The Electrical Power System of the Future: DC systems' role in the Future

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Abstract

Throughout the world there is great concern over climate change due to human activity (anthropogenic). International organisations (e.g. IEA) and Governments are setting policies to reduce carbon footprint and dates for achieving net-zero carbon emission. Electricity is central to many parts of modern society and has an important role to play in enabling the energy transition to lower greenhouse gases to net-zero by 2050. However, to do so power generation must be renewable and not contributing to greenhouse gases. First the electrical power system needs to be decarbonised. This has spurred the rapid uptake of renewable generation, both utility scale and consumer based. This does add complexity in the design and management of the electrical network. The intermittent nature of solar and wind resources requires a range of backup generation options to be available.

The rapid electrification of numerous end-uses from transport to industry, is driving an increase in power demand and it is important this extra demand is met by renewable sources rather than fossil fuels (gas and coal).

The electricity network is a key component for enabling this energy transition by connecting generation to the loads and must be able to cope with increasing use of distributed energy resources and the intermittent nature of some.

Electricity security and affordability are high priorities for society. Electricity security requires resilient infrastructure and a reliable electricity system, which are key to this energy transition. Worldwide there is a significant effort to build new transmission capacity for the rapidly expanding levels of renewable generation, however, maintenance is also important to reduce risk on existing assets.

The MBIE programme "*Architecture of the Future Low-Carbon, Resilient, Electrical Power System*" (short-form is **F**uture **A**rchitecture of the **N**etwork, FAN) is investigating use of DC subsystems in an AC system. The proposed hybrid AC-DC electrical network enables the advantages of both AC and DC to be used.

This paper will first review similar research programmes internationally that are looking at an increased use of DC and secondly highlight the progress on the FAN programme to date. The two spokes to the programme are; (i) technical development in the use of DC subsystems and (ii) capability building in terms of training the people to be competent and able to design and build the future hybrid AC-DC electrical power system.

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1. Introduction

Electricity is essential for our modern society to operate. To reduce the impact on the environment and achieve a sustainable future there is a great need to move to renewable energy resources and increase efficiency of both conveyance and loads. This energy transition is essential to address climate change. Many of the new technologies that are key to this energy transition are DC based and interfacing these technologies to our existing AC system requires power electronic converters, with their inherent losses and complexities. The development of power electronics coupled with rapid deployment of renewable energy resources (solar, wind, etc), battery-based technologies (energy storage, EVs, etc), and efficient end-user equipment based on variable speed drives has raised the profile of DC.

Having DC subsystems at various voltage levels will allow more efficient conveyance of electricity, reduce the number of AC/DC and DC/AC converters and hence losses, and result in a more reliable system. There is always an optimum voltage level for the conveyance of electricity based on distance and power level and hence always a need to transform voltage levels. Although DC/DC converters exist, the traditional AC transformer is mature technology, very reliable and efficient and can operate at very high voltages and power levels. Although DC/DC converters are a good choice for lower voltage and power levels, at higher voltage levels a high frequency transformer is needed. Moreover, the lifespan of DC/DC converters does not match that of the traditional AC transformers. Therefore, the planned architecture of the future electrical network is a hybrid AC-DC system as exemplified in Figure 1.

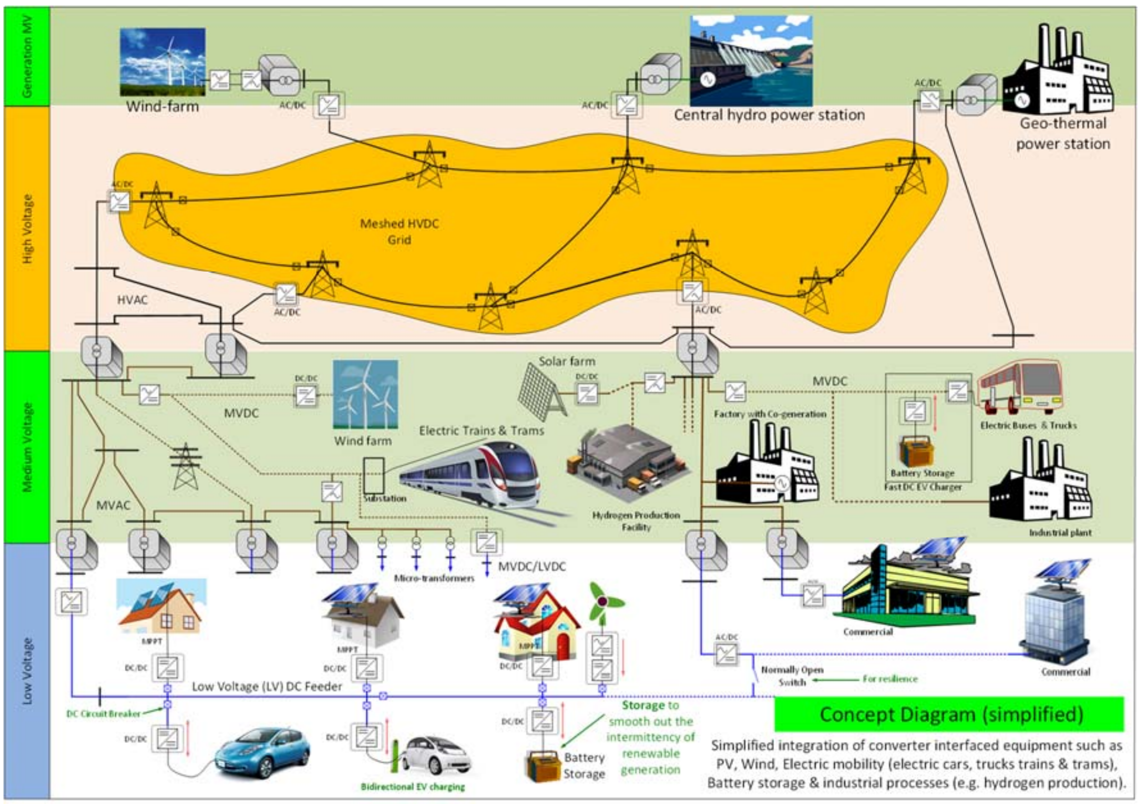

Figure 1: Future Hybrid AC-DC Electrical Network

The Future Power Systems Architecture (FPSA) programme, which was a collaboration between the IET (The Institution of Engineering and Technology) and the Energy Systems Catapult identified the new capabilities required by the electricity system in 2030 in order to decarbonise [1], their reports did not offer a solution [2].

2. International interest in DC systems

The new renewable energy resources such as wind and solar (Photovoltaic) are DC based and require a conversion stage to integrate them to the AC system. Due to the intermittent nature of these resource batteries are often used. Batteries are inherently DC and used to overcome intermittency of supply, as well as in electric transportation. Electrification of transport and process heat are major pillars in reducing emissions and these are DC based.

At the household level, the drive for energy efficiency has caused most appliances that previously used a direct-connected induction motor to become inverter-based (that is use a variable speed drive (VSD)). There are great efficiency gains in using a VSD driven motor to drive a compressor motor in heat-pumps, fridges and freezers rather than an ON/OFF cycle based on a thermostat. Modern washing machines and clothes-dryers are also inverter-based. There are heat-pump based hot water heaters due to the coefficient of performance of the heat-pump cycle over direct resistive heating. Electronic loads are already DC based (entertainment equipment (TV, stereo, etc), bedside clock/radio, computers, chargers for various appliances, LED lighting). Other loads are resistive and hence can run on AC or DC.

This transformation is also occurring at the industrial and commercial level. Large VSD drives are being used in large numbers in numerous industries. Using DC reticulation will remove the need for the AC/DC conversion stage, bringing many benefits. Some industrial processes are inherently DC such as metallurgical processes (smelting), hydrogen production (electrolysis), electroplating to name a few. Data Centres are also DC based.

Around the world there is growing recognition that power electronic-based DC systems have significant advantages [3,4] and this is seen in the growing number of other universities and research organisations working on DC systems for the future power system. For example the Open Direct Current Alliance (ODCA) was formed by companies from industry, academia and research. ODCA promotes the activities of DC grids and to bring them to the market [5].

Technische Universität Dresden has started phase 2 of its AC2DC project funded by BMWi - Federal Ministry for Economic Affairs and Energy [6]. At present some of the FAN and AC2DC teams meet online every 6 weeks to share progress and learnings. Also a Post-doctoral fellow from FAN has visited T.U. Dresden and used their laboratory facilities.

The Japanese Government department New Energy and Industrial Technology Development Organisation (NEDO) is working on DC grids, more in the area of HVDC and MVDC [7]. Representatives from NEDO have visited the FAN programme and there is a plan for ongoing collaboration.

Another major DC related programme in Germany is Flexible Elektrische Netze (Flexible Electrical Networks) (FEN) hosted by RWTH Aachen University [8]. Their aim is to research and develop a flexible power grid that will better accommodate a high proportion of decentralised and renewable energy sources, so as to deliver a secure and affordable energy supply in the future. FEN focuses on the integration and development of DC technology. Again joint meetings have occurred online and one FAN researcher has visited RWTH Aachen University.

There exists an IEEE Power and Energy Society adhoc Committee on End-to-End Direct Current Power Networks [9]. The vision for this committee is end-to-end DC for the complete system, which is different to the hybrid AC-DC system FAN is pursuing. The chair of this IEEE committee visited the University of Canterbury in 2024. They are pursuing high voltage and power DC/DC converters utilising a solid-state transformer (high frequency coupling transformer).

IEC is producing technical reports and documents such as [10-14]. Ref. [10] covers AC, DC, AC/DC hybrid decentralized electrical energy system, such as distributed generation, distributed energy storage, dispatchable loads and virtual power plants.

Interest in DC systems is also shown by the increasing number of papers on the subject [15-19], technical conferences (such as the biannual *ICDCM* and *DC distribution networks* (Görlitz, 11-12 April 2024) and *I see DC Summit 2021: Direct Current. Your next energy* (May 2011) [20]).

HVDC has been continually of interest for the transportation of high power over long distances or to connect asynchronous AC systems, however, meshed HVDC is now a focus. More recently organisations such as IEEE [21] and CIGRE working groups have been developing reports on DC systems. The more notable are Technical Brochures [22- 29]. CIGRE technical brochures are reports outlining the state-of-the-art on the subject area.

In Europe, DC systems are of high interest for offshore windfarms, both for collector systems and transmission to the mainland. An example of this is the EU's Horizon 2020 Research Program *Progress on Meshed HVDC Offshore Transmission Networks* [30].

Another measure of the increased interest in DC systems for the future electrical network is in the advertisement for Ph.D. students and Post-doctoral fellows in avenues such as Powerglobe forum (an online community of those work in Power Systems).

Besides the above work on DC systems there is collaboration between the MBIE SSIF programmes *Aotearoa: Green hydrogen technology* and *High power electric motors for large-scale transport* with regular monthly meetings. Green Hydrogen is a promising fuel source for decarbonisation as it produces water when used and has great potential for aviation and ground transportation. DC is needed for electrolysis to produce hydrogen. Also hydrogen could be used as a storage medium to supply power to the electrical network when needed. *High power electric motors for large-scale transport* also relies on an electrical power system to be able to operate and the use of DC could be of advantage.

3. Structure of the Future Architecture of the Network (FAN) Programme

This programme aims to develop knowledge and understanding of the extent to which DC technology should penetrate the existing AC network, and also the associated challenges and solutions. A transition pathway is to be determined that makes the best use of existing infrastructure. The programme is strategic as the time horizon is 2050 and beyond. Besides the technical KPIs, there are also KPIs around training researchers in this emerging technology as well as creating benefit to Māori and under-represented groups. Training can involve undertaking Ph.D. studies/research, it also involves bringing expertise to New Zealand or sending researchers overseas for a period. Input via co-supervisors overseas also contributes to the outcome of the projects. The initial FAN team consisted of five New Zealand universities (University of Canterbury, University of Auckland, Auckland University of Technology, University of Waikato and Victoria University of Wellington) and one overseas university (University of Cambridge). Since then others have started contributing to FAN. An affiliate agreement was developed as an umbrella document to circumvent the need to have individual MOUs with each. As of the 23 February 2024, FAN had an affiliate agreement with: Aalborg University (Denmark), TU Dresden (Germany), TUMCREATE (Singapore), Prof Ioannis Lestas at the University of Cambridge (UK), University of New South Wales (Australia). Also, the University of Canterbury is in the process of signing the MOU with RWTH Aachen to join their International Energy Cooperation Programme and receiving a signed copy our affiliate agreement with them.

The FAN programme is split into five workstreams, four technical workstreams and Vision Mātauranga. Although Vision Mātauranga is identified as the fifth workstream it is to be embodied in all the four technical workstreams in some way.

4. Workstreams

4.1 Workstream 1 (WS1) Network Architecture

The objective of this workstream is to investigate what level of penetration of DC systems within the AC network is desirable, hence the architecture of the whole system. In order to achieve this, large-scale digital models encompassing DC grids and their interface to AC grids need to be developed. WS1 is developing techniques and prototype simulation tools to perform power-flow analysis, fault analysis and dynamic/transient analysis on large systems with a high penetration of DC subsystems.

To date, the power-flow analysis tool has well advanced and has been beta tested on a number of final year honours projects sponsored by industry (an energy company and an EDB). The fault analysis tool is well underway with a Ph.D. student working on this. The dynamic/transient tool is in the early stages with several options being investigated.

4.2 Workstream 2 (WS2) Topology

The next level down is looking at the topology of the circuits that make up the system. The configuration of the circuit and the control and protection are being investigated.

4.3 Workstream 3 (WS3) Converter topology, operation and enabling technologies

WS3 is very diverse as it covers the building blocks needed for the hybrid AC-DC system. To enable a proliferation of DC grids within AC grids many issues need to be addressed so that untoward behaviour is not experienced. Unwanted control interactions need to be avoided to ensure stable operation in a system with switching noise from multiple converters and possibly low network inertia. Also, attention needs to be paid to avoid DC egress into the AC network. Bidirectional AC/DC converters and DC/DC converters are being investigated. Good progress is being made on converters utilised in ancillary circuits such as DC breakers for circuit isolation.

The development of the control algorithms for the converters is progressing significantly, with dedicated Ph.D. students actively engaged in this research. Their work focuses on optimising and refining the algorithms to ensure efficient and reliable performance of the converters in various applications.

In parallel, the investigation and development of DC circuit breaker topologies are also advancing. This research aims to create innovative and effective solutions for interrupting DC currents in power systems, which is a critical aspect of ensuring safety and stability in DC networks. This ground breaking work is based on super-capacitor technology.

Preliminary results from these studies, based on comprehensive digital simulations, have shown promising outcomes. These findings have been disseminated and shared with the wider academic and professional community through presentations and publications in international conference proceedings. This dissemination not only highlights the progress made but also invites feedback and collaboration from experts in the field, fostering further advancements and refinements in the research.

4.4 Workstream 4 (WS4) Transition Path

Due to the extensive infrastructure already in place for AC networks, transitioning to a hybrid AC-DC system must be done incrementally. This approach ensures that existing investments are utilized effectively and the transition is smooth. This workstream has focused research on a number of key areas, including MVDC cables and insulators, LV cables, modelling and testing of transformers, and household equipment testing.

We have assessed the feasibility of reusing Medium Voltage (MV) AC cables and insulators in a DC system. This involves studying the degradation rates and determining the appropriate DC operating voltage for these components. The goal is to understand how these AC components perform under DC conditions and whether they can be reliably used in the new system. The research shows a DC system can greatly increase the power through a given corridor than an equivalent AC system. Similar assessments have been conducted for low-voltage (LV) cables. This involves evaluating their performance and suitability for DC applications, ensuring that they can handle the different electrical characteristics of DC.

Transformers have been modelled and tested to understand the implications of DC egress into the AC system from DC subsystems. This work has been centred around laboratory experiments on 15 kVA test transformers and through DC injection on large in-service power transformers. This helps identify potential issues and determine if any mitigation measures are needed to ensure the stability and reliability of the hybrid system.
A variety of household equipment has been tested and categorized based on their compatibility with DC power: We have categorised appliances into three categories:

- Can run on DC: Equipment that can operate directly on DC power without any modifications.
- Can run with minor modification: Equipment that requires slight adjustments to function on DC power.
- Cannot run on DC and needs redesigning: Equipment that is incompatible with DC power and requires a complete redesign to operate.

Following on from this, a university house has been made available to the FAN project. This house is being converted into a DC home to demonstrate the technology and showcase the practical applications of a hybrid AC-DC system. This real-world example helps in understanding the challenges and benefits of such a transition.

4.5 Workstream 5 (WS5) Vision Mātauranga (VM)

Vision Mātauranga (VM) is a government science and technology policy that seeks to unlock the innovation potential of Māori knowledge, resources and people. For the FAN project, giving effect to VM means encouraging and training Māori students. A summer project undertaken by several students developed ideas and a presentation as an outreach linking VM and FAN with the goal of empowering more Māori students in STEM related fields.

Another way FAN is giving effect to VM is by growing capability, understanding and interest working with Māori communities. One of these communities is located in Rangitikei/Manawatū and was represented by Graeme Everton. We sadly note the passing away of Graeme, who was a director of a Māori led start-up business (Sensing Value) and helped with the FAN's application.

We are thankful to now have Tipene Merritt, Kaiārahi Māori Research (Ngāti Kauwhata, Rangitāne, Ngāpuhi, Ngāi Te Rangi) joining the FAN team as the VM lead. Tipene is carrying on the VM work and is exploring additional Māori partnerships, most recently with Ōnuku Marae in Banks Peninsula. Tipene is also building and developing VM capability across all of the FAN workstreams (the third way FAN is giving effect to VM), by developing and delivering workshops. Further to this, Tipene is a part of FAN's leadership team, which meets fortnightly with other workstream leaders and is exploring co-authored articles where mātauranga Māori (Māori knowledge) and western science are used to complement each other.

5. Training the next Generation

One Ph.D. student has completed. He developed a new inverter control system that did not use a PLL and hence suitable for Type 4 Wind-turbines connected to a weak AC system. This concept has applications in other power electronic inverters.

In terms of research and developing capability the FAN programme has had:

- Five Masters students (of which 2 have completed)
- Five Postdoctoral fellows
- Eighteen Ph.D. students plus two Ph.D. students related to but not funded by FAN. One Ph.D. has completed and seventeen are still pursuing their Ph.D. studies.
- Forty summer students (plus thirteen student projects currently being advertised for summer 2024-2025)

- Sixty two undergraduate student projects
- Two interns
- One postgrad cert. student (completed)

6. Conclusions

The FAN project was awarded near the end of 2020 and progress was initially hampered by COVID which made it difficult to get Post-doctoral fellows and Ph.D. students working on the project. Since the COVID restriction have been lifted every effort has been made to accelerate progress and now significant advancement is being made.

Rather than designing fixes to allow the new technologies to operate in the present AC system, this project looks at what would be the best system for the future in order to meet the many objectives, such as allowing easy integration of new technologies, improve efficiency and thereby developing a low-carbon system, which is good for our planet. At the same time it needs to be cost-effective, reliable and resilient, particularly as more extreme weather events seem to be more common. Continuing to apply fixes to allow the new technologies to operate in the present AC system will result in a patch-up network that does not meet these objectives.

The world is moving to a DC world and there are many advantages and also many challenges to overcome. One of the biggest issues that is not talked about enough is standardisation. Until standards are established and accepted then equipment manufacturers will not have the confidence to build DC equipment without the AC/DC conversion stage. Also standardisation is needed to allow interoperability of equipment from various sources. The DC summit [20] had a session on IEC DC Standardization.

With a system dominated by power electronic converters, their topology and particularly the controller design is critical to ensure untoward interactions do not occur and to ensure stable operation. More work is needed on the controller design to ensure stability.

Protection systems still need development so that faults can be detected and isolated quickly and effectively. Safety and grounding also must be considered. Although DC circuit breakers at both HV and MV levels have been demonstrated at present, their cost and availability hinder their adoption, however, these barriers are expected to be broken down in the future.

Power Quality (PQ) is well developed for AC systems, however, power quality in DC system is in its infancy. First, the types of phenomena that constitute PQ issues in DC systems need to be identified and suitable indices developed. Then immunity, emission and compatibility levels need to be determined based on these PQ indices.

The FAN project has momentum now and is delivering on its KPIs. It is encouraging that many other groups are picking up the challenge to move to DC. The 2024 FAN Conference, when the FAN team met to present their progress, was held on 12th -13th of February in Christchurch. The next FAN Conference will be held on 4th -5th of February 2025 in Auckland. We warmly invite those interested to register, attend and participate. Please find out more at www.fan.ac.nz or futurearchitecturenetwork@canterbury.ac.nz .

References

[1] IET, Future Power System Architecture (FPSA) programme. [https://www.theiet.org/impact-society/sectors/energy/future-power-system-architecture]

[2] Catapult Energy Systems, Future Power System Architecture report - FPSA1, [https://es.catapult.org.uk/report/future-power-system-architecture-report-fpsa1/]

[3] N. Ertugrul and D. Abbott, DC is the Future, Proceedings of IEEE, Vol. 108, No. 5 May 2020

[4] F. Blaabjerg and S. Round, Power Electronics: Revolutionizing the world's future energy system, Hitachi ABB (August 2021)

[https://www.hitachienergy.com/news/perspectives/2021/08/power-electronics-revolutionizing-the-world-s-future-energy-systems]
[5] Open DC Alliance (ODCA) [https://odca.zvei.org/]
[6] New Energy and industrial technology Development Organization NEDO (Japan)
[7] AC2DC project, Technische Universität Dresden, Dresden, Germany
[8] Flexible Elektrische Netze (Flexible Electrical Networks) (FEN), RWTH Aachen University, Germany, [https://www.fenaachen.net/]
[9] R. Singh (Convenor), Report of the IEEE Power and Energy Society adhoc Committee on End-to-End Direct Current Power Networks, June 2024
[10] IEC, LVDC: electricity for the 21st century, 2017
[11] IEC TR 63282 ED2, LVDC systems - Assessment of standard voltages and power quality requirements, 2024
[12] IEC TR 63410:2023 Decentralized electrical energy systems roadmap, 2023
[13] IEC 61000-4-17:1999, Electromagnetic compatibility (EMC) - Part 4-17: Testing and measurement techniques - Ripple on d.c. input power port immunity test
[14] IEC 61000-4-29:2000, Electromagnetic compatibility (EMC) - Part 4-29: Testing and measurement techniques - Voltage dips, short interruptions and voltage variations on d.c. input power port immunity tests
[15] AC/DC Backing up AC grids with DC technology, p. 34 – 36, ABB Review: Special Report 60 years of HVDC, [https://library.e.abb.com/public/aff841e25d8986b5c1257d380045703f/140818%20ABB%20SR%2060%20years%20of%20HVDC_72dpi.pdf]
[16] S. Krahmer, S. Rupp, R. Adam, et al., "*Conversion of Existing AC into DC Cable Links in Distribution Grids: Benefits and Challenges*," ETG Congress 2021, Online, 2021, pp. 1-6.
[17] J. Zahid, I. Kocar, W. Holderbaum, and U. Karaagac. Future Distribution Networks: A Review" Energies 17, no. 8: 1822, 2024, https://doi.org/10.3390/en17081822
[18] E. Rodriguez-Diaz, M. Savaghebi, J. C. Vasquez and J. M. Guerrero, An overview of low voltage DC distribution systems for residential applications, 2015 IEEE 5th International Conference on Consumer Electronics - Berlin (ICCE-Berlin), Berlin, Germany, 2015, pp. 318-322, doi: 10.1109/ICCE-Berlin.2015.7391268
[19] W.A.G. de JAGER, P.J. Bos, I. Melnik, T. Brand, Design of the first public DC distribution grid in The Netherlands, Paper B4-201, CIGRE Paris Session, 2018
[20] I see DC Summit 2021: Direct Current. Your next energy, 18-20 May 2021, [https://new.abb.com/low-voltage/direct-current-systems/dc-summit accessed July 2024]
[21] IEEE Std 946-2020, IEEE Recommended Practice for the Design of DC Power Systems for Stationary Applications, vol., no., pp.1-74, 23 Sept. 2020, doi: 10.1109/IEEESTD.2020.9206101
[22] CIGRE WG A3.40, TB 93, Technical requirements and field experiences with MV DC switching equipment, May 2024
[23] CIGRE JWG C6/B4.37, TB 875 Medium Voltage DC Distribution Systems, June 2022
[24] CIGRE WG B4.74, TB 804 DC grid benchmark models for system studies, June 2020
[25] CIGRE WG B4.62, TB 831 Compact DC overhead lines, March 2021
[26] CIGRE WG B1.38, TB 841, After laying tests on AC and DC cable systems with new technologies, September 2021
[27] CIGRE JWG B4/A3.80, TB 873, Design, test and application of HVDC circuit breakers, July 2022
[28] CIGRE WG B4.76, TB 827, DC-DC converters in HVDC grids and for connections to HVDC systems, March 2021

[29] CIGRE WG B4.56, TB 657, Guidelines for the preparation of "connection agreements" or "grid codes" for multi-terminal DC schemes and DC grids, May 2016
[30] EU's Horizon 2020 Research Program Meshed HVDC Offshore Transmission Networks (PROMOTioN) [https://www.promotion-offshore.net/ accessed July 2024]