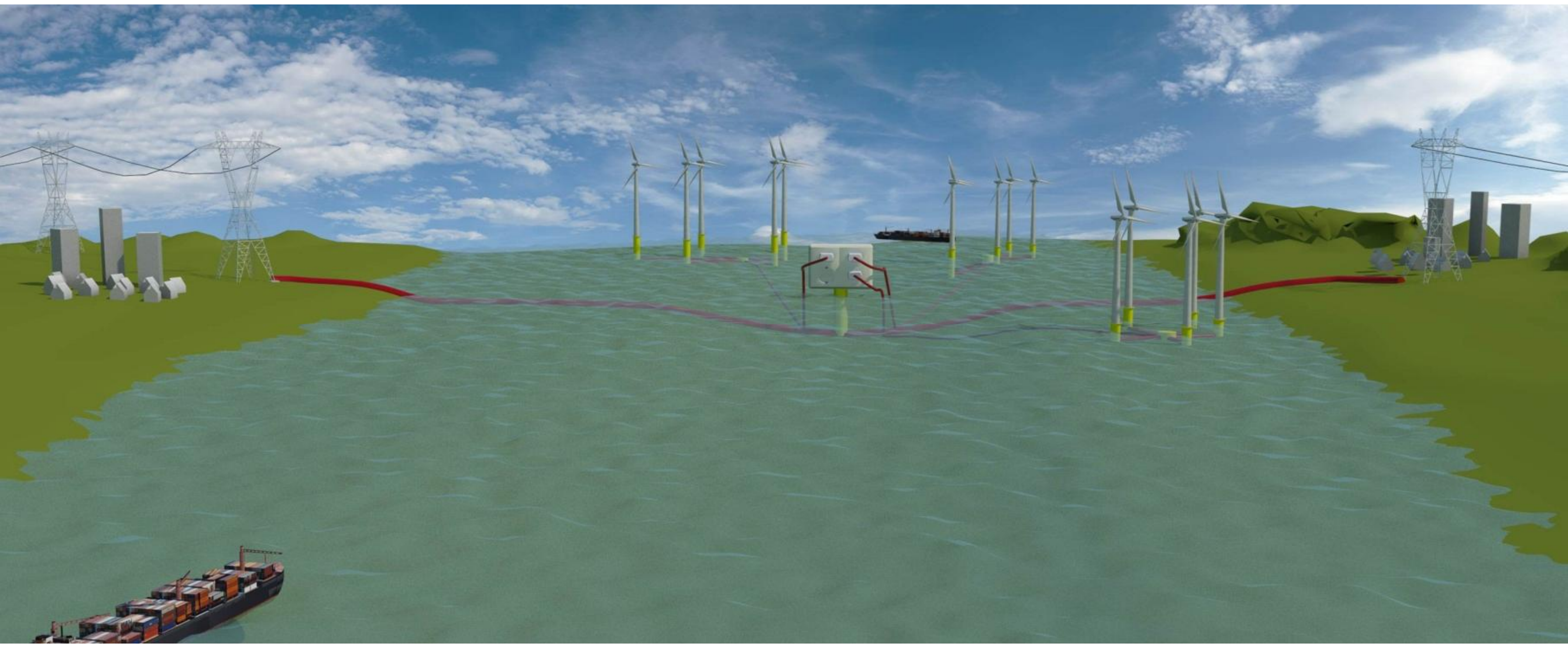
< DOCUMENT ECN-O--16-052>

TKI WIND OP ZEE

TKI Wind op Zee - Synergies at Sea

Sub-Project 1, Phase 2: Design study of a combined infrastructure for offshore wind and interconnection



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Preface

This report is part of the project Synergies at Sea. Synergies at Sea is conducted by a consortium that examines technical solutions, necessary changes to international legislation and regulations and new financing models. The consortium comprises eight members: Nuon/Vattenfall, ECN, Royal HaskoningDHV, Groningen Centre of Energy Law of the University of Groningen, Delft University of Technology, DC Offshore Energy and Energy Solutions, and is coordinated by Sweco.

The Synergies at Sea project has started in 2013 and will be finished in 2016. It comprises the following sub-projects (SPs):

- SP1 UK-NL Interconnector: Feasibility and Design study on the Offshore Wind Interconnector
- SP2 New Financial Structures and Products
- SP3 Regulatory Framework
- SP4 Distributed Temperature Sensing
- SP5 Value Engineering

The research for Synergies at Sea is carried out within the scope of the Top Sector Energy. The Top Sector Knowledge and Innovation - Offshore Wind (TKI-WoZ) leads the research, innovation and implementation activities concerning off shore wind technology, for the industry (small and medium sized enterprises) in the Netherlands. The aim is an effective cost reduction of 40 % for offshore wind as well as reinforcing the economic activities in the Netherlands, ensuring the international leading position of the Dutch offshore wind sector. The current project is part of Research and Development (R&D) line 3 of TKI-WoZ "Internal electrical network and grid connection".

This report contains the final results from the design study of a combined infrastructure for offshore wind and interconnection, which has been conducted by ECN and TU Delft,

Acknowledgement

We like to thank the Energy Technology Department of Aalborg University, Denmark for providing us the opportunity to conduct tests at their Power Electronic Systems Section laboratory facilities, and Professor Remus Teodorescu, for his supervision and collaboration.

The work has been performed within the project “Synergies at Sea” (TKIW01008). This project is supported by the Dutch Ministry of Economic Affairs through the R&D program “TKI Wind op Zee” under contract TKIW01008. The opinion expressed by the authors does not necessarily reflect the position of the Ministry of Economic Affairs, nor does it involve any responsibility on its part.

Summary

This report of Sub Project 1 of the Synergies at Sea project, presents the results of the design study of an interconnection between the United Kingdom (UK) and the Netherlands (NL) via two planned offshore wind farms.

Feasibility study results

This design study has been conducted in parallel with the reported feasibility assessment, **Report 1** which concluded that 'integrated solutions', where wind farms are connected to an interconnector are technically and economically feasible. The two most favorable scenarios have been used as a starting point for the system design.

Two scenarios were found to be substantially beneficial for private investors as well as for society, cf. Figure 1-1:

1. UK4, consisting of an High Voltage Direct Current (HVDC) connection between a 900 MW wind farm in the UK to the Dutch grid, and
2. UK-NL7, consisting of an HVDC connection between a 900 MW UK wind farm to a 900 MW Dutch wind farm.

Compared to separate wind farm connections and an additional interconnector, these integrated scenarios show additional net societal benefits over the lifetime, as well as sufficiently high benefits to a private investor.

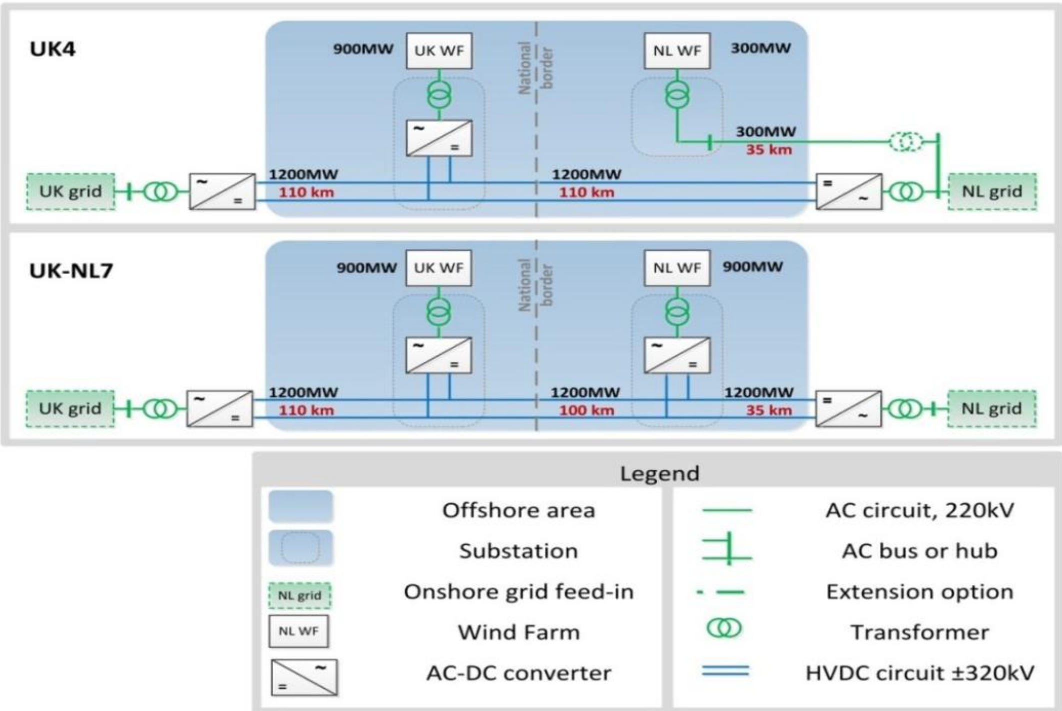

Figure 1-1: Two most attractive scenarios

Technology selection

Both scenarios apply High Voltage DC (HVDC) technology in a multi-terminal configuration (MTDC). As elaborated in **Report 1**, HVDC technology is required for at least one section of the interconnection as the Dutch and UK grid are not synchronized. Within several HVDC converter technologies only Voltage Source Converter (VSC) technology is feasible for offshore application, i.e. to connect offshore wind farms.

Another advantage of HVDC-VSC technology is its capability to support the onshore grid, through voltage and frequency control, back start, etc. Also the harmonics emission levels of VSC are relatively low. Therefore VSC does not need additional provisions to comply with the grid codes in both the UK and the Netherlands. The HVDC VSC interconnecting link might even be used to increase frequency stability in the UK, although the design of such frequency support concepts, are beyond the scope of this study.

Although in the feasibility study it was already concluded that the preferred scenarios are technically and economically feasible, a number of technical challenges remain, which have been addressed in this study:

Challenge 1: Modelling of MMC-type converters

Multilevel Modular Converters (MMCs) have several distinct advantages over 2-level VSCs or classical Line Commutated Converters (LCCs). However these converters are more complex both in construction and control. In order to apply MMCs in system design, models that capture all the important operation modes need to be developed. For this study, these models should accurately represent their behavior with respect to losses, dynamics and protection. Also these models should be easy to parametrize and should be computationally light.

Challenge 2: System design – protection concepts

DC fault protection is a very challenging task for the realization of MTDC networks. As a result, different fault detection, isolation and grid restoration techniques need to be investigated. In general, protection techniques can be summarized in four main categories, as shown in Table 1-1, summarizing their main application areas with advantages and disadvantages.

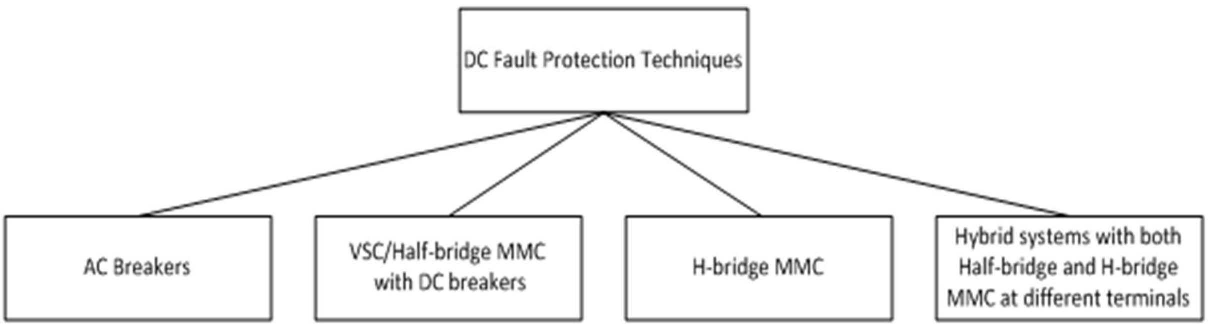

Figure 1-2: Different DC fault protection techniques.

Table 1-1. Application and advantages of different protection techniques.

Protection concept	System application	Advantage	Disadvantage
Half-bridge MMCs with AC Breakers	Point-to-point and small HVDC systems up to 4-5 terminals	No additional capital investment	Shutdown after DC fault
Half-bridge MMCs with DC Breakers	MTDC networks	Fast dc fault isolation and selectivity	DC Breaker costs
Full-bridge MMCs	MTDC networks	Inherent fault blocking capability; STATCOM operation during DC faults	Full-bridge MMC more expensive
Hybrid systems: Full-bridge MMCs onshore and Full-bridge MMCs offshore	MTDC networks	Selectivity at sensitive lines; STATCOM at weak ac grids and optimization of capital costs	

Note: Full-bridge MMCs are also denoted ad “H-bridge” converters, where “H” represents the topology of the modules, each with 4switching arms.

Besides the evaluation of these concepts, a methodology for the design of dc limiting reactors, as well as for the dc fault ride-through in a given system has been proposed. The developed converter and grid models have been implemented on down-scaled MMC models to validate the proposed methodologies and to evaluate the response of the DC grid to different type of contingencies.

Another important aspect in the operation of HVDC grids is controllability of converters during grid contingencies. More specifically, in this study we investigate the operability of MMC converter stations as STATCOMs during a DC fault. If a converter station is isolated from the rest of the dc grid due to a fault on the connected line, this converter station should be able to continue operation and provide support to the connected AC grid for as long as the line is repaired, until power flow can be restored.

Challenge 3: System design –DC-hubs for modular DC-grid expansion

Active DC-hubs, which are essentially multi-terminal converters, can become a key element for modular DC-grid expansion and interoperability between different voltage levels and vendor technologies.

Results

The operation of the MMC was analyzed and both time-averaged models, as well as full switching models with different control schemes were developed. The developed mathematical models of the converters were integrated into an MTDC network including more than 3 terminals. For this purpose, the dc cables were modelled as series connected pi-sections and thus, the DC grid was modelled based on state-space equations. At present, the mathematical model is able to describe accurately both normal and DC fault operation of different grid topologies. More specifically, results were obtained and compared for symmetric monopole and asymmetric monopole configuration with metallic return. The mathematical model was also verified when compared to equivalent Simulink models for all operation modes.

Regarding the system design, the DC fault ride-through performance of different MMC technologies (half-bridge and H-bridge) was evaluated and the STATCOM operation of the MMC during DC faults was also investigated.

During a research visit of 4 months at the Energy Technology Department of Aalborg University (AAU) the MMC models and MTDC system designs have been successfully verified in Grid Integration Lab of the Power Electronic Systems Section. For practical reasons MMC modules built at UAA were applied in these tests, however, the control algorithms developed at TU Delft were applied in these MMC modules and also at system level.

Conclusions and future work

The integrated solution of offshore wind farms feeding in to an interconnector can be implemented using MMCs, creating a multi-terminal DC grid. This is based on the technical capabilities of the MMCs, as well as on the verified MMC models and the design and operation of the MTDC system.

From the different protection solutions have been evaluated, the AC protection solution is the most cost effective, however limited to 4-5 terminals and a power level of typically 1500 MW, depending on the grid stability requirements in the connected countries. A combination of offshore half-bridge MMCs and full-bridge MMCs onshore promises to provide a good trade-off between costs and technical capabilities.

Future work planned until September 2017 within the PhD project of Minos Kontos at TU Delft is to develop multi-terminal DC hubs based on MMCs, addressing Challenge #3.. Key aspects are to define its functionality (versus costs) and resulting design specifications, to model these DC-hubs and apply these in system design.

Contents

1 Introduction

1.1 Background

With the growth of offshore wind the need for offshore electricity transmission grid expansion arises, including transnational links to support an increase in cross-border electricity exchange. This expansion is also a pre-requisite for market integration towards a single, more efficient European electricity market, leading to cost and emission reduction. The benefits of more interconnection capacity between North Sea countries, e.g. between The Netherlands and the United Kingdom, as well as coordinated offshore grid development, have been identified in several grid studies[1], [2].

By building interconnections between offshore wind farms in different countries, the offshore electrical infrastructure can be used both for wind power export and for cross-border trade. The average load of dedicated offshore wind grid infrastructure, which is typically 40% to 50%, offers room for additional electricity transport and thereby more efficient utilization. Electricity can be traded to neighboring countries via the same infrastructure and for the offshore wind farms there is a redundant connection to shore. This helps to lower average electricity prices in Europe and could lead to a higher turnover of the wind farm and lower risk of power loss, reducing the needed amount of government support for offshore wind.

1.2 Feasibility study

This report focuses on a number of major technical challenges of designing integrated solutions of offshore wind farms and interconnectors. This study complements the feasibility study that has also been reported in the Synergies at Sea project, see **Report 1**.

The feasibility study of an interconnection between the United Kingdom (UK) and the Netherlands (NL) via two planned offshore wind farms focused on economic, regulatory and technical aspects. The main conclusion is that 'integrated solutions', where wind farms are connected to an interconnector are technically feasible, and in particular cases lead to significant societal benefits, while solving regulatory issues was considered as main priority. All integrated solutions were compared with the related 'stand-alone solutions' in which the same amount of offshore wind is installed, but connected directly to the land network, and not to the interconnector.

In total 17 scenarios have been defined and evaluated. With respect to the technology choice and characterization of these scenarios an extensive technology review has been conducted. In this review the technical feasibility was assessed, and technology challenges and development needs were identified, both for the short term (before 2020) and long term (until 2030), see **Report 1, Appendix B1** and **Publication 6**.

The feasibility also included a comparison between different rated capacities sections of the offshore transmission system sections, considering losses, reliability and effects on the connected markets. Despite the limited number of studied variants, it has resulted in a good insight in proper sizing of the offshore transmission system to obtain maximum net revenues.

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1 www.northseagrid.info

2 www.offshoregrid.eu

1.3 Design study scope

Starting point is the set of the most favorable scenarios that have been identified and analyzed in the feasibility study, see Figure 1-1. These scenarios have been selected, based on an assessment including technical, regulatory and (socio-)economic aspects.

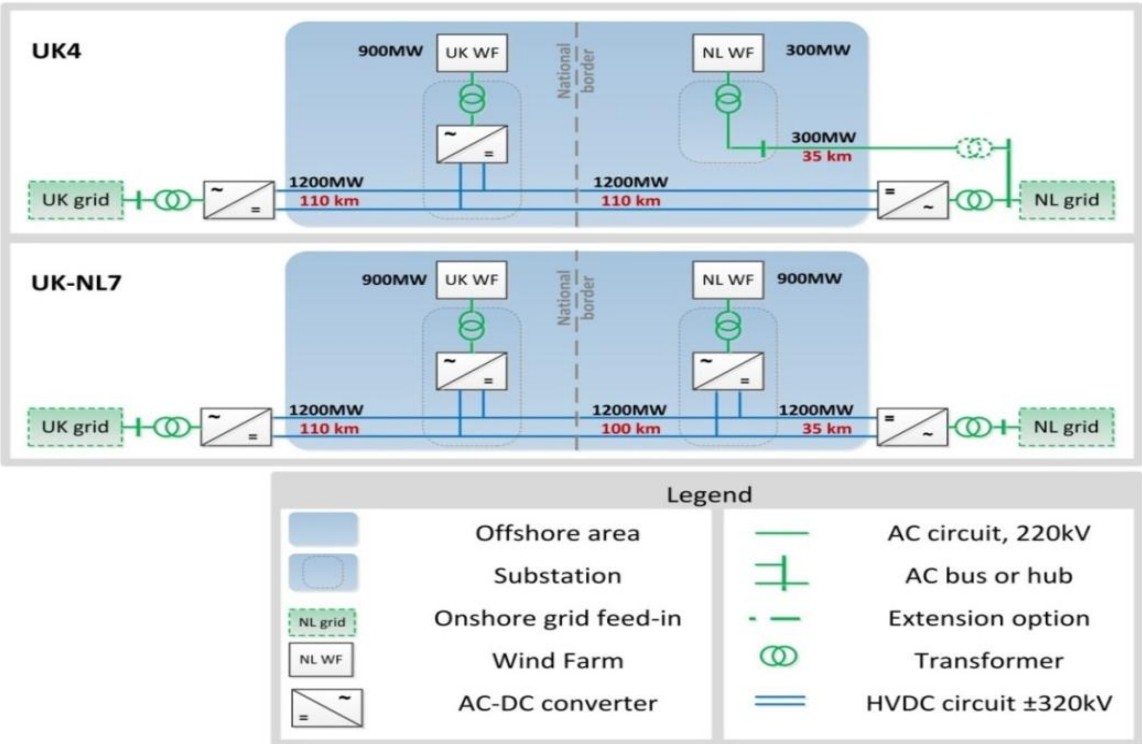

Figure 1-1: Two most attractive scenarios

1.4 Technical challenges

Concerning the transnational offshore grid realization, it can be concluded from the technology review that several technological limitations need to be overcome first. More specifically, high power ac cables cannot yet transmit sufficient power over long distances. Moreover, AC technology cannot be applied to interconnect a-synchronized networks.

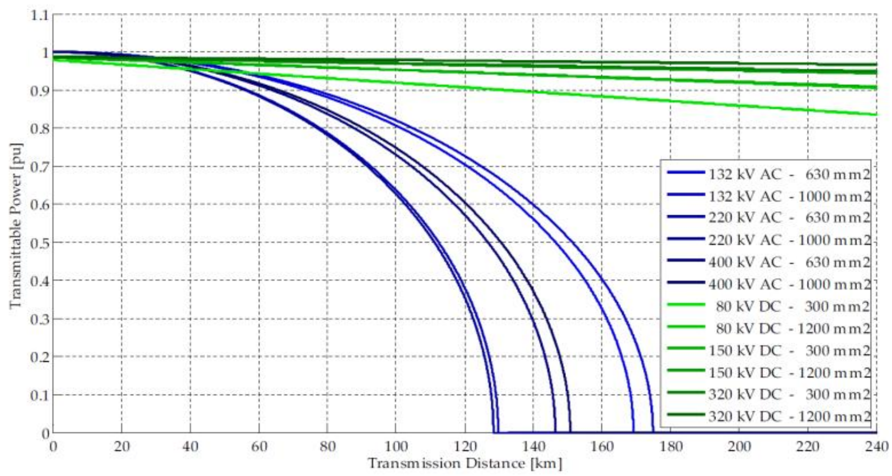

Figure 1-2: Maximum transferrable power as a function of transmission distance.

On the other hand, applying DC technology, in particular Voltage Source Converters (VSC) requires complex multi-terminal DC (MTDC) transmission networks based on control and protection concepts and equipment that are not yet available on the market. Also most VSCs are based on 2-level switching concept, while Modular Multilevel Voltage Source Converters (MMC), which are more efficient and can be deigned to block DC faults, are more complex and also less mature.

Alternative DC technologies, involving Current Source converters (CSC), possibly in combination with VSCs have been considered, combining the advantages of both converter technologies, e.g. on protection and multi-terminal concepts. However networks based on CSCs lack bi-directional power flow capability and have therefore not been studied further.

Furthermore, stepwise extension of DC grids poses significant technical challenges as the complexity rapidly increases with the number of nodes and branches and with the power levels, and technologies of different suppliers are not yet compatible, i.e. no inter-operability.

Summarizing, the main technical challenges of this study are to model, design and verify:

1. MMC models that accurately represent losses, dynamics and protection characteristics
2. Control and protection concepts of MTDC-VSC networks based on MMCs
3. Modular MTDC-VSC design concepts, for stepwise development towards large, meshed offshore DC grids

As challenge #3 is very extensive, a specific key-aspect of an active DC-hub was selected.

1.5 Report structure

The next section 2 addresses the modelling of MMC-VSCs and optimization of their internal topology and control settings.

Section 3 presents and assesses different protection solutions for MTDC grids based on MMC-VSCs, including an optimization of the DC grid design.

Section 4 presents and assesses additional functionality of MMCs within a MTDC grid, providing continued support of the AC grid during DC faults.

Section 5 presents the DC-hub concept with the proposed approach for its development in the course of 2017 as part of the PhD project.

Section 6 summarizes the main results and their implications for system design, including the estimated cost savings.

2 HVDC connection modeling

2.1 Motivation

HVDC connections are more and more based on the advance of power electronic converters and especially the multilevel modular converter (MMC) technology. Due to the high number of elements involved in the design and the complex control structure, a lot of research is done on the optimization of the design and control parameters of such converters. The design optimization of MMC converters creates the need for fast and computationally light modelling approaches. Moreover, at the same time, models need to be accurate enough to reflect the impact of different parameters in reality. Depending on the design parameter under consideration, different models have been developed, trying to address the trade-off between accuracy and computational speed.

2.2 Modelling approaches

The most common way of modelling the MMC is by using a software platform like Matlab/Simulink or Electromagnetic Transient Simulation Programs, such as EMTP/PSCAD. The main advantage of such software is that it offers ready-made blocks to simulate the switches and the main converter components, as well as it also provides the solvers to solve the admittance matrices of the simulated system. Also, by modelling each component, the user has all the available information of the design and can inspect the impact of any change in the system immediately. On the other hand, the main disadvantages stem from the inability of the user to change all the parameters of the components and are limited to the tunable parameters of the ready blocks. Moreover, the models become very computationally heavy when increasing the number of levels in an MMC. As a result, most of the performed studies so far use small number of levels as proof-of-concept and the simulation of full-scale HVDC converters is nearly impossible.

2.3 Selected approach

The grid is split into parts which are analytically modelled independently. Depending on the configuration of the dc grid and thus, it can describe any grid topology under all operational conditions. The difference to already described analytical models is that the proposed model does not assume a steady dc voltage equally distributed among the upper and lower arms. Moreover, the full switching operation is simulated using the equivalent Thevenin circuit for each submodule. At the same time, state-space equations are used to describe both normal and dc fault operation of the grid, by applying different matrices depending on the operational state. As a result, there is no need for complex equations to describe the contribution of each fault current source in the grid.

The main modelling assumption was made regarding the ac transformer representation. This representation is sufficiently accurate for normal operation description, but in case of dc faults the new post-fault steady-state voltage is dependent on the configuration of the secondary of the transformer. Although this is a limitation of the developed model, we approximate the faulty operation of the transformer assuming that there is no circulating current between the dc ground and the ac side ground.

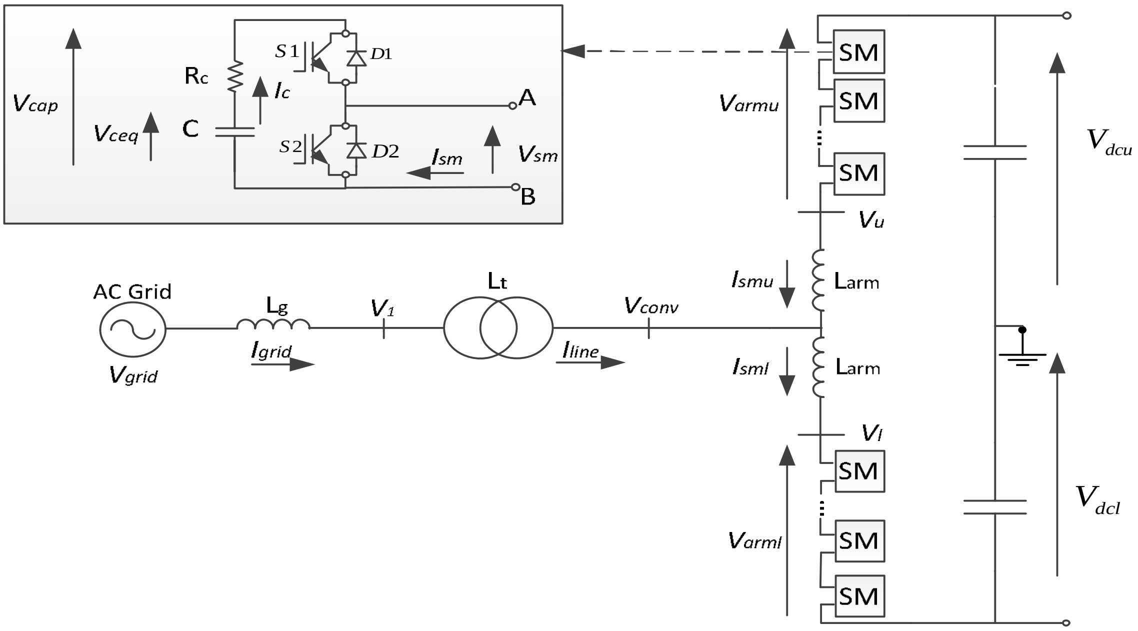

Figure 2-1. Model of a half-bridge MMC.

2.4 Result

The main contribution of this part of the study is the development of an integrated mathematical model to describe the dynamic operation of an MTdc grid. All the aforementioned models are coded using Matlab code and therefore, the whole grid operation can be simulated very fast without computationally heavy Simulink models. Finally, a comparison was made with results obtained with switching models implemented in Matlab/Simulink, which showed that the model can accurately approximate the important values for each operation mode of the grid (e.g. Figure 2-2). The converter modelling approach and the model evaluation is presented in detail in **Publication 1**.

Contribution: Integrated mathematical model that accurately describes the dynamic operation of a MTdc grid based on MMCs and that is computationally efficient.

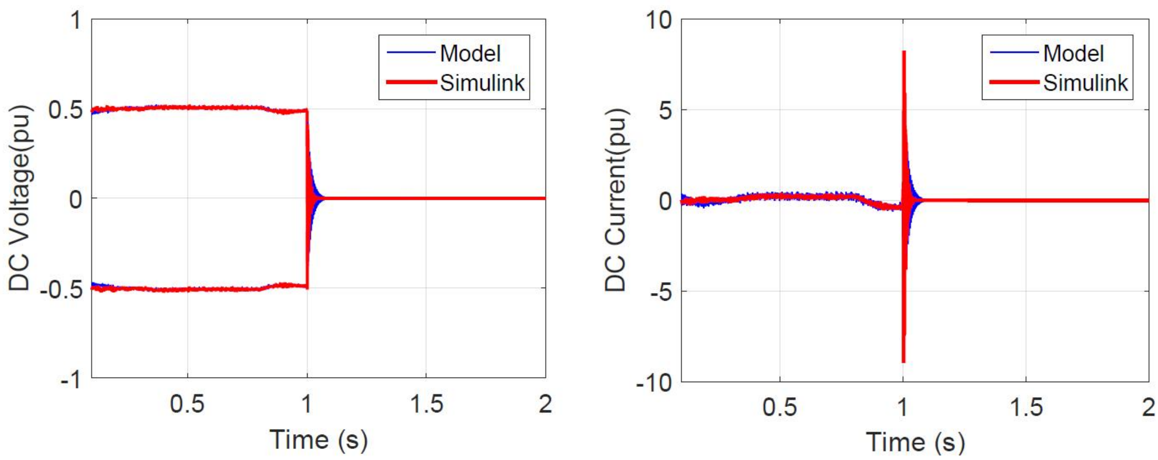

Figure 2-2. (a) Pole dc voltage and (b) Pole dc current at the output of an MMC attached to the dc faulty line.

3 Protection concepts

3.1 Motivation

The dc fault response of VSC-based MTdc networks represents a significant bottleneck to their deployment. As soon as a dc fault occurs, the system has only a few milliseconds to react and isolate the fault before critical current levels are reached. As a result, it is important to consider all grid assets that contribute with their operation on the developing fault currents.

3.2 Approach – Selected concepts

DC fault protection techniques include fault detection, isolation and grid restoration and can be summarized in four main categories, as shown in , with

Table 1-1 summarizing their main application areas and advantages and disadvantages.

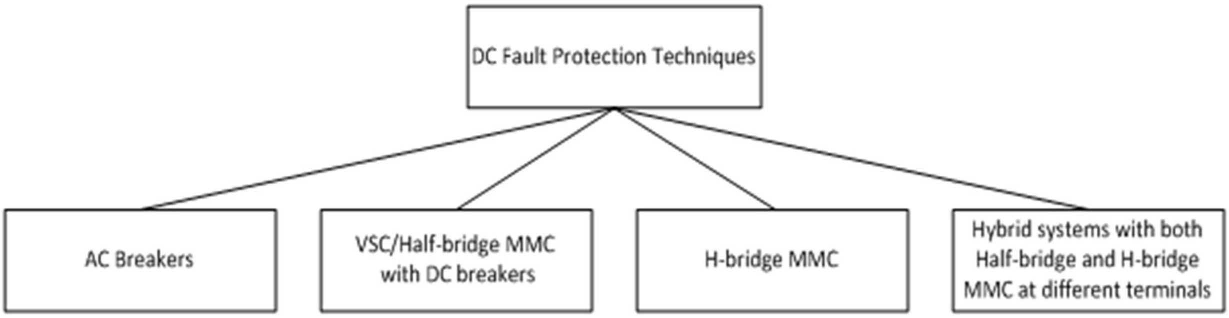

Figure 3-1: Different DC fault protection techniques.

Table 3-1. Application and advantages of different protection techniques.

Protection concept	System application	Advantage	Disadvantage
Half-bridge MMCs with AC Breakers	Point-to-point and small HVDC systems up to 4-5 terminals	No additional capital investment	Shutdown after DC fault
Half-bridge MMCs with DC Breakers	MTDC networks	Fast dc fault isolation and selectivity	DC Breaker costs
Full-bridge MMCs with AC breakers	MTDC networks	Inherent fault blocking capability; STATCOM operation during DC faults	Full-bridge MMC more expensive
Hybrid systems: Full-bridge MMCs onshore and Full-bridge MMCs offshore	MTDC networks	Selectivity at sensitive lines; STATCOM at weak AC grids and optimization of capital costs	

Note: Full-bridge MMCs are also denoted as “H-bridge” converters, where “H” represents the topology of the modules, each with 4 switching arms.

Two main approaches are analyzed regarding the dc fault protection system, namely:

(a) Two-level VSC or half-bridge MMC with dc breakers and dc limiting reactors (**Publication 5, 7**);

(b) H-bridge MMC with mechanical AC disconnectors (**Publications 2, 3 and 4**).

Besides the evaluation of these concepts, a methodology for the design of dc limiting reactors, as well as for the dc fault ride-through in a given system has been proposed. The developed converter and grid models have been implemented on down-scaled MMC models to validate the proposed methodologies and to evaluate the response of the DC grid to different type of contingencies.

3.3 VSC and half-bridge MMC with dc breakers and dc limiting reactors concept

3.3.1 Effect of power flow control methods on the dc fault response of MTdc network

There are two important aspects to the dc fault response of an MTdc network: (1) the fast fault isolation and; (2) the post-fault control of the system to recover operation. On this basis, in **Publication 7**, the Distributed Voltage Control (DVC) strategy, in which all the interconnected converters control the dc voltage on their terminal at setpoints determined by a central controller, and the Single converter Voltage Control (SVC) method, in which only one station directly controls the dc voltage level of the grid and the rest control their active power levels, were compared regarding their impact on the dc fault response of the system.

From the obtained results, it can be concluded that the SVC method has the same impact on the post-fault operation of the network as the DVC strategy, only in case the fault occurs to a line that connects a converter controlling active power. In this case, as long as the system protection is designed to isolate the faulty line in a fast and selective way, there is always a converter maintaining the dc voltage control post-fault. On the other hand, when SVC is used, as soon as the only VSC controlling the dc voltage is blocked, the system cannot resume normal operation after the dc fault is cleared. However, in case of the DVC strategy, while the dc voltage-controlling converter closer to the fault will be blocked first, the protection has more time to ensure that the remaining converters will ride through the fault, maintaining the dc voltage control capability of the system. Considering bipolar converter topologies, the ‘healthy pole’ converters are affected more, by the circulating fault currents, when DVC is employed, and power flow needs to be controlled anew, post-fault, by setting new voltage setpoints. On the contrary, the power flow balance is inherently resolved in SVC, as N-1 network converters control their power flow.

In conclusion, despite minor DVC effects on the post-fault control of the converters, if the DVC strategy is used in combination with fast fault isolation methods and additional protection measures, it offers redundancy to the MTdc network and contributes to the fault ride-through capability of the system in a wider range of dc fault cases.

3.3.2 Design of protection system

3.3.2.1. Problem

To overcome the time restrictions of dc faults, one of the proposed protection concepts includes the use of limiting reactors at the output of the stations. Limiting reactors can decrease the peak as well as the rate of rise of the developing dc fault currents. Thus, they can give the system more time to isolate the fault with the existing breaker technologies, allowing a fast MTdc network operation restoration. However, there are certain limitations regarding reactors cost and mass that need to be accounted for, especially for offshore applications, and also constraints arising from the power flow control, since higher inductance decreases the response time of the grid to fast power changes.

3.3.2.2. Methodology

The main contribution of this part of the study is the development of an optimization methodology for the limiting reactor design for the protection of MTdc networks, as shown in Figure 3-2.

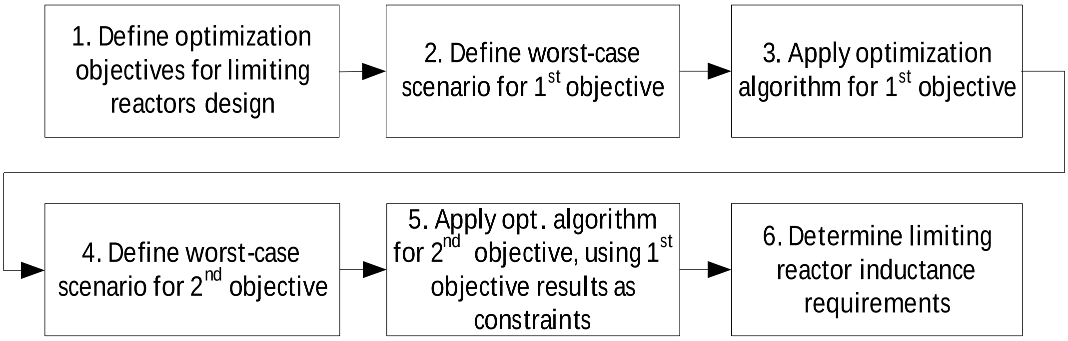

Figure 3-2. Methodology for the design of dc limiting reactors.

Following this methodology, the minimum inductance requirement for a system to be N-1 secure is determined. Moreover, the design of the limiting reactors is optimized, through the use of the multi-objective CMA-ES (MO-CMA-ES) optimization algorithm, based on the considered trade-offs, i.e. cost, mass and peak fault current, which are described by the following equation:

$$C, M \propto I\sqrt{L} \qquad \text{(Equation 1)}$$

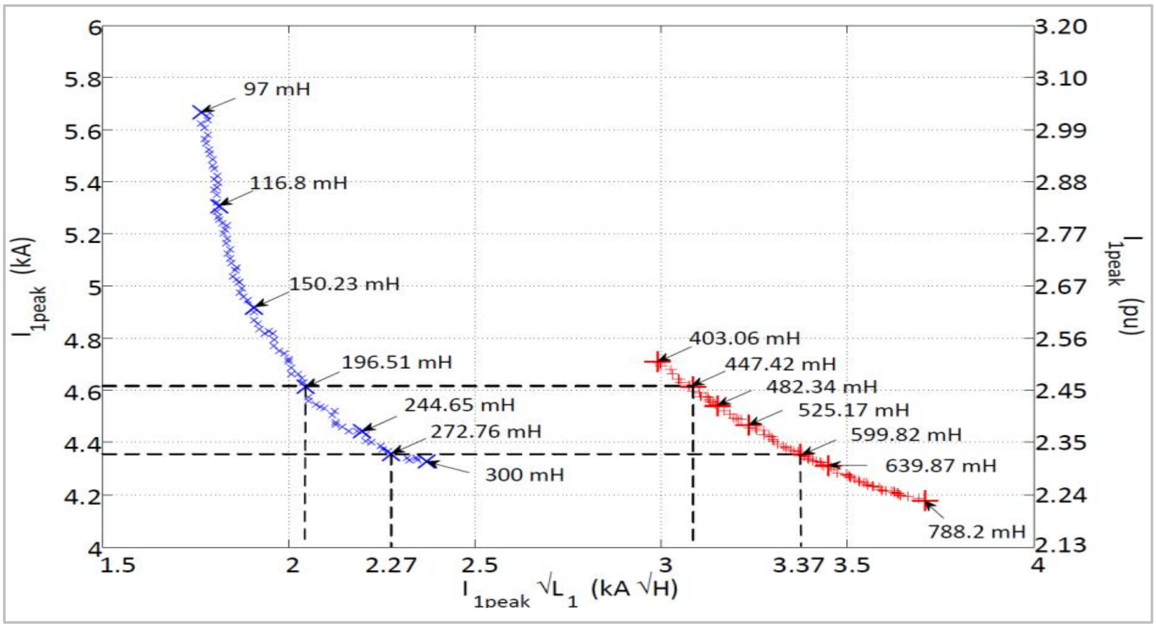

Figure 3-3. Relative cost, mass and peak dc current for optimized limiting reactor solutions at one converter stations (blue: solid-state breakers, red: hybrid breaker).

3.3.2.3. Conclusion

This study showed that converters controlling the dc voltage level of the MTdc network set the most stringent time constraints for the dc fault protection, as they are the first to respond to the fault within 1-2 ms. The closer a fault is to the central node of a radial network, the faster the dc breaker needs to act to ensure stability of the 'healthy' grid part. Moreover, higher pre-fault converter power levels lead to faster triggering of the switch valve overcurrent protection. There is a clear trend of diminishing returns between the reactor size and the peak dc fault current, as well as between the peak dc current and the reactor cost and mass. The implication of the proposed methodology is that system designers can ensure successful dc fault isolation when the optimized reactors are combined with dc breakers with fault isolation time lower than 5 ms. The proposed methodology can be applied to all MTdc network topologies, i.e. symmetric monopole and asymmetric monopole configuration with metallic return.

Contribution: Optimization of used assets can lead to reduction of the involved CAPEX and converter footprint.

3.4 H-bridge MMC with mechanical AC disconnectors concept

3.4.1 Problem

In case of H-bridge MMC, as soon as a dc fault occurs, the grid response is divided into three parts. First, the dc fault needs to be detected and localized. Secondly, the system needs to ensure the protection of the different assets and isolate the fault before the developing dc currents reach critical levels. Finally, the operation in the 'healthy' part of the grid should be restored as fast as possible, minimizing the financial and power losses. This part addresses HVdc grid restoration after faults in the dc transmission system.

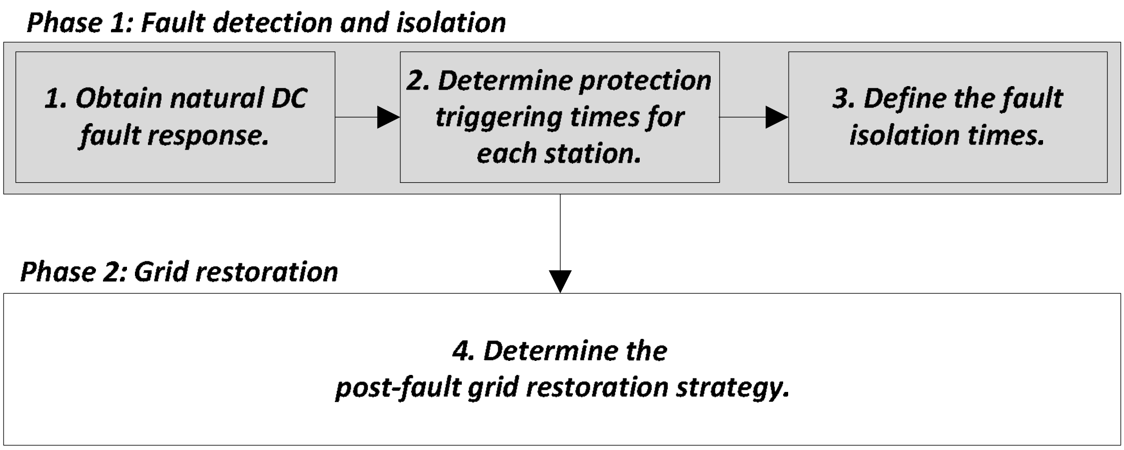

Figure 3-4. Methodology for dc fault ride-through studies.

3.4.2 Methodology

The following framework that provides step-by-step fault ride-through capability to HVdc networks that are based on H-bridge MMCs coupled with mechanical disconnectors on the dc side is proposed.

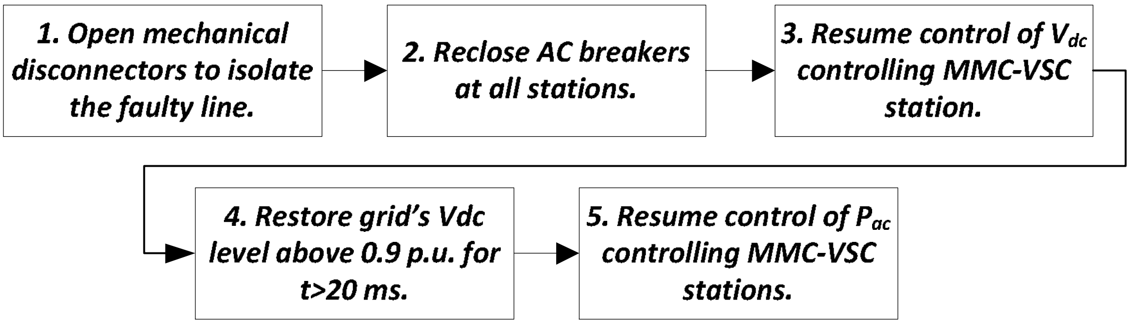

Figure 3-5. Framework for dc grid restoration.

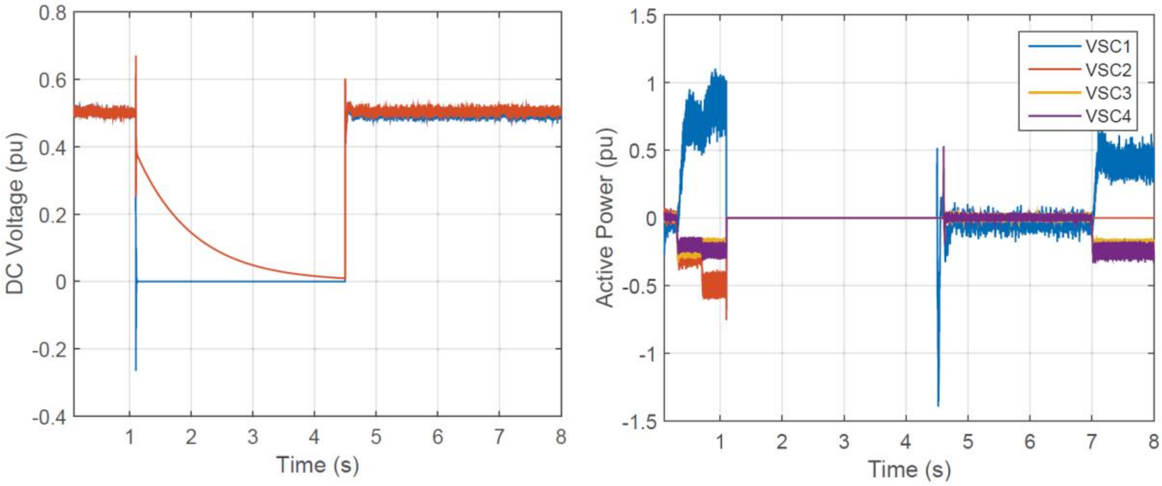

Figure 3-6:. Results for application of dc grid restoration framework.

3.4.3 Limitations

Although the restoration framework can work successfully under all types of faults and grid topologies, the main time constraint is imposed by the length of the MTdc grid lines and thus, by the energy storage elements that need to get discharged before simple mechanical disconnectors, which are placed on both ends of each grid line, can isolate the faulty part. To overcome this limitation and accelerate the restoration process, both poles should be connected momentarily to the fault ground.

3.4.4 New approach

A control technique is proposed to allow the fast discharging process of both poles during a dc fault without compromising the blocking action of the H-bridge MMC-VSC stations. To momentarily allow the connection of the 'healthy' pole to the dc fault ground, independent of the fault type, the submodule switch S3 is turned on, as shown in Figure 3-7. In this way, there is a free path connecting the dc poles through the MMC-VSC while the ac side is still disconnected from the dc side. The S3 switch is turned on once the ac breakers of the MMC-VSC stations are open. As a result, the switch does not experience dangerous overcurrents, as it closes only after the initial discharge phase of the 'faulty' pole. The switch remains on until the dc link voltage becomes lower than 10% of its nominal value. At this point, the mechanical disconnectors can isolate the faulty line and control can be resumed.

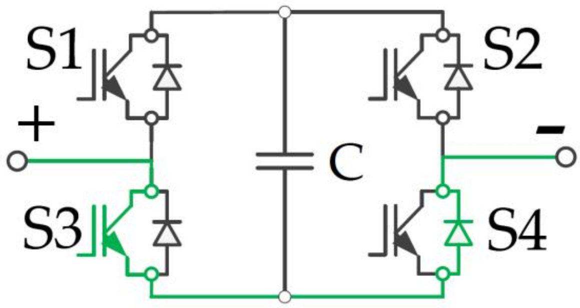

Figure 3-7: Current path through the H-bridge submodule.

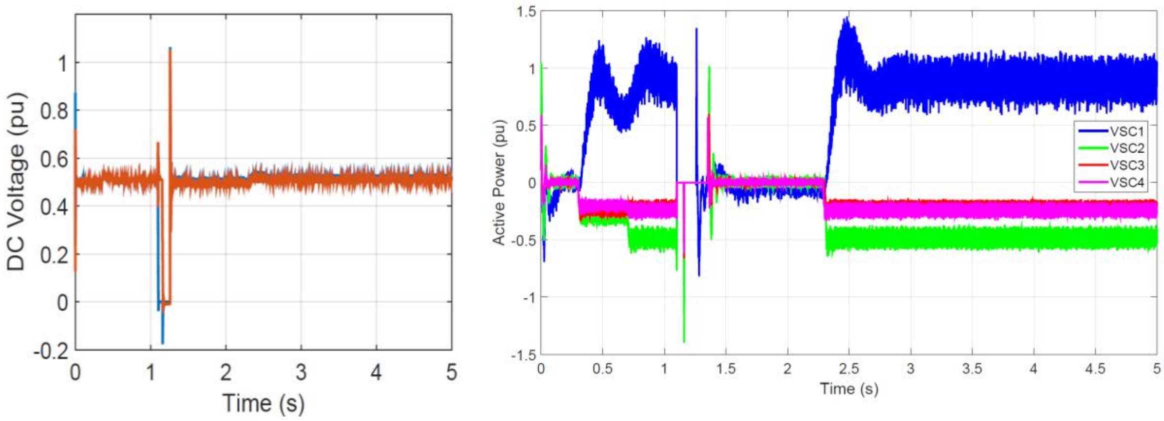

Figure 3-8. Results for application of new control approach in dc grid restoration framework.

3.4.5 Conclusions

Hereby, the black-start capability of the MTdc network is investigated and the timeframe in which the power flow can be restored is evaluated. More specifically, it was shown that restoration largely depends on the dc lines length. However, if long lines are involved this can take up to several seconds. As a result, a new control approach is proposed that if combined with the proposed dc grid restoration framework, it can provide fast and safe fault isolation and system restoration without the need of costly and not yet commercially proven dc breakers. Depending on the fault location, the onshore converters can be assigned a different control mode than pre-fault, to achieve a smooth and controlled post-fault operation. The results for the two grid restoration methods are presented in **Publications 2, 3 and 4.**

Contribution: Proposed methodologies can reduce the downtime of the system and protect the assets from dangerous transients.

4 Additional functionality of MMCs in HVDC grids

4.1 Grid support of MMC converters during DC faults operating as STATCOM

In case of an HVDC link, when a dc fault occurs, the faulty line needs to be isolated and remains so until the fault is resolved. This can take significant time, during which the converter connected to this line remains isolated from the rest of the HVdc network and thus, cannot supply active power. However, since the infrastructure is already in place, the MMC can be controlled as a STATCOM to provide support and ancillary services to the respective ac grid. To validate the results, a laboratory set-up was made in collaboration with AAU, as shown in **Figure 4-1**, and its parameters are given in Table 4-1.

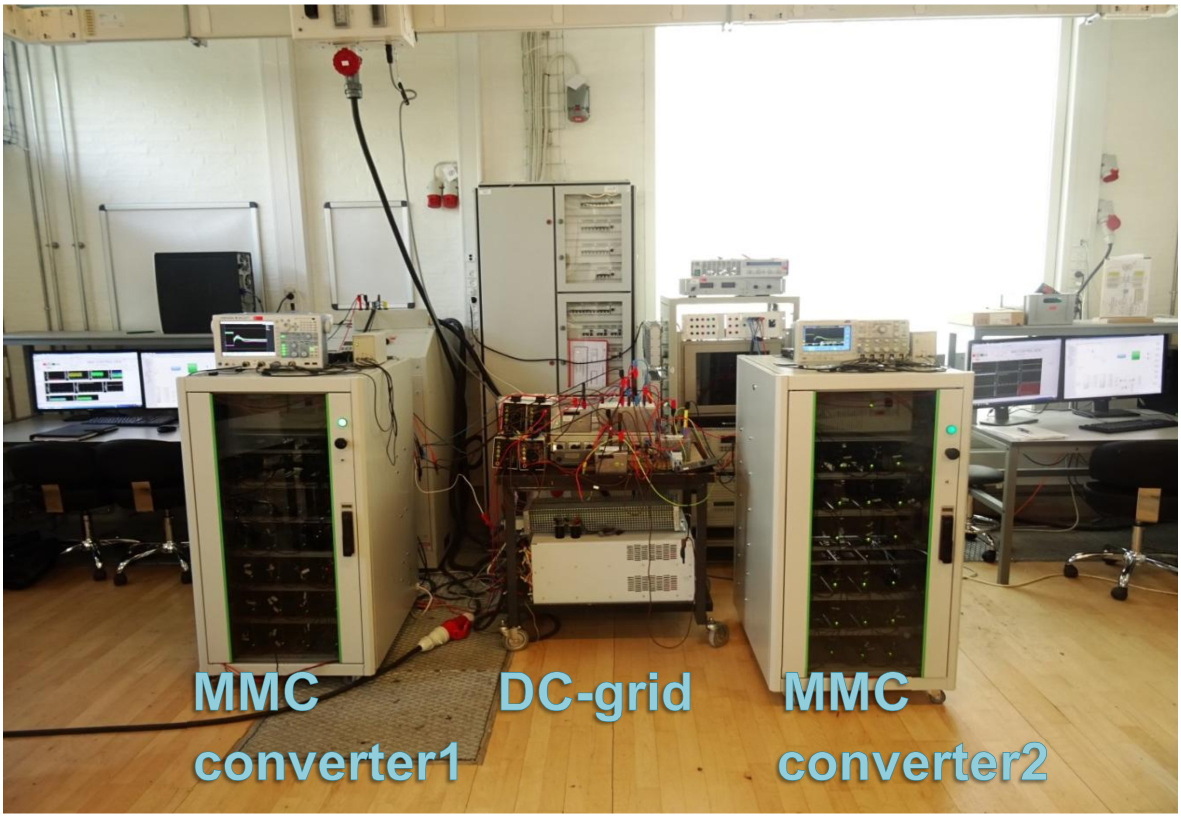

Figure 4-1: Laboratory set-up at Aalborg University applied for validation

Table 4-1. Parameters of experimental set-up.

Description	Symbol	Value
Rated Power (kVA)	S	1.25
Rated RMS Voltage (V)	V_{ac}	150
Pole-to-pole Voltage (V)	V_{dc}	300
Submodule's Capacitance (mF)	C_{sm}	4
Arm Inductance (mH)	L_{arm}	20
Number of SMs per arm	N	4
Transformer Turns Ratio	n	$1:\sqrt{3}$

4.1.1 Motivation

An attractive STATCOM configuration is the Double-Star (DS) topology of the MMC using half-bridge (HB) submodules. More particularly, the DS-MMC was proven to be superior against the FB-D (topology with Full-bridge (FB) submodules in delta connection (FB-D)) when the focus is laid on negative sequence current injection. Nevertheless, high power quality is a major concern nowadays with the grid codes requiring efficient control of both positive-sequence and negative-sequence reactive current in a droop fashion. Therefore, this study focusses on the performance of the control system of the DS-MMC STATCOM under grid disturbances.

4.1.2 Approach

The main focus of this paper is the application of the MMC with its internal controls and the selection and tuning of the respective controllers for the Low-Voltage Ride-Through (LVRT) response of a STATCOM. More specifically, the performance of the MMC-STATCOM in different ac fault cases is presented. Moreover, the improvement in the LVRT operation of the MMC-STATCOM, when employing the proposed controllers, and the performance of the internal balancing controllers is verified and quantified using extensive experimental results. For this purpose, a DS-MMC STATCOM laboratory prototype was developed. The STATCOM used and the laboratory configuration under investigation is presented in **Figure 4-2**. An ac controllable source, emulating the ac grid, was used to create the voltage sags. Only asymmetrical voltage sags at different voltage levels on phase-a and phase-b were investigated.

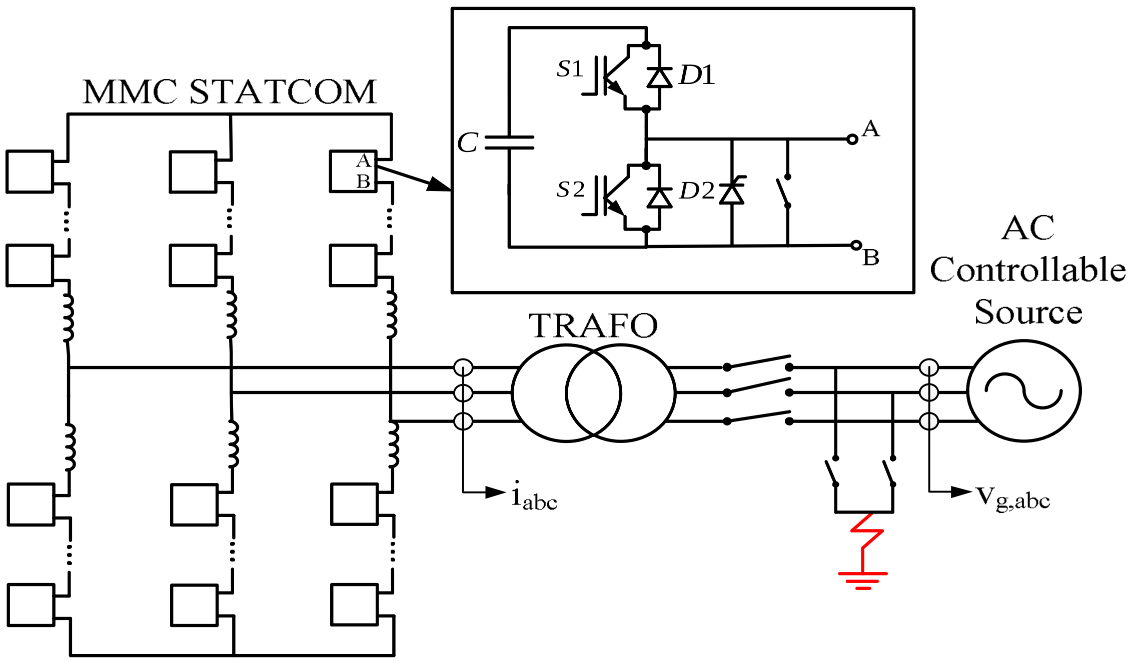

Figure 4-2: STATCOM Lab connection.

4.1.3 Conclusions

Through simulations and experiments, it was shown that the combination of leg and arm energy balancing controllers allows the independent control of each arm energy and consequently, of the voltage levels of each arm. The energy controllers along with the circulating current controller were designed and tuned to ensure internal balance during ac voltage sags. These were subsequently tested both in simulation and experimentally under different fault scenarios. The results highlighted the improved performance of the MMC STATCOM during voltage sags when the energy controllers are activated. In all the tested cases, the converter managed to ride through the fault while at the same time keeping its internal balance. Indicative results for the internal energy balancing of the MMC are presented in Figure 4-3 and Figure 4-4, for the experimental scenario in which a more severe asymmetrical voltage sag occurs at the ac-side of the MMC STATCOM for 300 ms. Phase-a voltage is reduced to 5% of its value and phase-b experiences a voltage sag of 50% while phase-c remains unaffected. The complete study can be found in **Publication 9**.

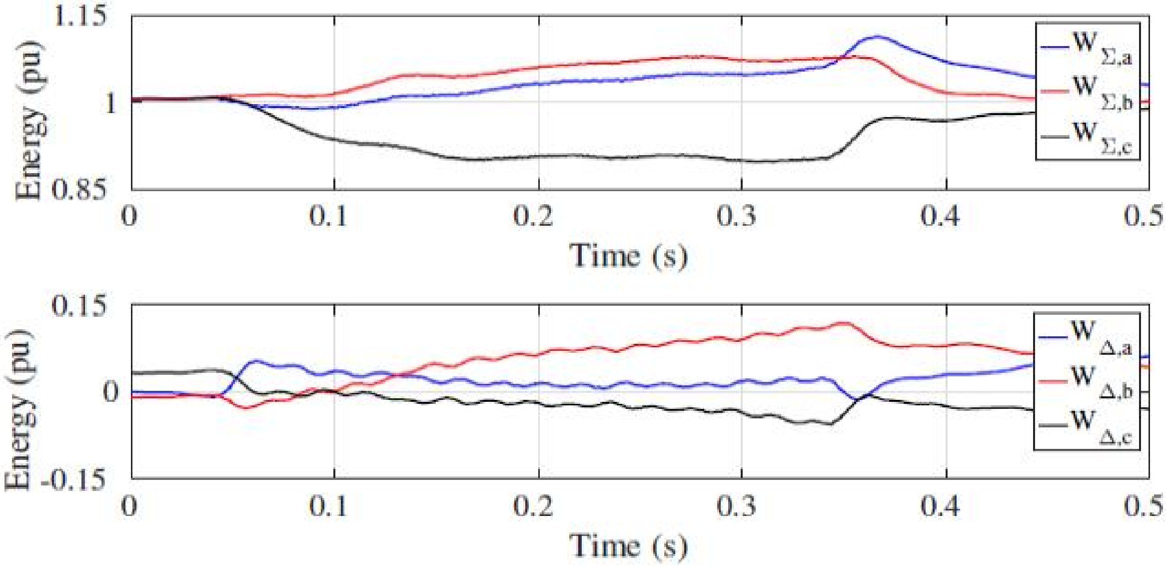

Figure 4-3. WΣ and WΔ for experimental scenario without energy controllers.

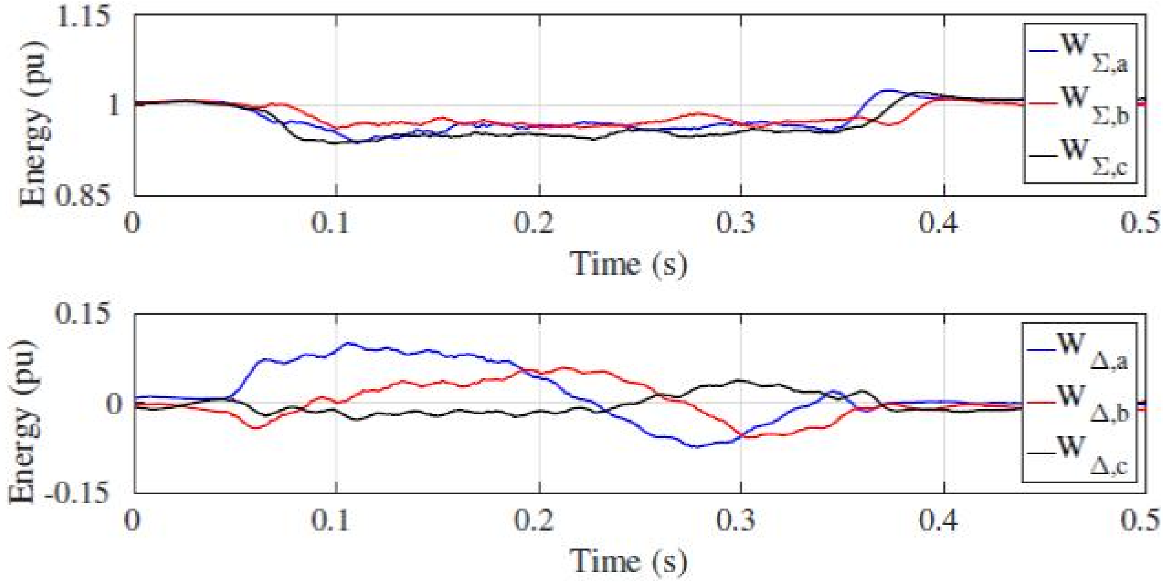

Figure 4-4: WΣ and WΔ for experimental scenario with energy controllers.

4.2 Active Filtering Capability of the MMC STATCOM

4.2.1 Motivation

A major problem in modern power systems is the pollution of power quality due to the introduction of harmonic content by various power electronic based loads. The current harmonics can cause voltage flicker and other undesired phenomena, such as malfunction of electronic equipment. One of the biggest challenges of the grid operators is to keep the power quality standards high, by limiting the Total Harmonic Distortion (THD) in the voltage and the line currents at the Point of Common Coupling (PCC). In this part of the study, the performance of the MMC STATCOM topology in the mitigation of current and voltage harmonics up to the 13th order will be evaluated.

4.2.2 Approach

Different detection techniques are investigated and filters are employed to detect each harmonic individually. Moreover resonant controllers are employed and tuned accordingly to control the output current harmonics. Two case studies are considered to evaluate experimentally the performance of the MMC as STATCOM. Namely, an electronic load is used to inject current harmonics, while a controllable ac source is used to inject voltage harmonics at the PCC.

4.2.3 Results

Figure 4-5 shows with red line the currents when the STATCOM does not compensate for the harmonic currents, but operates close to its nominal power, injecting 3.6 A of inductive reactive current to the grid. The total current flowing to the grid is highly distorted with approximately 26% Total Harmonic Distortion (THD), mainly due to the presence of the 5th, 7th, 11th and 13th order current harmonics. With blue color are depicted the current waveforms after the application of the compensation, with resonant controllers and detection blocks up to 650 Hz. It can be seen that the THD of the grid currents has been reduced to 9%. It has to be noted that similar results were obtained for the voltage harmonics and are presented in the submitted **Publication 8**.

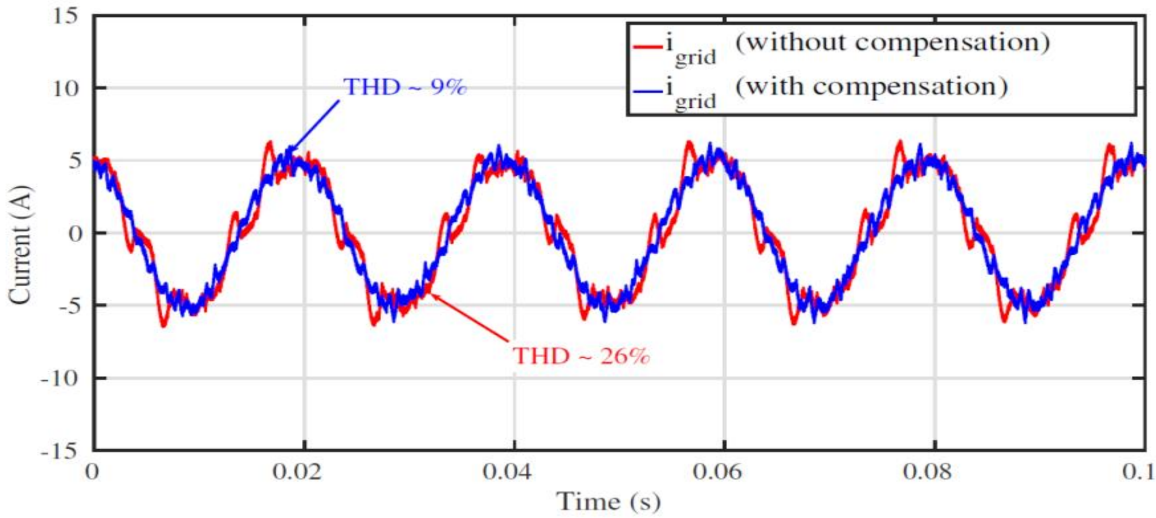

Figure 4-5: Grid currents before and after compensation.

4.2.4 Conclusions

In the experimental part, the efficiency of the MMC in mitigating higher ordered current harmonics with a relatively low switching frequency was demonstrated. The increased bandwidth of the MMC due to its modularity allowed for the control of current and voltage harmonics up to the 13th order, demonstrating great performance. The detailed results will be shown in **Publication 8**.

Contribution: Achieving additional operability of the converters of the HVDC system, providing extra value through support of weak AC grids.

5 DC Hub Concept

5.1 Motivation

Small HVdc networks involving up to five terminals are expected to be possible with the existing technologies. However, as more point-to-point HVdc connections are proposed or are under construction, the lack of standardization in the utilized equipment and in the used voltage and power levels will eventually lead to significant problems moving towards the realization of a highly meshed North Sea Transnational Grid. In this case, already established projects that operate at different voltage levels would need to get interconnected with similar future projects on the dc side. Therefore, there is the research opportunity to study the solution of a dc interface to achieve this transition from dc point-to-point connections to dc grids.

5.2 Approach

The role of an interface could be played by multi-port dc-dc converter stations which can be placed either onshore or offshore and will be able to accommodate the interconnection of HVdc projects. These multi-port converters are called dc hubs and could operate as dc "plugs". The main advantage of these hubs is the interconnection possibility of different HVdc projects that operate at different voltage and power levels, as well as the reduction of costs resulting from the placing of additional converters as soon as a new HVdc project is realized.

5.3 Implementation

We propose the implementation of a multiport dc hub (dc-ac-dc converter) based on the MMC technology for high power applications, as shown in Figure 5-1. This hub has the ability to interconnect more than two dc lines in a back-to-back configuration. This is ongoing work covering the last part of my PhD project. More specifically, the dynamic response of the converter and its control is evaluated during normal and faulty operation and the main parameters that affect its performance are identified. Based on those, a framework for the design of a scalable multi-port dc hub is developed to facilitate the connection of more dc grids from future projects.

The use of dc-dc converters as dc circuit-breakers is also investigated. This property needs to be studied as there is still no device which can assure safety of an electric circuit from damage caused by overload or short circuit, as it exists in ac systems. For this reason, the ac conversion stage of a dc-ac-dc converter could be used to break the current at zero crossing, within the MTdc network. In this way, the converter itself could potentially act as a dc circuit breaker. However, the dynamic analysis of its operation needs to be made.

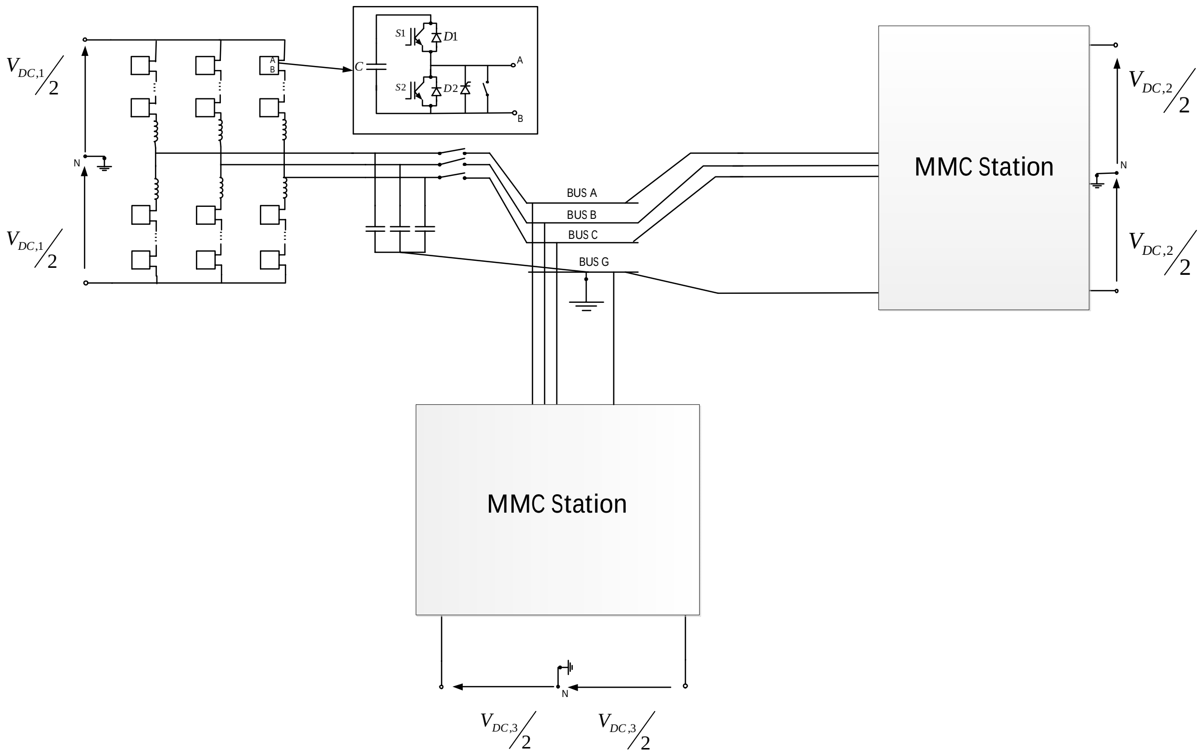

Figure 5-1. MMC-based DC hub.

6 Conclusions

6.1 Results summary

The design study has resulted in integrated mathematical models that accurately describe the dynamic operation of a MTdc grid based on MMCs and that is computationally efficient.

Based on these models, control and protection strategies have been proposed for all DC system concepts, as shown in Figure 6-1. These concepts have been evaluated both by simulations and in a down-scaled laboratory setup.

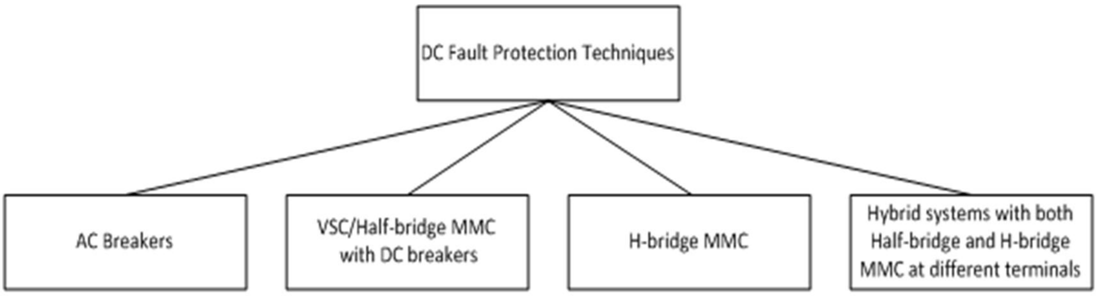

Figure 6-1: Different DC fault protection techniques.

The “AC breaker” solution results in the lowest CAPEX but is limited to 4-5 terminals and also in the rated power level, as DC faults will result in disconnecting the complete DC grid.

For the so-called “VSC/Half-bridge MMC with DC breakers solution”, the system was optimized for a minimum mass and costs for the limiting reactors. For the solutions employing H-bridge MMC, namely the “H-bridge MMC” solution and the “Hybrid systems with both Half-bridge and H-bridge MMC at different terminals” solution, the recovery time and reliability were improved.

Additional functionality of the MMCs was tested successfully to provide continuous grid support during DC faults and to improve the AC grid power quality, significantly reducing the harmonics distortion until the 13^{th} order harmonic.

Finally, the concept of an active DC-hub was presented, which will be studied in the course of 2017 as part of the PhD.

6.2 System design implications

From a qualitative perspective the following design improvements have been achieved:

1. Faster DC fault recovery allows:
    a. larger HVDC systems -> more trading benefits for operators, no need for parallel systems
    b. less redundancy or backup power -> saving on hardware costs
2. Novel techniques for dc fault ride-through:
    a. allow simpler (i.e. half bridge instead of full-bridge) converters or protection devices -> saving on hardware costs
    b. reduce losses and downtime -> increasing revenues for operators

3. STATCOM operation during DC faults, supporting the AC grid
    a. saves on additional onshore control and filtering equipment (and on their costs and losses -> operator revenues)
4. Harmonics cancellation by MMCs
    a. Reduces filtering needs, saving costs and losses
    b. Reduces losses in AC grid, e.g. in transformers

6.3 Estimated cost savings

Assumptions

For the different protection concepts the estimated cost reduction has been derived, taking the DC-breaker concept as a reference. The estimated capital costs of the HVDC components include MMC-type converters, platforms and DC cables. These costs are based on the ENTSOE offshore technology report, published in 2011. In additional estimates for novel components, such as H-bridge (or Full-bridge) MMCs and DC-breakers are required. Full-bridge MMCs are assumed to be 50% more expensive than Half-bridge MMCs. Further, DC-breaker costs are estimated as 50% of a Half-bridge MMC with a small platform when located offshore, costing a third of an MMC offshore platform as an estimate.

The resulting costs in percentages are presented in Figure 6-2.

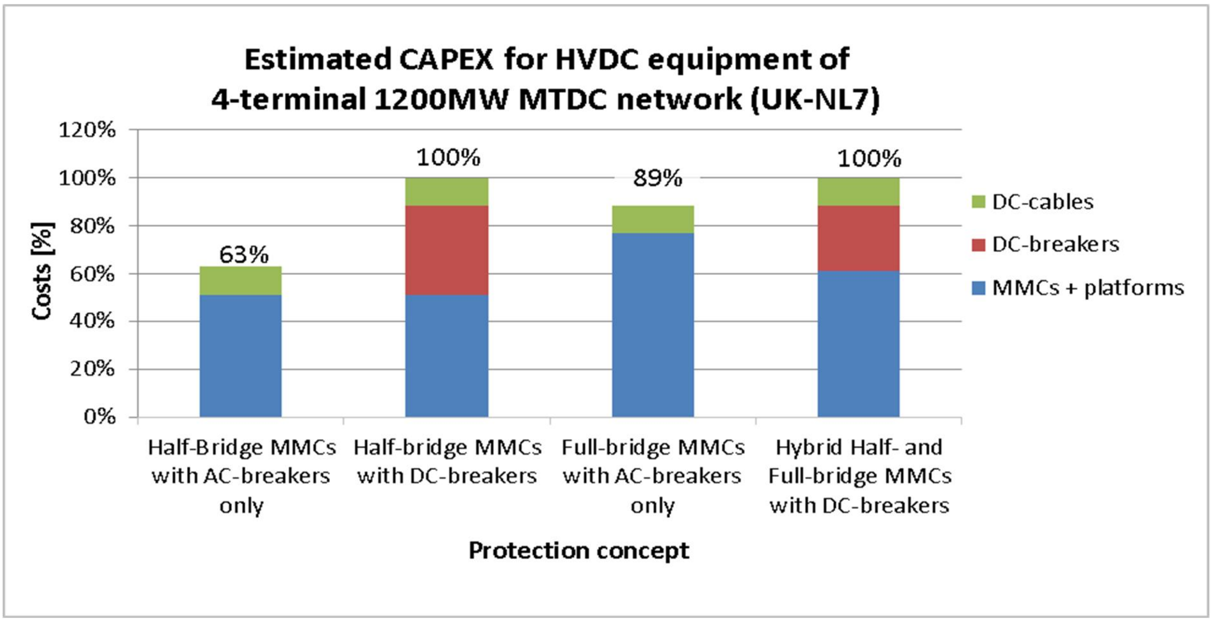

Figure 6-2: Estimated costs for HVDC components relative to DC-breaker solution

Comparison of estimated costs between protection concepts

The AC-breaker solution with Half-bridge MMCs, which is only feasible for point-to-point HVDC networks and small MTDC grids, is estimated to be 29% cheaper than the cheapest DC-protection option that is also suitable for larger HVDC-grids (Full-bridge MMCs with AC-breakers only).

For MTDC grid protection the assumed costs of the DC-breakers located offshore show to be decisive for the total costs, with the Full-bridge MMC protection solution (no DC-breakers required) is estimated to be 11% cheaper than the Half-Bridge-MMC, requiring six DC-breakers.

The costs of the hybrid protection solution are estimated to be the same as the concept that fully relies on DC-breakers. The cost reduction by optimizing limiting reactors for this concept has been estimated as 1% of the HVDC component costs.

The contribution of the faster and more reliable DC-fault protection and of the harmonics reduction are each valued as 1% of the HVDC component costs.

For impact on total CAPEX, assuming that electric system accounts for 35% of total costs for offshore wind, which is higher than current offshore wind farms because of the additional interconnection infrastructure and the larger distance to shore, resulting in a 5% CAPEX reduction, as presented in Table 6-1.

Reduced OPEX has been derived from the reduced capital costs (i.e. less or no DC-breakers), while the reduced losses and improved availability are related to the faster and more reliable DC-fault protection and less DC-breakers and harmonics mitigation, both leading to lower losses.

Table 6-1: Estimated cost reduction for offshore wind

Cost Element		X	Estimated % cost reduction "low end"	"high end"	Design study (estimates)
1. CAPEX	a. Consenting/ Development		-5%	-10%	0
	b. Project Management		-10%	-10%	0
	c. Turbine				0
	d. Support Structure				0
	e. Array electrical/ shore connection	X	-20%	-40%	5%
	f. Installation		-3%		0
	g. Decommissioning				0
2. OPEX	a. Operations & Maintenance	X	-1%	0%	0
	b. Insurance	X	-20%	-30%	2%
	c. Transmission charges	X	0%	+ 15 €/MWH	0
	d. Other				0
3. AEP	a. Gross AEP				0
	b. Losses	X	2%	2%	1%
	c. Availability	X	2%	2%	1%
	d. Net AEP to offshore substation				0
4. WACC	a. Cost of Equity	X	5%	5%	0
	b. Cost of Debt	X	5%	5%	0
	c. Gearing				0
5. Timing	a. Phasing of CAPEX, OPEX and AEP over time				0
	b. Re-financing / Changes in WACC				0
6. Extra profits	a. Incoming profits from interconnector	X	10%	0%	1%

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