Energy Ville

Neptune - project

Research project supported by the Energy Transition Fund

economie
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Neptune, the project

The Neptune project is a research project supported by the "Energietransitiefonds". This 5 year research project has opened the door for a consistent and broad research program that addresses different challenges related to the future offshore grid. High voltage direct current transmission is seen as the key technology that offers opportunities for high power, long distance transmission.

The Neptune project was realized by the KU Leuven/EnergyVille, under the direction of prof. Dirk Van Hertem, together with prof. Jef Beerten, Dr. Hakan Ergun, Dr. Willem Leterme and prof. Erik Delarue.

The project has brought together a wide group of junior and senior researchers to advance the knowledge in offshore systems.

The infographic shows the key achievements of the project:

>30 number of publications

>15 number of keynote presentations and invited talks

>22 number of deliverables

>50 number of involved staff

>6 number of PhD's from Neptune

>20 number of follow up projects

The energy transition and the evolution towards offshore HVDC grids

The energy transition is a process in which we transition from traditional, large and fossil fuel-based generators into an energy provision which is based on clean and renewable sources, increasingly from wind and solar. The ongoing energy transition process is driven by a growing awareness of climate change and environmental concerns, and facilitated by an opening of the energy market allowing also smaller players to participate with innovative solutions. The introduction of new generators in the power system is taking up quickly: where wind and solar provided only 0.8 % of the electricity generated in Europe in 2000, this has increased to 22.28 % by 2022, overtaking coal (from 2019) and gas fired power plants (source: Ember). The compounded annual growth for solar and wind in the last decade has been 29 % and 15 % per year respectively. For wind, the initial installations were realized onshore, but due to the better conditions offshore, we see a fast increase in offshore wind today. The ambitions for offshore wind development are high. In 2023, the North Sea energy ministers made an Ostend declaration, committing to 120 GW of offshore wind by 2030 and 300 GW by 2050 in the North Seas. Today, less than 30 GW is installed by those countries.

To unlock the full potential of offshore wind farms, they need to be connected to the transmission system. The high power ratings and the long (undersea) connections make new transmission technologies such as high-voltage direct current (HVDC) inevitable. Indeed, as compared with the first offshore systems, the sites of new wind farms are located at increasing distances while their installed capacity increases also. Consequently, conventional radial connections making use of AC cables at lower voltages (150 or 220 kV) are no longer a technically feasible option and HVDC in either point-to-point connections or offshore meshed grid must be used.

The use of HVDC for offshore systems gives rise to a paradigm shift in the development of the future grid. HVDC converters behave in a fundamentally different manner compared to traditional AC components. These systems are far more complex as they consist of thousands of power electronic switches and a complex control system. However, their full controllability offers new options for smarter operation of the power system, making it possible to reroute energy and offer ancillary services virtually for free. Lastly, HVDC grids make the use of long distance high power cable connections possible. These developments will require system operators and wind developers to rethink the manner in which the systems are designed, operated and protected.

Whereas current offshore systems (HVDC as well as AC) are still connected radially to the transmission system, future meshed offshore grids will lead to considerable advantages, both technically and economically[2] [3]. Through the variability of wind at a local level and the smoothing effect over larger distances, the large-scale development of offshore wind should be accompanied with a much stronger transmission infrastructure, increasing the capacity between different regions, ideally meshed in nature for the sake of reliability. Meshed HVDC grids are the future of the power system, first offshore, but later also as a new backbone grid for Europe.

Belgium has been at the forefront of the offshore wind developments, with early far-shore developments, and a current installed capacity of 2.3 GW. As an early adopter, Belgian industry has taken up the challenge and provides innovative offshore wind solutions at a global level. With an additional 3.15-3.5 GW expected in the next 5 to 10 years, Belgium has the ambition to remain at the forefront of the offshore grid development.

The Neptune project fits within that ambition, and focusses on the development of knowledge for the future offshore grid, based on HVDC grids.

The Neptune project has 6 main objectives:

1. To develop new methods and tools for more reliable and cost-effective offshore grid expansion planning, using HVDC systems. (WP1)

2. To ensure more reliable HVDC grid operation using innovative and conventional protection devices and algorithms validated using laboratory hardware tests. (WP2)

3. To ensure interoperability in order to avoid unexpected outages in offshore systems. (WP3)

4. To provide recommendations for future grid codes related to system protection and converter control. (WP2&3)

5. To develop competences and knowledge base , essential for the Belgian offshore industry, technology vendors and transmission system operator. (WP1-3)

6. To accelerate the offshore grid development in Belgium as an integrated part of the interconnected European power system, towards a supergrid. (all WPs)

The need for HVDC grid investments and adequate planning models

In the light of this massive deployment of renewable power-based generation, meshed HVDC networks will play a key role to allow for an affordable and reliable electricity transmission on a European scale. At this moment, DC technology is on the rise worldwide. By 2030 alone, the European Network of Transmission System Operators for Electricity (ENTSO-e), projects that 59% of the transmission network investments in Europe will be in DC technology[1]. The European Commission estimates that 2050 offshore energy objectives will require 800 billion Euros of investments of which two thirds will be attributed to grid infrastructure. Similarly, a study performed by the US National Renewable Energy Laboratory (NREL) concludes that HVDC interconnections on a continental level will achieve significant cost savings in the presence of large renewable energy resources and that investments in HVDC grids will bring a threefold reduction in power generation costs[2]. In a complementary study in the US, HVDC grid investments of 350 billion Euros have been identified to create value of 1 trillion Euros by 2050[3].

Considering such large investment volumes, we need optimization-based planning models for HVDC grids minimizing the investment need. Such planning models need to incorporate future planning uncertainties to provide financially robust investment decisions.

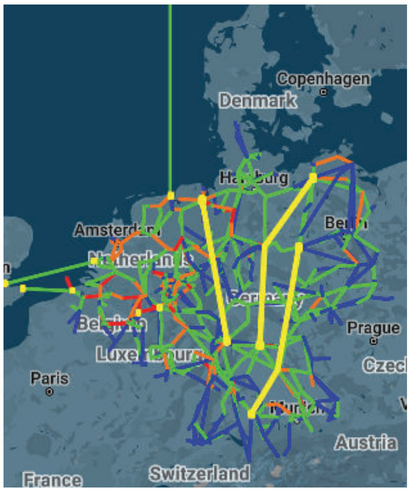
Further, technical characteristics of HVDC technology and operational constraints for HVDC grids need to be considered within the planning model to obtain a technically feasible grid topology.

The NEPTUNE approach

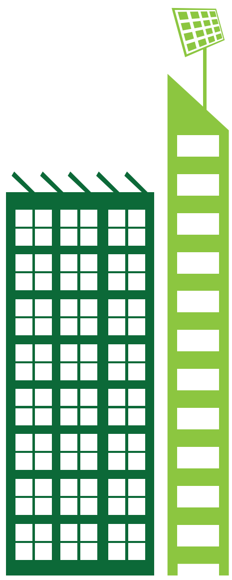
Using optimization different optimization models, within NEPTUNE, we improved the existing grid planning procedures by

1. Bridging the gap between high-level generation and transmission planning models and engineering challenges
2. Finding trade-offs between classical grid expansion and flexibility investments such as storage
3. Bridging the gap between HVDC planning and operational models to better represent protection system design, frequency stability and unbalanced operation of HVDC grids

The NEPTUNE approach provides a set of models and open-source tools that can be flexibly used and extended to investigate different types of network planning problems and operation concepts for AC/DC grids.



Credible generation scenarios are required as input for each transmission system planning model. With increasing share of renewables, typical generation expansion planning and unit commitment models fail to capture the necessary geographic granularity for renewable energy sources.

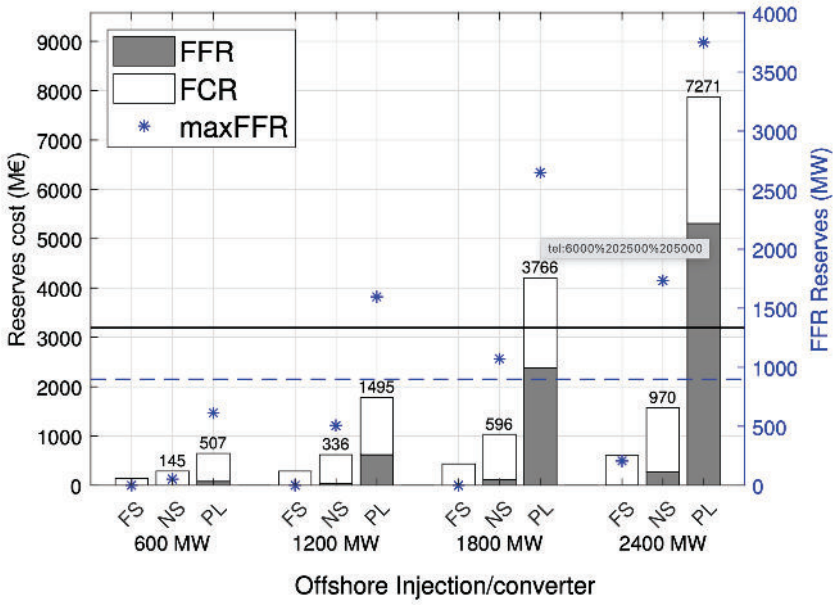


[1] ENTSO-e, Ten Year Network Development Plan 2020, Main Report, January 2021, Version for ACER opinion.
[2] F.Acevedo, et al, Design and Valuation of High-Capacity HVDC Macrogrid Transmission for the Continental US, IEEE Transactions on Power Systems, Vol 36, no 4, 2021
[3] Lew, et al, Transmission Planning for 100% Clean Electricity, IEEE PES Magazine, Nov/Dec 2021

Within NEPTUNE, we have developed a technique to determine the best spatial resolution with respect to planning accuracy and computational efficiency for the generation of the required input scenarios[4]. Further, we have improved on existing spatial clustering methods for determine the optimal geographical size of renewable regions that can be clustered together, considering existing transmission infrastructure.

By using a renewable based approach, as opposed to a country-based approach as classically used, we have been able to better identify the regions with capacity bottlenecks.

Within NEPTUNE we have developed an optimal power flow and grid expansion planning model for AC/DC grids, that allow to determine the optimal AC and DC grid expansions under a multitude of different scenarios. The developed model allows to find trade-offs between accuracy and computational efficiency depending on the time horizon of the planning exercise and the number of relevant operational scenarios relevant for analysis. Our models have been made available open-source[5] and have also found application in different research projects[6].



Extending the planning models by incorporating HVDC grid protection strategies and frequency stability constraints, we have identified the trade-offs between investment into HVDC grid protection systems, interconnection needs, and reserve requirements. We have demonstrated the importance of considering the stability of the system in the long-term planning objectives. We have also concluded that for future HVDC grids, dimensioning incidents used as the basis for reserve sizing, needs to be re-thought in a fundamental way, as the currently used methods are not applicable to offshore HVDC grids hosting hundreds of GW of installed capacity[7].

NEPTUNE has also investigated new operational concepts such as the unbalanced operation of bipolar offshore HVDC grids, as a means of increasing the availability of offshore grids in cases contingencies. By utilizing such an operational scheme, the disconnection of large parts of the HVDC system during single pole outages of HVDC converters and cables can be avoided. This significantly increases the available capacity for interconnection and offshore wind integration[8].

[4] Phillips, K., Moncada Escudero, J., Ergun, H., Delarue, E. (2023). Spatial representation of renewable technologies in generation expansion planning models. Applied Energy, 342, Art.No. 121092. doi: 10.1016/j.apenergy.2023.121092

[5] https://github.com/Electa-Git/PowerModelsACDC.jl

[6] https://github.com/Electa-Git/FlexPlan.jl

[7] Dave, J., Van Hertem, D. (sup.), Ergun, H. (cosup.) (2022). DC Grid Protection Aware Planning of Offshore HVDC Grids, PhD Thesis KU Leuven

[8] CK Jat, J Dave, D Van Hertem, H Ergun, Unbalanced OPF Modelling for Mixed Monopolar and Bipolar HVDC Grid Configurations arXiv preprint arXiv:2211.06283, 2022

Protection of power electronics based systems

1. Introduction

Reliable protection is essential for secure operation and efficient use of the transmission system. The reliability of today's protection is challenged due to the integration of renewable energy sources such as offshore wind and the increased use of HVDC point-to-point links and grids. This poses two challenges which have been addressed within NEPTUNE:

1) HVDC grids require fundamentally different protection compared to AC systems,
2) the existing AC protection algorithms must cope with a fundamentally changed short-circuit current.

2. Tools and competences build-up

Traditional AC protection algorithms as well as promising novel upcoming concepts have been thoroughly analyzed. To this end, an in-house real-time hardware-in-the-loop simulation setup, featuring accurate models for HVDC converters and automation routines, has been developed within NEPTUNE. The setup enables to perform hardware experiments involving real-life commercially available hardware devices that host protection algorithms, so-called relays or Intelligent Electronic Devices (IEDs). The experiments showed that IEDs may fail in systems where the power-electronics dominate the fault responses, and also novel concepts show less robust behavior in such systems.

For DC-side protection, NEPTUNE has set steps towards hardware implementation of DC-side protection algorithms. DC protection algorithms must detect and identify faults in less than a millisecond. As a proof-of-concept, an ultra-high-speed relay has been developed, making use of a sampling step up to 1 MS/s, which is 10 to 100 times higher than earlier developments. Furthermore, NEPTUNE has investigated novel voltage sensors with a small footprint and enabling measurements along a cable, closer to the fault location and as such providing more accurate information.
A tool has been developed for a cost-benefit analysis of HVDC grid protections, especially those relying on HVDC circuit breakers. Even though HVDC circuit breakers represent a large investment cost, it is still cost-effective for large-scale grids to implement selective DC-side protection in light of AC system frequency impact. In light of future large-scale HVDC grids, AC and DC sides will be more tightly coupled and grid codes should not consider both sides separately.
To verify the outcomes of the analyses, an in-house tool and component library for time-and frequency-domain analysis has been developed. With the in-house tool, the accuracy of commercial simulation tools used within the test setups can be determined. The NEPTUNE project has produced new and accurate models for electromagnetic transient simulation of systems involving cross-bonded cables, HVDC circuit breakers and HVDC converters.

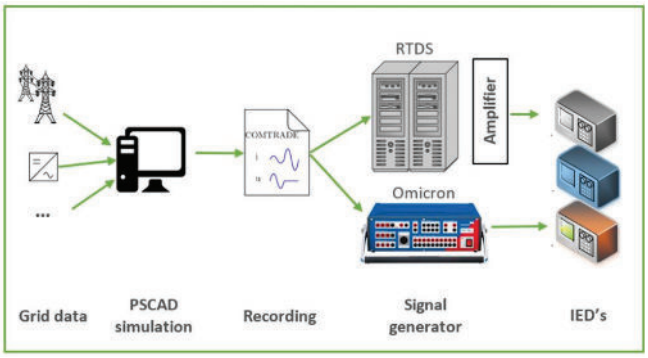
3. Main findings

- Existing AC protections may fail in systems where the power-electronics dominate the fault responses, and also novel concepts show less robust behavior in such systems.
- Practical DC protection algorithm design does not directly benefit from speed gains due to higher sampling rates, and requires trading-off hardware constraints and noise filtering.
- Even though HVDC circuit breakers represent a large investment cost, it is still cost-effective for large-scale grids to implement selective DC-side protection in light of AC system frequency impact

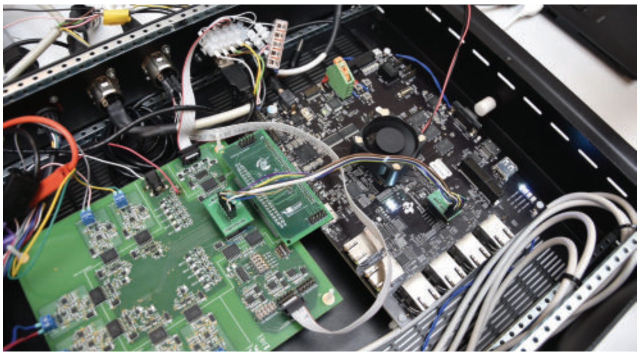
4. The main recommendations based on the work from the NEPTUNE project are:

- There is a need for an automated test setup for AC and DC protection testing, with ever increasing modeling detail to account for increasingly complex fault currents
- There is a need for integrated HVDC grid protection design methodologies, where protection design cannot be decoupled from system impacts
- As HVDC grids grow in size, a separate treatment of AC and DC sides is no longer sufficient, and grid codes must be specified for the future hybrid AC/DC grids

Figures



Non-real time emulation setup for AC protection testing



DC Protection IED featuring enabling sampling rates of 1 MS/s

Building the workforce for the energy transition

One of the key challenges for making the energy transition happen, lies in building up the human capital across the entire value chain. The offshore energy sector is a strategically vital sector in the Belgian industry and will continue this growth over the coming years as a result of the energy transition. WindEurope put forward a vision for 450GW of offshore wind by 2050, of which 380 GW would be placed in the North Seas.

Achieving these targets will create challenges across the entire value chain, and not at least in terms of the development of human capital. Facing these unprecedented growth challenges, skilled workforce is in high demand in the offshore energy sector.

Neptune has, over the course of 4 years provided substantial contributions to the development of key human capital, by providing a fertile ground for training researchers for the energy transition. In total, the project has resulted in the training of over 50 junior and senior researchers, who have found their way to key positions within both industry and academia.

The Neptune project has given me an opportunity to investigate how HVDC grid protection systems should be designed when connected to AC systems with low inertia. Through this investigation, I have had the chance to learn one of the most urgently needed technologies for power systems with a high share of renewables: grid forming controls. Currently, I am working as a senior consultant with one of the leading HVDC manufacturers. Building upon the knowledge I have gained through the Neptune project, I am working on developing grid forming solutions for offshore HVDC systems connecting large wind farms to unlock the full potential of such systems.

Dr. Mian Wang, Senior Consultant Siemens Energy, Digital Grid, Grid Consulting

Participating in the NEPTUNE project has been the start of my academic career. Working on generation planning scenarios, this project has helped me grasp the vital relationship between transmission and generation expansion models. NEPTUNE's pursuit of integrating sustainable wind energy in the North Sea region revealed to me the intricate balance between energy generation and transmission. Moreover, being a member of a research group focused on electricity markets, the interactions with other project members have made me much more aware of the complexities of transmission modeling than I would have ever been otherwise. This project has equipped me with a growing understanding of both the generation and transmission importance in the energy transition.

Kristof Phillips, PhD Student
KU Leuven, Research Division TME

The need for new models and software tools to study the control of HVDC grids

Future offshore transmission networks are envisioned to be hybrid, that is, involving both AC and DC infrastructure. Contrary to traditional power systems, the dynamic behaviour of such hybrid networks will be strongly dependent on the control of the converters that connect the AC and DC systems. The controllers of these converters have to be designed such that the interconnection of several converters does not lead to an unstable operation. To ensure stability over a wide range of operating conditions, highly accurate and computationally efficient simulation models are needed. Such models are also of paramount importance in the design of controllers, such that these controllers can help in minimising the risk of negative interactions between converters and the hybrid AC/DC transmission network in the design stage and can mitigate such interactions during operation. This work package focused on the development of accurate and computationally efficient simulation models and methodologies to study converter interactions and to design controllers to be used in next-generation power-electronics-based transmission networks.

The NEPTUNE approach

Over the last decade, the number of dynamic converter-related challenges in power systems has increased significantly. Contrary to traditional power systems, where the physical properties of large rotating generators located in conventional power plants have determined the overall system dynamics, the converters have dynamics which can be one to several orders of magnitude faster compared to those of traditional machines. The high degree of controllability of the devices is an advantage, however, it also brings a number of challenges with respect to accurate system modelling.

Indeed, it is becoming increasingly clear that converter-related issues typically do not fit into traditional power system stability classifications. Moreover, alternative classifications proposed over the last couple of years do not always grasp the full complexity of the situation. In order to provide an overview and to evaluate the different ways to look at the challenges converters can bring to power system operation, the NEPTUNE project has, through a comprehensive literature survey, analysed a wide range of observed problematic real-life events in the electrical power industry that have involved power electronic converters. Through this analysis, this comparative study has identified a number of patterns amongst the events, in order to pinpoint underlying mechanisms to explain the converter-related issues. From these events, it is becoming increasingly clear that these converter interactions can extend over a much wider frequency range than traditional AC system due to the inherently fast converter dynamics. However, existing available software tools to analyse power system stability are typically not able to cope with the associated modelling challenges, as the underpinning assumptions on which the models are based, are often no longer applicable. For this reason, the NEPTUNE project developed a new tool to study converter interactions in hybrid AC/DC power systems over an extended frequency bandwidth. The tool starts from highly accurate state-of-the-art models, valid over a wide frequency range, and allows not only to assess the impact on the system stability when adding a converter to an existing AC power system, but also to study interactions within a future offshore HVDC grid, as well as potential impacts

<table>
<tr><th colspan="3">CONVERTER OR CONTROL LIMITATIONS</th><th>POWER QUALITY DEGRADATION</th><th>CONTROL INTERACTIONS</th></tr>
<tr><td>(A1) limited under/over-voltage ride-through capability</td><td rowspan="2">(B1) limited/inadequate voltage support</td><td rowspan="3">(C) limited synchronization capability</td><td rowspan="2">(D) nonlinear converter or control behavior</td><td>(F) electrical interactions among converter controls and/or with passive grid components</td></tr>
<tr><td rowspan="2">(A2) limited under/over-freq. ride-through capability</td><td rowspan="2">(G) electrical interactions between converter-controlled rotating machines and passive grid components</td></tr>
<tr><td rowspan="2">(B2) limited/inadequate frequency support</td><td rowspan="2">(E) amplification of converters emissions by passive grid components</td></tr>
<tr><td>(A3) limited over-current ride-through capability</td><td></td><td>(H) electromechanical interactions between converter controls and rotating machines</td></tr>
<tr><td colspan="2">fundamental frequency phenomena</td><td></td><td colspan="2">non-fundamental frequency phenomena</td></tr>
</table>

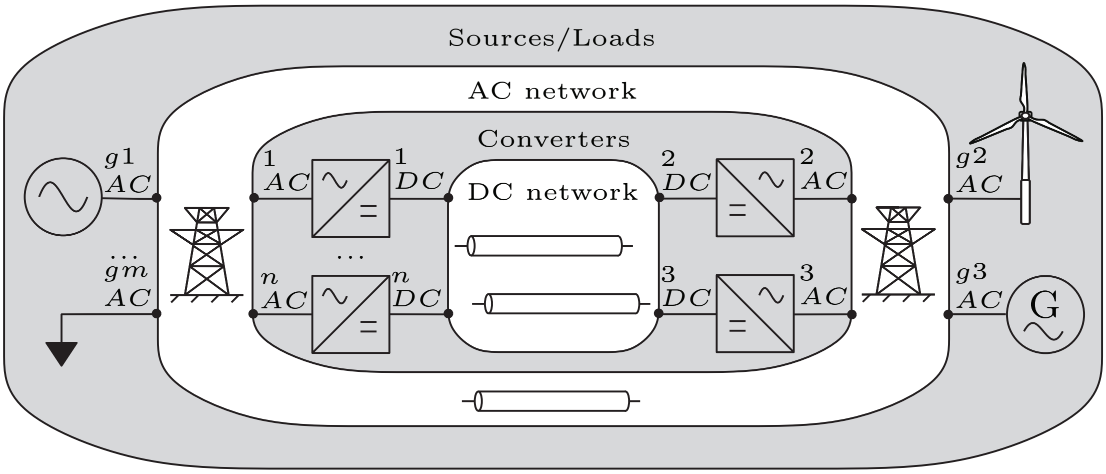
of the AC system on the DC system and vice versa, such that the stability of future hybrid AC/DC systems can be assessed in full.

On the modelling side, the project has also developed highly accurate converter models that allow for the presence of harmonics. In this way, the internal harmonics inside the modular multilevel converter (MMC), which has become the de-facto solution for HVDC projects, can be accurately accounted for in the stability analysis. By relying on dynamic phasor theory, these models have been used within NEPTUNE to design active filtering solutions as add-on features in HVDC converters in order to suppress harmonics in the surrounding AC power system. In terms of control solutions, the project also investigated grid-forming control solutions, which allow the converters to contribute to the inertial response of the power system, similar to traditional synchronous machine-based generation.

Whilst modelling detail can be increased in order to study high-frequency interactions, for large power system studies, there are significant computational advantages in keeping the modelling order limited when possible. However, it is becoming increasingly difficult to draw the line. To this end, the NEPTUNE project analysed in detail the repercussions of key modelling assumptions in traditional phasor-based approaches, in order to provide modelling recommendations for converters when carrying out power system studies. Likewise, in order to avoid extensive power system models for large systems, the project investigated the impact of the modelling detail of the surrounding AC power system on the accuracy of the outcome of the stability analysis.

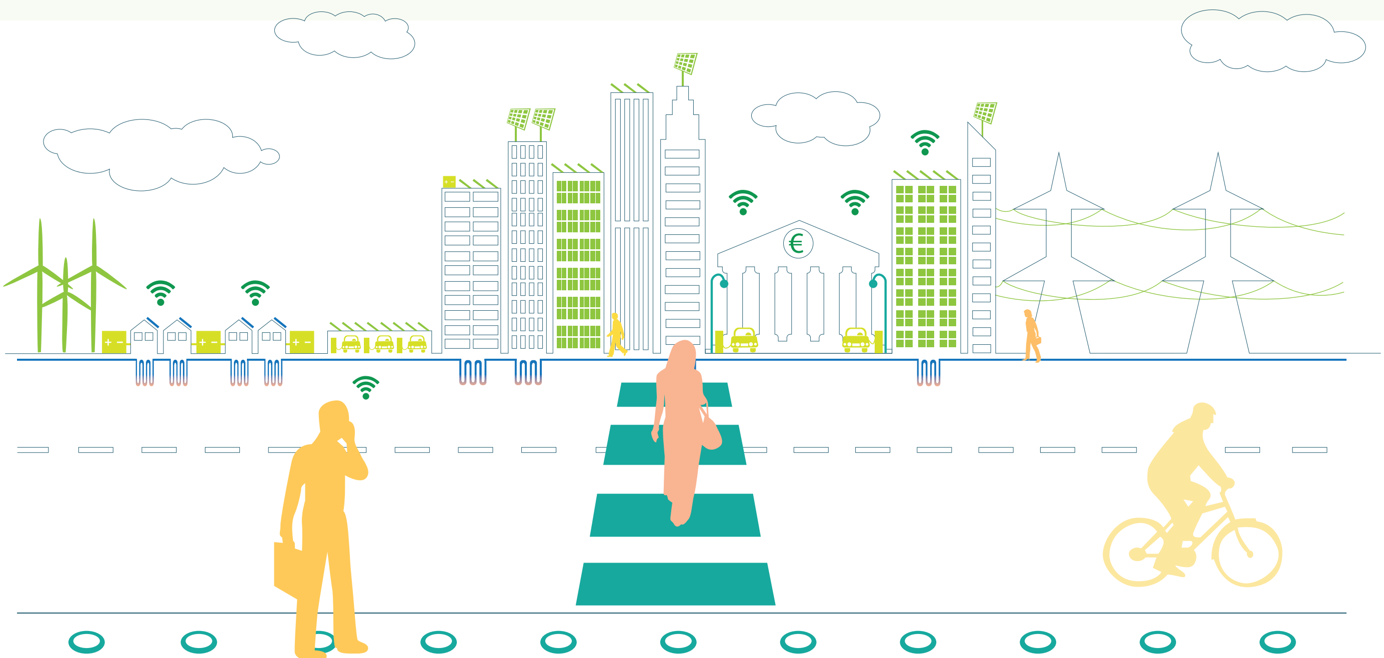
Since in practical projects, control implementation are typically IP protected, the project also investigated how to integrate black-box modelling approaches into the stability analysis, by fitting the input-output response of components to approximative state space formulations. This way, the project developed a method that is able to predict which components in the power system are involved in unwanted system interactions, without the knowledge on IP-related control implementations.

Finally, in order to verify the control dynamics closer to real-life conditions, a controller hardware in the loop (CHIL) demonstrator was built in the lab. The set-up allows to study the dynamics and interactions on a full-detailed switching model of a point-to-point MMC-based VSC HVDC link. Within this demonstrator, the individual converter controls are running on programmable DSPs, which are interfaced with accurate MMC models on FPGAs.



The main recommendations based on the work in NEPTUNE are:

- Software models and methodologies have to be updated in order to be able to represent the behaviour of converters and the other components in the power system over an extended frequency range. In light of the real-life problems observed over the past decade, failing to do so poses risks to system security, given the observed inaccuracies of traditional power system modelling paradigms relying on phasor theory.
- In an environment where control implementations are subject to stringent IP-related limitations, models of the control implementation and the hardware should be embedded in highly accurate blackbox models, for instance using DLL's for time-domain models. Over the next years, methods need to be developed further to screen for potential problems, both in the time-domain as well as in the frequency-domain.
- In future power systems, the overall converter control design should evolve in such a way that interactions with the system can be largely limited to lower frequency ranges linked to traditional power system operation. By solving high-frequency problems and challenges mainly in the system design phase, the applicability and accuracy of more traditional phasor-based tools for large-scale system studies can be reassessed and re-evaluated, such that they can stay at the core of power system operational studies.



Conclusions and Outlook

Over the course of the last five years NEPTUNE has given the direction of how power system planning should be approached, how the performance requirements for AC/DC grid protection should be defined, and how the dynamics and interactions of complex systems with many power electronic devices need to be modelled and studied for modern offshore AC/DC grids to facilitate the renewable energy transition.

The various research results of NEPTUNE have supported decision making processes and have helped to shape the research and innovation agenda on AC/DC grids for the coming decades. In line with NEPTUNE results, the EU Strategic Energy Technologies (SET) Plan for HVDC Technologies defines a number of innovation challenges with respect to HVDC technology development, control and protection systems, operation and planning of AC/DC grids. The SET plan explicitly puts forward the importance of multi-vendor interoperability, grid forming control of HVDC systems, AC and DC grid protection interactions, power flow control and congestion management in AC/DC grids, and adequate cost benefit analysis tools for AC/DC grid planning as some of the innovation areas. Each of these areas were part of the research scope of NEPTUNE which shows the relevance of NEPTUNE's contributions.

NEPTUNE has also paved the way for fundamental research to be incorporated within the context of industrial research and has led to a number of collaborations with a number of system operators, equipment vendors and offshore wind farm developers. To name a few highlights, within the CORDOBA project, our offshore grid planning tools have further been extended in collaboration with Belgian offshore wind farm developers and flexibility providers by incorporating aspects of market design. As a continuation of NEPTUNE, within the DIRECTIONS project, we are studying operational concepts, protection and control system modelling challenges for the Princess Elizabeth Island with the Belgian TSO Elia. Furthermore, NEPTUNE has led to a number of bilateral research projects with European transmission system operators on studying the behavior of power electronic converters on the network or how to develop such systems. The transition to a power electronics based power system will also Last but not least, NEPTUNE has also given us the opportunity to increase our international visibility and has led to a number of national and international academic collaborations.

Tackling the energy transition is a global effort that also requires a new set of competences throughout the academia, the industry, the financial sector, policy makers and the general public. The expected amount of renewable energy and grid investments is massive and will create bottlenecks not only with respect to the available financial resources but also on availability equipment, raw materials, spatial availability, supply chains, and skilled human resources. To that end importance of the research driven approach of NEPTUNE has been validated by the Flemish government investing into establishing an HVDC and underground cable competence center (HC3), where we will have the possibility to go beyond NEPTUNE and upscale our capabilities in modelling future power systems, educating the next generation of power system engineers, and helping the industry to gain the competence needed to achieve the renewable energy targets.

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