Institution: University of Aberdeen

Unit of Assessment: 12 (Engineering)

Title of case study: [IC2] Development of DC transmission grids using DC-DC converters

Period when the underpinning research was undertaken: 2010-2018

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Dragan Jovcic	Chair in Engineering	09/2004 - present

Period when the claimed impact occurred: 2014-2020

Is this case study continued from a case study submitted in 2014? Y

1. Summary of the impact (indicative maximum 100 words)

The expansion and secure transmission of large-scale offshore wind energy is likely to require direct current (DC) high-voltage electrical grids. Research undertaken at the University of Aberdeen High Voltage Direct Current (HVDC) research centre, led by Professor Jovcic, has demonstrated the advantages of building DC offshore grids using DC/DC converters designed in his research projects. Building on this research, Jovcic has contributed to the development of influential documents via the establishment of working group B4.76 in the International Council on Large Electric Systems (CIGRE - a leading organisation, which informs decision-makers and regulators). The team's research has underpinned the implementation of a hardware prototype DC/DC converter for Réseau de Transport d'Électricité (RTE) in Europe and shaped the development of a CIGRE DC grid benchmark system, used around the world including in Norway and China.

2. Underpinning research (indicative maximum 500 words)

The International Energy Agency predicts that wind will become Europe's number one source for power generation by 2027, and European Green Deal estimates that European offshore renewable energy capacity needed by 2050 is 240-450GW, mostly located 100-200km from the shore. Existing onshore power networks are based on AC, which can only be used offshore over relatively short distances (tens of kilometres). High voltage Direct Current (HVDC) is considered suitable for the transmission of power over long distances, but needs to be substantially further developed to facilitate high-reliability, meshed, offshore DC grids. The technologies for DC circuit interruption and DC/DC voltage transformation at high powers do not exist, and their perceived costs present a major barrier to uptake by industry.

The Aberdeen HVDC research centre has attracted significant external funding to develop high gain, GW-scale DC/DC converters, which will be one of the building blocks in the development of a multi-terminal HVDC network in the North Sea. Jovcic has developed new DC/DC converter topologies, which offer benefits in terms of efficiency, reliability, and cost compared to the alternatives. In collaboration with colleagues at McGill University, he evaluated the potential benefits of DC/DC conversion over traditional methods of offshore wind energy integration and found that a DC collection grid using DC/DC converters would allow a substantial reduction in the weight of the cables and magnetic components [1].

This research led to a new project, sponsored by the *Engineering and Physical Sciences Research Council (EPSRC),* to investigate the feasibility of developing the DC/DC converter technology [P1]. The designed converter achieves current regulation even under extreme external DC faults and, therefore, can operate through DC faults [2]. In the subsequent EPSRC research project [P2], together with 3 Chinese institutions and the University of Strathclyde, Jovcic's research team

evaluated applications in DC grids and developed 30kW prototypes in Aberdeen [3] and at the Chinese grid operator site, thereby increasing confidence in the technology. The hardware results have confirmed the technology's techno-economic advantages over other DC/DC systems studied worldwide, and removed perceived barriers related to losses and feasibility of DC/DC at high power levels.

In parallel to [P2], Jovcic was also awarded a starting grant under the FP7 Ideas programme by the European Research Council [P3] to develop modelling tools for designing high-power, multi-terminal DC grids. Additionally, through this project, the DC/DC concept is expanded towards advanced multi-port converters (hub or electronic substation), resulting in a converter with the ability to operate normally through DC faults on any single port [4]. The findings attracted the attention of French company RTE, Europe's largest grid operator. RTE have an interest in utilising DC grids as the means to connect numerous offshore wind farms in the Mediterranean and the North Sea with the French electricity transmission system. Based on the findings, RTE provided funding for a new project [P4], which compared a range of DC transmission options, concluding that the use of DC/DC converters may enhance operating flexibility and power security while keeping costs and power losses competitive [5].

With increasing interest from industry, the HVDC Research Centre began an initiative in 2013 to explore the use of modern modular multilevel converter (MMC) technologies for building DC hubs. With this aim, a new project was subsequently funded by Scottish grid operator, SSE (Scottish and Southern Energy) [P5]. Through the SSE-proposed MMC DC hub test case, the team has shown an acceptable frequency range for onshore and offshore applications, considering detailed loss, weight, and harmonic analysis [6].

3. References to the research (indicative maximum of six references)

[1] J Robinson, **D Jovcic** and G Joos, "Analysis and Design of an Offshore Wind Farm Using a MV DC grid" in IEEE Transactions on Power Delivery, Vol. 25, Issue 4, Oct. 2010, pp 2164-2173, **DOI**: 10.1109/ISGTEurope.2011.6162829

[2] **D Jovcic** and L Zhang, "LCL DC/DC Converter for DC Grids" in IEEE Transactions on Power Delivery, Vol. 28, Issue 4, Oct. 2013, pp 2071-2079. **DOI:** 10.1109/TPWRD.2013.2272834

[3] S M Fazeli**, D Jovcic** and **M Hajian**, "Laboratory Demonstration of Closed-Loop 30 kW, 200 V/900 V IGBT-Based LCL DC/DC Converter" in *IEEE Transactions on Power Delivery*, Vol. 33, Issue 3, Jun. 2018, pp 1247-1256. **DOI:** 10.1109/TPWRD.2017.2756987

[4] **D Jovcic** and W Lin, "Multiport High-Power LCL DC Hub for Use in DC Transmission Grids" in IEEE Transactions on Power Delivery, Vol 29, Issue 2, Apr. 2014, pp 760-768. **DOI:** 10.1109/TPWRD.2013.2280759 (RTE)

[5] **D Jovcic,** M Taherbaneh, J P Taisne and S Nguefeu, "Topology Assessment for 3 + 3 Terminal Offshore DC Grid Considering DC Fault Management" in IET Generation Transmission and Distribution, Vol. 9, Issue 3, Feb. 2015, pp 221-230. **DOI:** 10.1049/iet-gtd.2013.0838

[6] Jamshidi Far, **M Hajian**, **D Jovcic** and Y Audachya, "High-Power Modular Multilevel Converter Optimal Design for DC/DC Converter Applications" in IET Power Electronics Vol. 9, Issue 2, Feb. 2016, pp 247-255, **DOI:** 10.1049/iet-pel.2015.0516.

Grants

[P1] Jovcic, Development of DC Transformer and Fault Current Limiter for high-power DC networks EPSRC (EP/H010262/1) (2010-2013; GBP297,055)

[P2] Jovcic, DC Networks with DC/DC Converters for Integration of Large Renewable Sources EPSRC (EP/K006428/1) (2013-2016; GBP734,786)

[P3] Jovcic, ERC FP7 'Ideas' programme Starting grant no 259328 "Modelling platforms for high-power resonant DC hub and power networks with multiple converter systems" (2011-2015; EUR718,016)

[P4] Jovcic, RTE (Réseau de Transport d'Électricité, France) "Development of RTE NorthSea DC grid" Post Doc fellow (2012-2013)

[P5] Jovcic SSE (Scottish and Southern Energy) "Isolated multi-terminal DC/DC converter for high power DC grids" Post Doc Fellow (2015-2016)

4. Details of the impact (indicative maximum 750 words)

Wind energy is expected to be the primary source of electrical energy by 2027, necessitating an increase in the pace of the renewable energy buildout. Considering the expected cost, in excess of GBP100,000,000 per gigawatt (GW) DC/DC converter, development of these technologies relies on scaled-down hardware prototypes, and simulation on full-power test cases and Benchmark models agreed with all stakeholders. Upscaling of these prototypes requires a long lead time and considerable investment. Research carried out at the University of Aberdeen has yielded important new evidence demonstrating the potential role for DC/DC converters in future offshore DC transmission grids.

The acceptance of new technologies is conditional on studies and consensus in international working groups, largely in the CIGRE community. CIGRE is the most influential international professional organisation in the power transmission industry, bringing together global expertise (manufacturers, grid operators, and developers) and is the authoritative source of power system technical reference documents. CIGRE activities (WG meetings, brochures, articles, conferences, green books) have substantial weight in the professional community in defining best practice, professional methods, in system planning and policy making, while brochures serve as de-facto standards.

Informing best practice and building confidence in the technology

Within the current REF period, Jovcic was an invited member of and representative of the UK in CIGRE WG (Working Group) B4.58, "Control Methodologies for Direct Voltage and Power Flow in a Meshed HVDC Grid" from 2013-2017. The findings, resulting from Aberdeen research on DC/DC converters were used as technical background for Chapter 5 of brochure 699 (B4.58) [S1] and were also employed as test cases based on research projects [P1, P2, P3] and results in [1-5]. This technical brochure represents an important attempt to provide international consensus on the requirements, classification and description of methodologies for direct voltage control and power flow control in a meshed HVDC grid. The working group affirmed that DC grids are feasible, enabling planning to move to the next stage, including more detailed component and system studies.

Jovcic, as WG B4.58 representative, participated in the development of a CIGRE DC grid benchmark test system, supported by two CIGRE working groups (B4.57 and B4.58), which is based on topology and parameters agreed by wider industry in CIGRE. In this regard, a DC grid benchmark model can provide a common reference and study platform for researchers to compare the performance and characteristics of different DC control functions and protection strategies [S2]. This model has become the primary DC grid test system, providing a common reference platform employed in most EU Horizon2020 research/demonstration projects on DC power transmission grids, allowing researchers to compare the performance and characteristics of a DC grid with different DC control functions and protection strategies. Major operators have used the model including SINTEF, the Norwegian grid operator [S8i] and the State Grid Corporation of China, which is the largest utility company in the world [S8ii]. EU projects that have used the model to address research challenges include Best Paths (2014-2018), which used the model to analyse the impact of various conditions on the degree of coupling of different subsystems in an interconnected AC/MT-HVDC system (http://www.bestpaths-project.eu/) and MEDOW (Multi-terminal DC grid for offshore wind; 2013-2017) to demonstrate a scaling method, which has potential for further development in order to achieve uniform dynamic responses between

experimental test rig and HVDC system. (https://cordis.europa.eu/project/id/317221, http://sites.cardiff.ac.uk/medow/) [S9].

Establishing and chairing B4.76 CIGRE working group

Jovcic recognised early on that there would be a necessity for DC-DC converters, which do not currently exist at transmission level, in order to build the safe, flexible and economical offshore DC transmission systems necessary for integration of 100s of GW of offshore energy in projects [P1-P5]. By 2017, the research and development of GW-scale DC/DC converters had advanced to a point where it was considered technically feasible but coordinated work across the professional community was needed for the acceptance of this new technology. To meet this need, in 2017 Jovcic submitted a proposal to establish a new Working Group on DC/DC converters in the CIGRE B4 study committee, which was approved under the title: B4.76, "DC-DC converters in HVDC Grids and for connections to HVDC systems" and Prof Jovcic was appointed WG chairman [S3].

CIGRE working group B4.76, consisting of 15 members and 5 corresponding members from 7 countries, provided the initial recommendation for high power test DC-DC converter based on non-isolated approach. While worldwide manufacturers have their own preferred topology for non-isolated DC-DC, commonly IP protected and only some reported in public, the developed test case is vendor-neutral but represents functionalities and performance acceptable for all vendors (manufacturers members of B4.76 included ABB, Siemens and Mitsubishi). In June 2019, Jovcic and members of the B4.76 working group (including representatives from ABB and Supergrid Institute) presented a CIGRE paper [S10] outlining the topology, test system parameters, performance and models for the CIGRE DC-DC test converter. The DC-DC test case enables DC grid developers to perform studies on a single DC-DC model, with the understanding that conclusions will be largely valid for DC-DC supplied by various vendors. The design study in [S10] further illustrates CIGRE expert consensus that the non-isolated DC/DC converter will have an overall semiconductor count comparable to an AC/DC converter of similar rating, which provides the first credible estimates for the system costs, size and weight and therefore reduces concerns relating to cost-effectiveness.

This case study forms a basis of technical work in B4.76, which includes a further isolated DC-DC test case developed on similar principles. The working group completed work in 2020 and a technical brochure 827 [S4] was released in March, 2021. This technical brochure includes a comprehensive survey of all worldwide DC-DC manufacturers, conducted in 2019 (5 responses were received). The responses present manufacturers views on the expected application areas, deployment, functionalities, technologies and readiness level, and these responses are provided in full in the Appendix of the brochure. They give first-hand information to DC grid developers and planners on the technologies under development.

Influencing decision making and strategic objectives of EU grid operator

As part of their 2017-2020 R&D programme, RTE indicated that their Research and Development (R&D) activities had oriented towards 'improving performance and securing its technical choices, including increasing the transmission capacity of cables, qualifying new technologies to master their impacts before deploying them on an industrial scale'. Towards meeting these objectives, RTE initiated a project that incorporated the Aberdeen DC/DC converter [P4] into a European laboratory DC grid prototype project at École Centrale de Lille, financed and operated by RTE [S7]. In 2017, in collaboration with Jovcic and Hajian, Spanish university UPC (Universitat Politècnica de Catalunya, BarcelonaTech) was contracted by RTE to build the 10-kW Aberdeen converter under a license agreement. The confirmation of performance and benefits of this demonstrator have been shared in a 2017 publication [S5].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] CIGRE WG B4.58 "Control Methodologies For Direct Voltage and Power Flow in a Meshed HVDC Grid" CIGRE Technical Brochure 699, Paris, September 2017 (Chapter 5 author), https://bit.ly/3tzJKIc

This source illustrates that Prof Jovcic is a member of B4.58 and that he wrote Chapter 5 of Technical Brochure 699 on DC/DC converters.

[S2] T K Vrana, Y Yang, D Jovcic, S Dennetière, J Jardini, H Saad, 'The CIGRE B4 DC Grid Test System", ELECTRA issue 270, October 2013, pp 10-19, https://bit.ly/2NE6mIo
This source confirms that Prof Jovcic is an author of the CIGRE DC grid benchmark system.

[S3] CIGRE study committee B4 chairman statement related to CIGRE B4.76 working group
This source provides relevance of CIGRE B4.76 activities

[S4] CIGRE WG B4.76, DC-DC converters in HVDC grids and for connections to HVDC systems, CIGRE TB 827, Paris, March 2021 https://bit.ly/3c20Ecv
This source confirms of CIGRE B4.76 brochure, and shows the list of experts, with Prof Jovcic as chairman.

[S5] CIGRE WG B4.58 "Control Methodologies For Direct Voltage and Power Flow in a Meshed HVDC Grid" CIGRE Technical Brochure 699, Paris, September 2017 (Chapter 5 author), https://bit.ly/3cSxJ9U
This source illustrates that Prof Jovcic is a member of B4.58 and that he wrote Chapter 5 of Technical Brochure 699 on DC/DC converters.

[S6] T K Vrana, Y Yang, D Jovcic, S Dennetière, J Jardini, H Saad, 'The CIGRE B4 DC Grid Test System", ELECTRA issue 270, October 2013, pp 10-19, https://bit.ly/3vASU98
This source confirms that Prof Jovcic is an author of the CIGRE DC grid benchmark system.

[S7] R. Ferrer San José et al., "Design and Implementation of an LCL DC/DC Converter Prototype for DC Grids" COSYS-DC 2017: International Conference on Components and Systems for DC Grids: Grenoble, France: 14-15 March, 2017, http://hdl.handle.net/2117/123053
This source confirms that Aberdeen DC/DC is incorporated in the Lille DC grid prototype, under the RTE funded project.

[S8] (i) Ting AN, Congda HAN, Yanan WU, Guangfu TANG, 'HVDC grid test models for different application scenarios and load flow studies', J. Mod. Power Syst. Clean Energy (2017) 5(2):262–274, DOI 10.1007/s40565-016-0214-7
This source illustrates that CIGRE DC grid benchmark system is used for R&D supported by the State Grid Corporation of China

(ii) S. D'Arco, J. Beerten, J. A. Suu, 'Classification and analysis of impact on small-signal dynamics and stability from expansion of VSC-HVDC systems to multiterminal HVDC grids', 13th IET International Conference on AC and DC Power Transmission - ACDC 2017, DOI: 10.1049/cp.2017.0050;
This source illustrates that CIGRE DC grid benchmark system is used for R&D at SINTEF Energy Research

[S9] Details of Bestpaths project (http://www.bestpaths-project.eu/) and MEDOW project https://cordis.europa.eu/project/id/317221, both of which used the DC grid benchmark model

[S10] D Jovcic, P Dworakowski, G Kish, A Jamshidifar, A Nami, A Darbandi, X Gulllaud, "Case Study for Non-Isolated MMC DC-DC Converter in HVDC Grids" CIGRE B4 Colloquium Aalborg Jun. 201CIGRE
This source describes non-isolated DC-DC test case developed by B4.76