Institution: Cardiff University		
Unit of Assessment: Engineering (12)		
Title of case study: Advancing the capacity, cost-effectiveness, and reliability of DC electrical transmission systems within the UK and Europe		
Period when the underpinning research was undertaken: 01/10/2009 – 31/12/2020		
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:
Carlos Ugalde-Loo	Reader	17/02/2010 - present
Jun Liang	Professor	01/01/2008 - present
Nicholas Jenkins	Professor	17/03/2008 - present
Wenlong Ming	Senior Lecturer	01/08/2016 - present
Jianzhong Wu	Professor	26/06/2008 - present
Period when the claimed impact occurred: 01/08/2013 – 31/12/2020		
Is this case study continued from a case study submitted in 2014? No		

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

Generation and transmission of offshore renewable electricity is complicated by transmission losses and integration of direct and alternating current (AC) operations. Cardiff research on control strategies for direct current (DC) grids and conversion to medium- and high-voltage systems resulted in:

- Europe's first upgrade of an idle AC transmission corridor to a 30MW medium-voltage DC link, creating 200 jobs and £35M of economic impact;
- the creation and verification of control strategies for offshore DC for National Grid, saving at least £10M through greater efficiency and risk mitigation;
- exploration of risk management for introducing DC circuit breakers, enabling confidence in National Grid strategies for large-scale high-voltage DC infrastructure projects.

2. Underpinning research (indicative maximum 500 words)

One of the most efficient solutions to reducing CO_2 emissions is through increased use of offshore renewable energy sources. However, connecting offshore power has one key challenge: the amount of transmission losses. This can be overcome by using DC links, which enables more efficient electrical power transmission but requires careful integration within the existing AC grid to maximise its potential.

Infrastructure can be upgraded via Medium-Voltage Direct Current (MVDC) and High-Voltage Direct Current (HVDC) systems, which expedite the delivery of power to AC grids while increasing flexibility and reliability of the transmission network. The Cardiff University Centre for Integrated Renewable Energy Generation and Supply has undertaken extensive research on MVDC and HVDC technologies since 2010, including developing a bespoke four-terminal 10kW DC test rig real-time simulator, and hardware-in-the-loop experimental studies. This has been used to explore the following:

2.1 Topologies

Topologies for the integration of large-scale renewable energy sources to AC systems from different countries were assessed. Working with Universidad Politécnica de Cataluña, Cardiff explored control systems to achieve automated coordination between HVDC systems for large offshore wind farms without the need for the HVDC systems to communicate among each other **[3.1]**. This supported the design of new control strategies, algorithms for converter coordination, offshore grid design, and system performance upon faults.

2.2 DC grid protection and control

Cardiff research verified advanced control methods for DC grids in collaboration with Alstom Grid (now General Electric) **[3.1, 3.2, 3.3]**. Carrying capacity of DC lines is limited by thermal and electric stress levels, placing line current restrictions to prevent damage. In dense DC grids, however, managing individual lines is impossible without additional current flow controllers (CFC). Cardiff developed a bespoke scheme that eases the workload of individual CFCs by sharing the control voltage between multiple CFCs **[3.2]**, avoiding control conflicts during communication failure. The CFC concept to improve the controllability of a DC grid, and the reliability and lifetime of DC cables, was verified through simulations and experimentally validated through small-scale prototypes. Protection strategies have also been verified, leading to the development of unique circuit breaker devices **[3.3]** subverting the current proliferation of AC circuit breakers to protect DC networks.

2.3 Ancillary services provision

Cardiff developed supplementary control algorithms embedded in HVDC converters to reinforce the safe operation of AC grids. Services include frequency support and the damping of oscillations. The algorithms contribute to the fast balancing of generation and demand upon major events impacting the power system (e.g. loss of a large wind farm or fossil-fuel based generation) and the damping of subsynchronous resonance affecting thermal-based generation connected to nearby series capacitive compensation **[3.4]**.

2.4 MVDC networks

In addition to HVDC analysis, Cardiff developed models for reliable operation of medium-voltage AC and DC networks **[3.5, 3.6]**. Networks now employ an increasing number of distributed generators, which can result in operational power losses and thermal overloads. Cardiff research into MVDC links as both a solution and enhancement of existing network assets included control and optimisation algorithms, verified converter configurations, and assessed power quality aspects.

Supporting research grants include multiple EU grants. The Cardiff-led MEDOW **[G3.1]** consortium, between 11 academic and industry partners, compared DC grid topologies and stability control strategies for interconnecting offshore DC grids to onshore AC networks. In the BEST PATHS project **[G3.2]** Cardiff worked with 39 EU partners (including eight transmission system operators) and led the development of an open-access toolbox for the grid-connection of offshore wind farms using HVDC. This has since been downloaded across the world. Cardiff also led the InnoDC project **[G3.3]** with eight universities and six industry partners to investigate connections from offshore renewable energy into existing power networks.

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

[3.1] **Liang J**, Jing T, Gomis-Bellmunt O, Ekanayake J, **Jenkins N**, 'Operation and Control of Multiterminal HVDC Transmission for Offshore Wind Farms,' *IEEE Transactions on Power Delivery*, vol. 26, no. 4, pp. 2596-2604, 2011 (doi: 10.1109/TPWRD.2011.2152864).

[3.2] Balasubramaniam S, **Ugalde-Loo CE**, **Liang J**, Joseph T, King R, Adamczyk A, 'Experimental Validation of Dual H-Bridge Current Flow Controllers for Meshed HVdc Grids', *IEEE Transactions on Power Delivery*, vol. 33, no. 1, pp. 381-392, 2018 (doi: 10.1109/TPWRD.2017.2752301).

[3.3] Dantas R, **Liang J**, **Ugalde-Loo CE**, Adamczyk A, Barker C, Whitehouse R, 'Progressive Fault Isolation and Grid Restoration Strategy for MTDC Networks', *IEEE Transactions on Power Delivery*, vol. 33, no. 2, pp. 909-918, 2018 (doi: 10.1109/TPWRD.2017.2720844).

[3.4] Joseph T, **Ugalde-Loo CE**, Balasubramaniam S, **Liang J**, 'Real-Time Estimation and Damping of SSR in a VSC-HVDC Connected Series-Compensated System,' *IEEE Transactions on Power Systems*, vol. 33, no. 6, pp. 7052-7063, 2018 (doi: 10.1109/TPWRS.2018.2854641).

[3.5] Joseph T, **Ming W**, Li G, **Liang J**, Moon A, Smith K, Yu J, 'Analysis of harmonic transfer through an MVDC link', *15th IET International Conference on AC and DC Power Transmission (ACDC 2019)*, Coventry, UK, 5-7 February 2019, pp. 1-6 (doi: 10.1049/cp.2019.0017).

[3.6] Qi Q, Long C, **Wu J**, Yu J, 'Impacts of an MVDC Link on the Performance of Electrical Distribution Networks,' *Applied Energy*, vol. 230, pp. 175-188, 2018 (doi: 10.1016/j.apenergy.2018.08.077).

Selected grants:

[G3.1] 'Multi-terminal DC grid for offshore wind (MEDOW)', EU FP7-PEOPLE, ID 317221, April 2013 to March 2018. Total award €3,925,537, Cardiff award: €1,568,052.

[G3.2] 'Beyond state-of-the-art technologies for power AC corridors and multi-terminal HVDC systems (BEST PATHS)', EU FP7-ENERGY, ID: 612748, Oct 2014 to September 2018. Total award: €62,802,255, Cardiff award: €643,249.

[G3.3] 'Innovative tools for offshore wind and DC grids (InnoDC), H2020-EU.1.3.1., ID: 765585, September 2017 to August 2021. Total award €3,893,199, Cardiff award: €1,093,151.

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

DC power enables more efficient electrical power transmission but requires careful integration within the existing AC grid to maximise its potential. The Cardiff Centre for Integrated Renewable Energy Generation and Supply advanced the capacity, cost-effectiveness, and reliability of DC electrical transmission systems within UK and Europe across three key areas:

1. The Angle-DC connection: a £15 million project for Europe's first AC to DC retrofit, designed to increase network capacity and regional economic growth.
2. Developed and de-risked control strategies for connecting offshore DC power, saving the National Grid at least £10M.
3. Enabled the introduction of DC circuit breakers into transmission systems, building National Grid's confidence for strategic HVDC infrastructure projects.

4.1 The Angle-DC Connection

The Angle-DC project is an industrial pilot project led by Scottish Power Electrical Networks (SPEN) to overcome limitations of the existing infrastructure connecting the Isle of Anglesey with Bangor by retrofitting AC circuits to MVDC. James Yu, the Future Network Manager at SPEN, noted that Cardiff was selected as the project's academic partner in recognition of twelve years of "*extensive and acknowledged research work*", and that it was **"***the strongest and most suitable institution to support the development of the investment case"* **[5.1]**.

Cardiff's wide-ranging support for the investment case – including simulation studies, models, and technical recommendations – resulted in Ofgem announcing a £13.5M investment in the Angle-DC project, with an additional £1.5M invested by SPEN (£15M total investment) **[5.1]**. The project completed the MVDC link between Anglesey and Bangor in April 2020, with functionality tests and full commission completed by end of July 2020 **[5.1]**.

By allowing a better utilisation of existing assets, additional network operational capacity has been made available. Conversion of the existing 24.8MW AC circuit to MVDC increased transmission capacity by 23%. SPEN stated: "*The [MVDC] link has increased the operational power transfer capability between Anglesey and mainland by 30.5MW.*" **[5.1]** SPEN further confirmed that, following the transmission increase, the "*previously normally open*" (meaning unused) transmission corridor between Anglesey and Bangor is now permanently connected **[5.1]**. Based on the trial validation period 2020-2050, SPEN forecast around £18.67M in economic energy savings and annual reduction of CO_2 of 128 tonnes a year, worth £20M in carbon benefits **[5.1]**.

The scale of the Angle-DC project enabled further impact through economic and social benefits that SPEN confirmed "*Cardiff was instrumental in supporting*" **[5.1]**. Between 2016 and 2020 the project created 200 FTE jobs (80 FTE direct and 120 FTE indirect positions) **[5.1]**. Through the jobs created, and with wider economic benefits from additional community engagements undertaken by the company, SPEN estimated that the project led to *"socio-economic impact of at least £20 million"* **[5.1]**.

Angle-DC has been enthusiastically received by Welsh Government, who in a report discussing the Angle-DC project, anticipated future low-carbon economic growth in North Wales through widespread "ripple effects across the system" **[5.2**, p.18**]** linked to increased renewable power whilst enabling greater transmission efficiency using existing infrastructure. Based on the success of Angle-DC, 25 additional projects across the UK are now being actively investigated **[5.1]** that could see significant economic and functional benefits to electrical transmission. SPEN forecast that the projects could bring economic impacts of £69.2M by 2030, escalating to £396M by 2050.

4.2 HVDC for National Grid offshore transmission

DC networks have a lower impedance than AC systems of equivalent rating and exhibit faster fault propagation and a higher rate of change in fault currents. Control strategies and protective devices are thus required for the safe and reliable operation of HVDC grids. Tools, such as the Cardiff-led BEST PATHS **[5.3]** simulation toolbox for HVDC grid-connection of offshore wind farms integral to transmission system operators, manufacturers, and companies for system studies, design, and performance improvement **[5.4]**. Cardiff also influenced grid design for National Grid through multiple Network Innovation Allowance (NIA) projects, including **a)** testing of control strategies for HVDC grids and **b)** investigation into DC circuit breakers, as detailed below.

a. Control strategies for HVDC grids

In 2012, Cardiff began collaborating with National Grid to investigate Voltage Source Converter-based (VSC) HVDC technology for integrating offshore wind power into onshore grids and interconnection with neighbouring countries. While the potential of VSC links was recognised, National Grid had not yet implemented VSC-HVDC converters in their transmission system prior to the NIA projects**.** National Grid's significant interest in HVDC control systems relates to HDVC systems suitability in high-power applications, such as the 2.2GW Western HVDC Link and offshore DC links for integration of large-scale wind farms. Paul Gallagher, Head of Innovation at National Grid confirmed that ensuring reliability of such high-power links is critical with "*potentially significant direct impacts on the NGET's network assets/performance*" **[5.5]**.

National Grid confirmed the Cardiff-developed VSC Control Strategy rectified the management of risks associated with introducing new technology into British electricity transmission networks**,** thereby "*derisking the failure caused by improper operation and control of HVDC systems*" **[5.5]**. Recognising that the overall savings of new HVDC operation and control strategies is approximately £100M, National Grid specifically highlight the "*autonomous converter control proposed by Cardiff University contributes up to 5% savings against this cost, i.e. £5 million*" **[5.5]**.

National Grid also note that the successful implementation of the control strategies was enabled by extensive testing at Cardiff. Delayed commissioning or interrupted HVDC links cost National Grid "*of the order of £5 million per month*" **[5.5]** with potential for additional further costs. The validation of operation within the Cardiff test-rig led National Grid to "*identify these potential problems before contract placement and allow the above costs to be avoided*" **[5.5]**. This represents a further £5M in economic savings.

b. DC circuit breakers

Between July 2012 and November 2017, Cardiff collaborated with National Grid on an NIA project (NGET0060) that investigated DC circuit breakers for HVDC grids **[3.3]**. Prior to this project, no DC Circuit Breaker was available for such application **[5.5]**, meaning a single fault would affect an entire DC network, limiting the deployment of DC grids. Cardiff's investigations into reliable and cost-effective protective devices and protection strategies formed "*an essential component of the risk managed introduction of the DC circuit breaker into the transmission system*" **[5.5]**. National Grid further stated: "*The main* *impact of the research outcome is that it directly built up confidence for the HVDC links in the technical roadmap developed by National Grid*" **[5.5]**.

National Grid confirmed that the implications of Cardiff's research translated into development of several strategic and operational plans. Specifically, National Grid specified the research informed development of National Grid Risk Registers, Policy Statements and "*Technical Specifications relating to both strategies and assets for fault management for high power DC applications*" for projects such as the GW-level Eastern HVDC Link: a proposed 400kV link between Aberdeenshire and North Yorkshire **[5.5]**.

4.3 Summary

Cardiff's research into converting medium- and high-voltage systems enabled Europe's first upgrade of an idle AC transmission corridor to a 30MW medium-voltage DC link, creating 200 jobs and £35M of economic impact. Further research created and verified control strategies for offshore DC connections for National Grid, saving at least £10M through greater efficiency and risk mitigation, and enabled confidence in UK-wide strategies for large-scale high-voltage DC infrastructure projects.

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

[5.1] Testimonial: Prof James Yu, Future Networks Manager, Scottish Power Energy Networks, July 2020

[5.2] Welsh Government, *Welsh Government Smart Living Initiative*, July 2018

[5.3] 'BEST PATHS Toolbox for HVDC connection of offshore windfarms featured in Venice', BEST PATHS project press release, April 2017

[5.4] 'BEST PATHS comes to an end and claims for further actions to improve Europe's energy grid', BEST PATHS project press release, September 2018

[5.5] Testimonial: Paul Gallagher, Head of Innovation, National Grid Electricity Transmission plc., January 2020