considering the practical limitations of the simulation platform.

HIL simulations would be the best choice considering the accuracy of the simulation models. If the validated EMT models (of the real hardware) are available, the simulations can be carried out using offline simulations.

2.1.7 Offshore system harmonics

When there are multiple power electronic devices producing harmonics, the harmonic distortion would be higher than a single HVDC system connected to the wind farms. The MMC VSC systems produces very small amount of harmonics compared to the wind farms with 2 or 3 level inverters with PWM switching. In an AC hub the amount of wind farms connected to any of the AC busbars is larger than the number of HVDC connections to the same busbar and therefore the risk of harmonic distortion is higher.

Offshore system harmonic study

The harmonic performance of the offshore grid needs to be evaluated using studies and measurements. The impact of a device on the harmonic distortion is evaluated by the manufacturer at the design stage. For this, the existing harmonic sources in the system need to be modeled properly. The TSOs have to collect the detailed harmonic models from the various manufacturers and provide the manufacturer of the device being designed with such models. The harmonic evaluation is usually done using offline EMT simulations.

Once the device is installed it is necessary to measure the harmonic content at the connection point and this can be compared with the earlier measurements performed prior to the installation of such device (for operational cases).

2.1.8 Inter-operability

The North Sea wind power hub is planned to be developed in stages. It is therefore likely that the multiple HVDC links connected to any of the hubs will be supplied by different vendors. The HVDC technology is also evolving and there is a possibility that the HVDC systems built at different times utilize different technologies or even topologies. Therefore there is a risk that the HVDC links supplied by different manufacturers and at different times are not compatible and cannot optimally operate together. Interoperability issues are difficult to fix as collaboration and exchange of information among manufacturers is usually impeded by commercial and legal barriers. It is therefore important to study the inter-operability of the systems at the design stage to address this risk.

Inter-operability performance study

The objective of the inter-operability study is to ensure all HVDC links connected to the hub can operate smoothly and according to the specifications under all operating conditions and contingencies. The study can be done in two stages: in the first stage detailed EMT models developed by vendors are used for an offline study, while in the second stage the actual control cubicles and/or replicas will be used in an HIL arrangement [6]. The purpose of using two stage approach is to identify and resolve the issues related to inter-operability at early stages to the extent possible. These fixes can be then put into test in the second stage using actual C&P cubicles.

It is important that the TSO have access to accurate models of all the devices (HVDC, wind farms, electrolysers etc.) connected to the hub for the accuracy of the inter-operability study. Therefore, the processes should be in place to obtain these models from each connecting party after the devices put in service. The models should be validated against the replicas and/or field tests. At the time of developing the specification for each project special attention should be given to the detailed requirements for the offline models to be delivered by the vendor and the validation process of those models. This is to ensure that the models are suitable for the inter-operability study. The specification for all HVDC projects should also define a standard set of interface signals to be exchanged with a master controller and/or other HVDC systems. As an example, power, frequency and AC voltage orders can be sent from the master controller to all HVDC converters and status of converters (blocked, standby etc.) and operating point (V, P, Q, …) can be sent back from converters to the master controller. The offline models and replicas (if replicas are acquired) from all vendors should comply with this requirement.

To address the confidentiality concerns the study should be performed by TSO. A wide range of tests should be performed including the start-up, shutdown, ramps, DC and AC faults etc. in different operating modes. The tests should also include the failure mode analysis such as the communication failure between HVDC links and/or the master controller.

2.1.9 Offshore AC grid Fault detection

The offshore network will almost entirely consist of power electronic devices. Unlike the traditional devices such as synchronous generators, the power electronic device performance is heavily influenced by their controllers. During faults, the special control features such as fault-ride-through functions, dynamic reactive current injection function, and negative sequence controllers may be activated. Some of these requirements are imposed by TSOs to cater for the needs of the AC systems and some are requirements imposed by the wind farm equipment. For example, negative sequence controllers are required to ensure safe operation of the wind turbine converters by avoiding excessive currents during asymmetrical faults. Although it may be possible to relax requirements for an offshore system that require special control functions, it may not be possible to eliminate these functions completely. Therefore, the performance of traditional current or impedance-based protection schemes may be impacted by the presence of a large number of power electronic devices [1]. Due to the activation of such functions, protections may fail to detect the fault or may inadvertently operate. For example, an over current relay may fail to detect a fault due to the decrease of the magnitude of the fault current during the fault by the activation of fault-ride-through functions or may mal-operate due to the dynamic reactive current injection. These problems are applicable for the existing offshore schemes as well. However, the offshore AC grid fault detection can be more challenging especially in the case of an AC connected hub due to the extensive power electronic device dominated AC network. Protection relays based on new methods such as travelling wave techniques may have to be employed in the case of an AC connected hub to achieve reliable AC fault detection [2].

AC fault study

An AC fault study should be performed to evaluate performance of the protection devices connected in the offshore system. This study is performed by the manufacturer during the design stage. It is important to accurately model the offshore system and the protection relays for this study. Typically the EMT models of the protection relays in EMT programs may have been simplified. Therefore, such simple models are not adequate for the study. If accurate relay models are available, the protection coordination study can be performed with offline EMT simulations. HIL simulations are advantageous in this study because of better accuracy, and the actual relays can be physically connected and tested, provided that an accurate model of the offshore AC network is also available. The study should demonstrate the impact of AC faults at various locations of the system and the capability of the selected protection strategies to isolate the faulty component reliably with minimal impact on the system.

2.1.10 AC breaker performance

The offshore AC system of the AC connected hub consists of an extensive network of cables which generate a considerable amount of reactive power. It may be required to use shunt reactors to compensate for the extra reactive power generated by the cables to maintain the voltage within operating limits. Delayed operation of AC breakers during switching is a known phenomenon when using shunt reactors to compensate long transmission lines [3]. Considering the similarities between the shunt compensated long transmission lines and the AC connected hub (high network capacitance in the presence of shunt reactors) the risk of delayed operation of AC breakers due to delayed zero crossings exists.

The AC breaker ratings need to be carefully evaluated in case of the AC connected hub especially considering the fact that the hub will “grow” over time.

AC breaker study

An AC breaker study is performed to evaluate the rating and the performance of the AC breakers in the AC hub. Each connecting device manufacturer can perform these studies during the design stage. This study can be performed with offline EMT simulations. This study should identify the requirements for the breakers to be installed and any measures to mitigate the problems identified. It has to be kept in mind that as the hub expands, breaker duty requirements will change/increase. This should be taken into consideration. Although, upgrading circuit breakers in AC substation is a common practice, one needs to consider the logistics of replacing breakers in an offshore facility.

2.1.11 Coordinated operation of AC protection

Like with any system all the protection systems in the AC connected hub needs to work in harmony with each other. As the hubs are expanding the protection systems in each device needs to maintain their speed, sensitivity, selectivity, and reliability.

Protection coordination study

A comprehensive protection coordination study should be performed whenever a new device is being added to the hub. Performing this study would be challenging as the manufacturers need to consider the protection strategies of the previously installed devices. In addition, this study should consider the protection strategies that may be employed in future devices connecting to the hub. The manufacturer may perform the protection coordination study during the design phase using offline EMT simulations. The study should demonstrate the performance of the overall system in case of faults in the various parts of the AC offshore grid.

2.1.12 Offshore network protection performance

As described in Section 2.1.9**Error! Reference source not found.**, there are challenges with the AC connected hub since the network is almost entirely a power electronic based system. To overcome these challenges relays based on new fault detection techniques may be required. Therefore, in order to ensure the selected relays operate as expected, and NSWPH consortium to get confidence in the new relays, they need to be tested prior to installing in the field.

Relay testing

The most suitable method to test the relay is to perform a HIL testing using a real-time simulator. If HIL testing is to be performed, it is important to model the AC network and the devices connected to the network accurately. The care should be taken to include proper model of the CTs and VTs considering their dynamic performance, saturation, clipping etc. HIL simulation provides a closed loop simulation with the action of the relay and the reaction of the AC system for the protective action.

Alternatively, the voltage and current waveforms may be recorded from offline EMT simulations and played back to the protective relay under the test. This method is an open-loop simulation where only the action of the relay can be tested. Closed loop testing is required when the result of the protective action needs to be evaluated.

The testing of the relays can be performed during the design phase of the project in collaboration between the TSO and the manufacturer.

2.2 DC Connected Hub

All the risks identified in AC connected hub are applicable to the DC connected hub as well. However, For the following issues, the level of risk would be similar to a single HVDC monopole connected to an offshore wind farm:

- Reactive power control
- AC resonances
- Transient stability
- Offshore system harmonics

The active power control and some dynamic performance studies are performed in a different manner as described below.

2.2.1 Active power control

One of the most important tasks in the DC hub is to maintain the active power balance and DC voltage of the multi-terminal DC network The active power may have to be distributed among the multiple onshore converters based on the market requirements (economic dispatch) while maintaining the converter DC voltages within the acceptable limits. This is a new risk and the risk under steady state operation needs to be evaluated using a new study: “Multi-terminal DC power flow control study” [10].

DC grid power flow control study

The multi-terminal power flow is evaluated under intact conditions and contingency conditions (converter outages, wind farm outages, DC cable outages, etc.) for different loading conditions. At least, the extreme loading conditions (i.e. min/max loading) need to be considered. The active power and DC voltage control mechanisms of the converters need to be considered (e.g. onshore fixed DC voltage, DC voltage droop or active power control, offshore HVDC frequency control and windfarm power control). The DC voltage operating ranges and the DC cable and converter loadings need to be evaluated. It may be necessary to introduce special protection schemes such as wind farm cross tripping to avoid overloads under certain conditions. Further the maximum DC voltage that can be applied on the cables must be respected.

This study is done at the feasibility, design and operational stages using offline simulations (EMT or RMS).

2.2.2 DC resonances

When multiple HVDC converters connected from the DC side, there is a possibility of having multiple resonance frequencies in the DC network (DC resonances). Similar to the AC hub resonances, the HVDC controllers may impact (positively or adversely) the damping of these resonances. Therefore, it is necessary to perform a special study to evaluate the DC side resonances.

DC resonance study

The DC side resonances can be identified by using one of the following methods:

- Detailed EMT models can be used to identify the DC resonances. For the two terminal systems, the resonances are identified using current/voltage injection techniques. In this technique current or voltage is injected at one terminal and the resonances are identified based on current/voltage amplification. The technique has been developed for a two-terminal configuration, therefore it would be difficult to use it for a multi-terminal system. Therefore, the resonances may have to be evaluated using small disturbance such as set point changes. However, it is difficult to capture all the resonance and the damping.

- A systematic approach would be to perform an Eigen analysis of the DC hub. Similar to the small signal stability analysis described in Section 2.1.1, the linearized model of the system is obtained, and the oscillatory modes and the damping is evaluated using Eigen values. The study shows all the oscillations in the system including controller modes, DC resonances and AC resonances. The DC resonances can be identified using the Eigen properties such as participation factors. The DC network electrical variables such as DC currents and voltages contribute most to the DC resonances. The locations of the DC resonances (i.e. most significant contributions of the DC cables, converters and controllers) can be identified from the participation factors.

If there are low damped resonances, it would be necessary introduce mitigation measures such as changes to the DC circuit (e.g. MMC converter, DC reactor changes) or damping controllers may have to be considered.

The DC resonance studies need to be performed at the feasibility stage (high level) and design stage (detailed) using offline simulation tools. Real time simulation tools such as HIL can be used for verification purposes, but it is optional.

2.2.3 DC fault detection and clearing

The most challenging task of the DC hub compared to the AC hub would be handling DC faults. The fault detection depends on the complexity of the multi-terminal DC system and the fault clearing depends on the availability of the equipment such as fast DC breakers. Furthermore, limiting the fault currents through the converters during the fault would be a challenge. Therefore, special DC fault study need to be carried out in addition to the dynamic performance studies.

DC fault study

A detailed representation of the DC hub including HVDC converters and controllers, DC breakers and DC cables would be required for the study. The DC faults at different locations are simulated and the fault clearing performance is evaluated. When the system is well designed, the DC fault clearing logic should be able to isolate the fault part (cable or converter) and to restore the rest of the system back to normal.

Considering the complexity of this study, HIL simulations with actual control hardware would be the best choice. Otherwise, the validated models (to the actual hardware) can be used in offline EMT simulations. Communication delays need to be included in the models. This study would be performed at the feasibility phase by TSO and at the design phase by the manufacturer.

2.2.4 Coordinated operation of DC protection

Coordinated operation of the DC protection is critical for the reliable operation of the DC connected hub. This can be challenging because the DC hub is going to expand over time and protections schemes from different vendors will be present. Furthermore, there may be communication requirements between different protective elements. For example, in order for the backup protection to operate, a breaker fail signal may be required [4]. To verify the coordinated operation of the DC protection a DC protection coordinated shall be performed.

DC protection coordination

A comprehensive protection coordination study needs to be performed whenever a new device is being added to the hub. Performing this study would be challenging as the manufacturers need to consider the protection strategies of the previously installed devices. In addition, this study should consider the protection strategies that may be employed in future devices. The manufacturer typically will perform the protection coordination study during the design phase using offline EMT simulations. However, due to the complexity of the system and speed of detection and operation required from the protection an HIL testing would be most suitable. The study would demonstrate the performance of the overall system in case of faults in the various parts of the DC offshore multi-terminal system.

3. Operational Studies

Once an HVDC link is in service a number of studies are required during its lifetime. In this context these studies are referred to as Operational Studies. These include studies related to the addition of new HVDC links to the hub and studies related to changes to the onshore or offshore network (other than new HVDC links). In addition, it is possible that the services provided by the HVDC link need to change during its lifetime due to changes in the network or market requirements. For example, a link originally built for wind power integration can later on serve as an interconnect between two countries or a supplier of ancillary services. To be able to make such changes a number of studies will be required. The following sections discuss the required studies in each case and whether an offline or HIL study is preferred.

3.1 Addition of New HVDC Links

The wind power hubs will be developed gradually and HVDC links will be installed over a time period of possibly decades. Every time a new HVDC link is planned to be added to a hub, studies need to be performed to ensure the performance of all the previously installed HVDC links is still satisfactory and is not impacted by the addition of the new DC link.

3.1.1 Control and protection studies

The studies related to the control and protection were discussed in the previous chapter of this report. There is a possibility to do all these studies using *offline* EMT simulations. However, the detailed models validated to the actual hardware and the actual control and protection functions is necessary. For this, a proper validation procedure needs to be implemented and the procedure need to be repeated every time when there is a change in the system such as controller parameter change. Most control and protection studies can also be done using *HIL*. The studies should be performed either by the *TSO* and/or the *manufacturer* of the new link, however, the TSO owning the exiting HVDC link should be fully involved in the studies.

3.1.2 Over-voltage and over-current stresses study

The voltage and current stresses of the existing HVDC links are affected by the installation of a new link. There is a risk that the equipment over-voltages or over-currents or arrester energy levels exceed the design limits. Therefore, some of the design studies of the existing links need to be checked or repeated to ensure the equipment stresses remain within the design limits. For both AC connected and DC connected hubs the insulation coordination and short circuit current stresses of the existing HVDC links are affected by the addition of the new link. Therefore, these design studies need to be reassessed. These are normally *offline* studies and should be done by the *TSO at the planning stage* of adding the new link and repeated by the *manufacturer at the design stage*. Further, similar to an AC network where a new HVDC system is added the specifications must be clear not to exceed the existing arrestor energies or the design stresses of the existing equipment.

3.2 Changes in the Onshore or Offshore Networks

Both onshore and offshore networks are expected to change during the lifetime of the HVDC links. There is a risk that the system short circuit level goes below or above the design level as a result of these changes. When the installation or the retirement of major equipment causes a significant change in the system strength at the HVDC terminal, a short circuit study should be performed to ensure the system strength is still within the design limit. The study is normally done *offline by TSO*.

There is a risk of control interaction with the newly installed dynamic devices such as wind farms or power-to-gas converters. Every time a new dynamic device is installed in the vicinity of an existing HVDC terminal an interaction study needs to be performed. The study is described in section 2.1.4 above.

In both AC and DC connected hubs the controls may include a master controller supervising the wind farms and HVDC links. When a new HVDC link or wind farm is installed the master controller needs to be updated. There is a risk that the changes to the master controller cause incorrect operation in any part of the hub. The modifications to the master controller therefore need to be tested in simulation, either offline or in a HIL setup, to minimize this risk. This study should be performed by TSO either offline (if validated models are available) or using HIL arrangement.

Changes to the AC networks may also affect the equipment stresses. If other studies indicate a risk of excessive stress on any equipment the studies mentioned in section 3.1.2 need to be performed to mitigate the risk. The studies are performed by the TSO.

The continued evolution of the power systems and replacement of the conventional power plants with renewable energy resources may even require the control philosophy of the HVDC to be changed during its lifetime. In this case a complete set of control and protection studies (as described in chapter 2 of this report) need to be performed. The studies should be performed by TSO at planning stage and then repeated by the manufacturer in design stage before being implemented.

3.3 Software Updates

During the lifetime of the HVDC link there will be a number of occasions that the control and protection or other software need to be updated.

3.3.1 Control and protection software

The control and protection software are required to be updated during the link's lifetime as a result of the operational experience, changes to the market drivers, changes to the grid code etc. In particular, investigation of faults and other events happening during the lifetime of the HVDC link may show the need for changes to the control and protection software. There is a risk that the updated software does not perform satisfactorily under all operating conditions. Therefore any change to the control and protection software should first be tested before it is uploaded in the actual control system. In a two terminal HVDC system, the system itself is not complex and the magnitude of the study is not typically complex. However, in this case the system is complex and the complexity of the study will depends on the magnitude of the change and how far the study should go.

Most changes can be simulated in an offline EMT environment (if the validated vendor models are available), however an HIL simulation is more effective. If an HIL simulation setup (i.e. control and protection replica connected to real time network simulator) is available the exact same changes to the software can be easily made to a replica and the impact on the operation is tested. The risk of control and protection maloperation would be greatly reduced once the software changes are tested. The control and protection software changes and the required studies may be done by TSO or by the manufacturer. However, this depends on how long the system has been operational. Meaning, is the change is an upgrade from the manufacturer or it is due to the TSO’s new requirements.

3.3.2 Other software

The HVDC system utilizes many devices such as the HMI computers, gateways and routers, firewalls, transient fault recorders, computers, communication devices, recording devices etc., each of which containing several software. The developers of these software continuously issue patches and updates to their software. There is a risk that installing any of these software updates cause HVDC system to operate incorrectly or trip. To minimize this risk the software updates must be tested prior to installation in the real system. The testing can be most easily done on a control and protection replica in a HIL set up provided that the relevant device is included in the replica. If the replica is not available or the relevant device is not part of the replica, the updates should be installed on the real system, one control and protection lane at a time, and when the HVDC is lightly loaded so that a pole trip does not cause a large disturbance to the AC systems.

4. Modelling requirements during different phases – with and without HIL

As described in this report, from the pre-feasibility to operational, a series of studies/evaluations need to be done. These studies require most accurate representation of the existing devices as well as the device being studied. A high-level illustration of the modelling requirements is shown in Figure 4-1. The modelling requirements at each study phase are as follows.

4.1.1 Feasibility and Specification Phase

At this phase the manufacturer of the planned project is not selected yet and therefore, the detailed models of the device being planned are not available. Therefore, the studies need to be performed using generic models but with detailed representation. The details of the expected electrical circuit and the generic control and protection functions similar to the manufacturer models can be used. For the existing devices, validated software models or hardware replications need to be used.

- If the HIL path is selected, the generic model of the planned device (software based) needs to be coupled with HIL model of the existing system. Note that, there are many studies at this stage that need to be performed using offline simulations and therefore, the validated software models (offline) of the existing projects are still required.
- If it is decided to move forward without HIL approach, all the studies need to be done using a generic model of the planned project and the validated models of the existing systems.

4.1.2 Implementation Phase

After award, the manufacturer has to start the studies using a software model. This stage is identified as design phase. Therefore, validated software models of the existing system would be sufficient. If the HIL path is selected, a software version of the OEM model can be combined with the existing HIL system. This stage contains a large amount of manufacturer studies to determine the best parameter set for the planned project. Therefore, from the manufacturer's perspective, the offline simulations would be preferred. Based on the outcome of these studies, the C&P hardware and software and the replica (if required) are developed.

In the second stage called Factory Performance Testing (FPT), further studies are performed using the developed C&P hardware and software. The existing system can be represented using validated software models of the existing system (no HIL path), alternatively the C&P replicas of the existing system can be used in a HIL arrangement. For the project under consideration the actual C& P cubicles will be used. One advantage of having a replica is that once the actual C&P hardware are shipped to the site the factory testing can be continued using the replicas. This will help achieve a shorter project planning timeline. The purpose of testing in stage is to demonstrate performance and optimize parameters. The testing performed in this phase is important for the tests to be performed during commissioning One major advantage of the HIL path is that the replica can be used during the commissioning for performance verifications and trouble shooting. This is very important for bug fixing as well as for model validation (an automatic field validation).

Once this stage is completed, it is necessary to develop the validated software models regardless of the availability of the hardware replicas. The model needs to be validated against the FAT test results as well as some of the commissioning tests. It is recommended to define a minimal set of validation tests by the TSOs.

4.1.3 Operational Phase

At the operational phase, either validated software models or the hardware replicas can be used for the studies depending on the nature of the studies and the availability of the HIL.

4.1.4 Requirements for validated software models

Regardless of the use of HIL simulations with C&P replicas, the validated software modes in both real time (e.g. RTDS) and offline (e.g. PSCAD) are required as described in the above sections. These models should have enough flexibility to be used by TSOs and other manufactures while securing IP rights of the manufacturer. In order to evaluate the power, voltage and frequency handling capabilities of the AC and DC hubs, at least the following control concepts should be visible (i.e. not black boxed) for all the parties:

- Master control concept and the signals transferred among master controller and the devices
- Higher level controls associated with offshore grid voltage and reactive power (e.g. HVDC converter voltage/reactive power controller and wind farm power plant controller)
- Higher level controls associated with offshore grid active power and frequency (e.g. HVDC converter grid forming control concept and wind farm power plant controller)
- Multi-terminal DC voltage/active power control concept of DC hub converters
- DC fault clearing logic of DC hub converters (a clear description of the concept used)
- Protection coordination of converters and wind farms (a clear description)
- Any special protection schemes associated with converters and wind farms

Usually, most of the proprietary information are associated with the low-level controls and therefore these IP rights can be still secured by black boxing these components.

The visibility of the high-level control concepts of the projects would be a new requirement based on the complexity and interoperability of the hubs. Therefore, it is necessary for TSOs to clearly identify these requirements and define in their specifications.

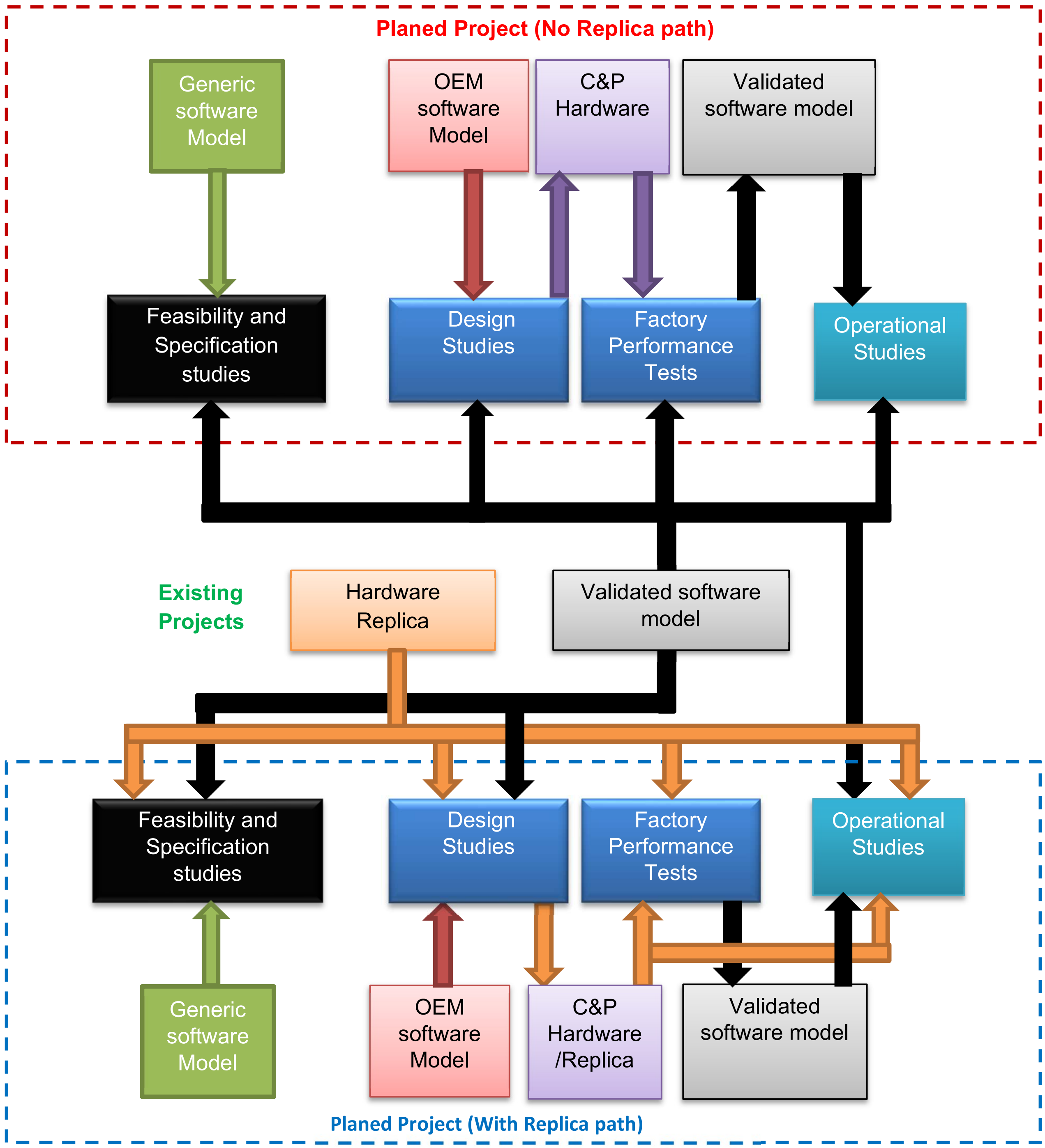

Figure 4-1: Model requirements with and without Hardware replica models

5. Hardware In the Loop Simulation Requirements

Hardware in the loop simulation is necessary for the factory acceptance testing of the control and protection. The objective of these tests are two folds: to ensure the correct assembly, connections and functionality of the control and protection hardware; and to test the functionality of the software. Traditionally in FST/FAT the control and protection cubicles of the new HVDC system are connected to a real time power system simulator. The wind turbines and other HVDC links in the hub are modeled in software within the real time power system simulator. To achieve good accuracy, the software models of these devices must represent the actual systems as closely as possible. This requires detailed real time models developed by the manufacturers of the devices. The models must be maintained to remain compatible with the real time simulator. Each model should also be updated every time a modification is made to the actual device. The detailed models require significant resources from the real time simulator.

Alternatively, a control and protection replica can be purchased with each HVDC project. All the replicas are connected to the same power system simulator where the remaining parts of the AC and DC network are modeled in software. This setup can also be used to perform many of the studies discussed in the previous sections.

5.1 Advantages and disadvantages of HIL studies

As discussed earlier, almost all studies required for de-risking can be done offline. To achieve the de-risking objectives however the models used in offline simulation must be verified against the actual hardware. The models must be updated every time there is a change to the actual system hardware or software. They should also be updated to make sure they are compatible with the latest version of the simulation platform (e.g. PSCAD). Clear guidelines should exist to ensure models developed by various manufacturers are compatible and can be used together.

The main disadvantage of performing the studies in a HIL setup is the cost. A replica of the control and protection system must be procured and maintained for each HVDC link. Large size real time simulators and other facilities must be acquired, and trained staff must be hired. Further details on the requirements are given in the next section, for now it is important to note that the capital expenses and operation costs of a real time simulation laboratory is significant. It should also be noted that the control and protection hardware typically need to be replaced every 15 to 20 years. Every time the C&P cubicles are replaced the replica also needs to be updated. This is an additional cost that should be considered in cost evaluation.

The main advantage of performing the studies in a HIL setup is the increased accuracy due to the detailed representation of C&P. The control and protection hardware and software in a replica are identical to the real system and the simulation results are the closest to the reality. It is true that some manufacturers create offline models using the same software (e.g. C code) as used in the real control system. However even for these cases there are parts of the control and protection system such as the communication delays, analog to digital conversion, saturation and limits of on-board current transformers, anti aliasing filters and other details that are typically not included in the offline model.

The HIL setup has a clear advantage for testing software updates and patches as described in section 3.3.2. However, it should be noted that the replica does not include all devices in a real control and protection system. Therefore the use of HIL setup for this purpose is limited to the devices included in the replica. In the absence of a replica the software updates and patches have to be tested on the real system. Considering the close interconnection of the HVDC links in a hub, there is a risk of multiple outages when such tests are done. The number of updates and patches issued for various devices is high and they need to be installed frequently. The risk of an issue occurring during the installation is therefore considerable.

Even if an HIL test facility is available it is sometimes necessary to use software models for other HVDC links connecting to the hub. This may happen when the time between two HVDC projects connecting to the hub is short. At the time of studying or testing one HVDC, the cubicles of another HVDC may still not be available for HIL.

5.2 HIL lab requirements

The backbone of the real time simulation laboratory is the real time simulator. The cost of the hardware is considerable and significant effort is required to make the models of the power system. It is therefore costly to switch from one type of real time simulators to another after the lab is established. The owner must make a strategic decision on selecting the supplier of the real time simulator.

There is a continuous need for developing new models or improvements to the existing models for various devices. There should be sufficient expertise in the lab and/or close relations to other knowledge centers to allow for this development.

The venue should be expandable as the number of replicas and simulation facilities increase. There should be provisions for keeping replicas from various manufacturers securely separate from each other while they are all connected to the same simulator. Physical and cyber security of the facilities are of utmost importance, however there should be facilities for the owners of the replicas to connect and run simulations remotely.

Although it is a fact that many TSOs and utilities have successfully integrated and operated point to point HVDC links without the need for replicas and real time digital simulation facilities, the situation we are facing here is different, whether it is the AC hub or the DC hub. Both need careful consideration of their complexities. For example if we consider the existing multi-terminal HVDC systems in operation, non of them are of the same magnitude and non employ DC breakers. Therefore, it is important to think of the HIL in this context.

5.3 Recommendation

The North Sea wind power hub consists of multiple HVDC systems, many wind farms and possibly hydrogen generation facilities. The HVDC links utilize bipolar configuration and submarine cables at very high DC voltage. Both DC connected and AC connected hub concepts require sophisticated control and protection methods, many of them being used for the first time. The HVDC links, wind farms and other devices are closely tied to each other and therefore their performances are affected by each other. The maloperation of each element of the hub is likely to affect the others and in the worst-case scenario can cause the loss of a large amount of energy supply to the network.

Considering the level of complexity, close interaction of large converters and the impact of loss of the hub, it is reasonable to study this system in the most accurate way possible. In particular, in the study of each HVDC system, other HVDC links should be represented as detailed as possible. For this reason it is our opinion to establish an HIL lab for real time simulation as described above.

6. Conclusions

A number of risks related to the control and protection of the NSWPH were identified and studies for minimizing the risks were proposed. For each study it was determined which party should perform the study, at which phase of the project the study is performed and whether it should be performed offline or in HIL setup. Tables 1 and 2 below present a summary of these findings.

Table 1 - Control risks and studies

	Risk	Study to perform	Phase	Performed by	HIL
AC Connected Hub					
1	Reactive power coordination	Reactive power study	Feasibility; Design; Operation	TSO; manufacturer	No
2	Load flow and control	Steady state study; Transient and frequency Stability of offshore system ; small signal stability	Feasibility; Design; Operation	TSO	No
3	Resonances	Network Resonance Study of the offshore network	Design; Operation (when the next HVDC is designed)	TSO; manufacturer	Both, designed offline and tuned with HIL
4	Control interactions	Interaction study (EMT; small signal analysis; etc.)	Design; Operation (when the next HVDC is designed)	TSO; manufacturer	Both, designed offline and tuned with HIL
5	Transient stability	Transient stability	Feasibility; Design; Operation (when the next HVDC is designed)	TSO; manufacturer	Optional (offline EMT study at the feasibility and design stages, possibly HIL at operational phase)
6	Dynamic performance	DSP	Design	Manufacturer	Optional
7	Harmonic performance	Harmonic study	Design; Commissioning (field measurement)	TSO + manufacturer	No
8	Inter-operability	Inter-operability performance evaluation	Design; Commissioning	TSO + manufacturer	Yes
DC Connected Hub					
1	All risks and studies mentioned for AC connected hub are applicable to DC connected hub too.				
2	Active power control	DC grid power control study	Feasibility; Design	TSO; manufacturer	No

3	DC resonances	DC resonance study	Design	manufacturer	No
4	DC power flow	DC power flow study	Feasibility; Design	TSO; manufacturer	No

Table 2 - Protection risks and studies

	Risk	Study to perform	Phase	Performed by	HIL
AC Connected Hub					
1	Offshore AC Fault detection	AC fault study	Design	Manufacturer	Optional
2	AC breaker missing zero crossing	AC breaker study	Design	Manufacturer	No
3	Coordinated operation of AC protection	Protection coordination study	Design	Manufacturer	No
4	Proper operation of the overall offshore network protection	Relay testing	Design	TSO + manufacturer	Yes
DC Connected Hub					
1	Fault current, time to clear the fault, selectivity	DC fault study	Feasibility; Design	TSO; manufacturer	Optional
2	Coordinated operation of DC protection	DC protection coordination	Design	Manufacturer	Optional

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