

HVDC – ENABLING THE TRANSITION TO AN ENERGY SYSTEM BASED ON RENEWABLES

O. Vestergaard¹, B. Westman², G. McKay³, P. Jones⁴, J. Fitzgerald⁵, B. Williams⁶

¹⁺²ABB AB, Sweden, ole.vestergaard@se.abb.com, bo.westman@se.abb.com

³⁺⁴ABB Ltd, United Kingdom, grant.mckay@gb.abb.com, peter.r.jones@gb.abb.com

⁵⁺⁶EirGrid, Ireland, john.fitzgerald@eirgrid.com, brian.williams@eirgrid.com

Keywords: HVDC, interconnection, transmission, renewable, wind.

Abstract

Submarine cable transmission and grid interconnections will play a critical role in enabling Ireland and the UK to develop their rich renewable energy resources, in particular offshore wind power. Generation based on renewables has a rapidly varying output, which requires complete control of the power flows to the main AC grid, as well as reactive power control at the transmission terminals. It also requires asynchronous interconnections between main AC grids for security of supply and power export. VSC-based HVDC transmission schemes can fulfil this combination of requirements.

1 Introduction

Harnessing renewable power sources, especially wind energy, has become a major task for European power companies and transmission system operators (TSOs). The driving forces have mainly been environmental, and formalized by legislation.

HVDC transmission technology is of particular interest for power transfer between asynchronous AC grids in order to increase the security of supply between grids with wind farm generation.

2 Firm EU commitments for renewables

The need to gradually replace fossil fuels with environmentally sound and sustainable energy sources is a major objective of the European Union [1]. The overall EU target is a minimum of 20 percent renewable energy generation by 2020. For Ireland and the UK the national targets differ from each other; the 2020 target for Ireland is 42.5 percent renewable energy and for the UK a minimum of 15 percent renewable energy.

2.1 All Ireland potential for renewables

In its National Renewable Energy Action Plan (NREAP) submission [2] to the European Commission the Government of Ireland increased its target from 33 percent [3] to 42.5 percent of electricity consumption from renewable generation by 2020. Together with the initiatives of Northern Ireland these represent ambitious targets for the all-island (Ireland and Northern Ireland)

power system with the bulk of this renewable capacity expected to be provided by wind farms.

To meet these targets it is envisaged that over 6000 MW of onshore and offshore wind farms will be required by 2020 and within the context of the all-island power system this will at times represent greater than 50 percent of the on-line generating capacity. To integrate this level of wind penetration will require rapid, efficient and reliable control of power flows, grid voltages and also of back-up generation.

These targets will be facilitated by subsea interconnections that provide the ability to export over-supply or import shortfalls of variable renewable energy between the interconnected markets of Ireland, the UK and Europe.

2.2 UK potential for renewables largest in Europe

Offshore wind farm development is making major progress in the UK. This commenced in 2000 with the announcement of Round 1, where awards were made for eighteen sites with a combined capacity of 1.5 GW. Following the success of this initial demonstration phase, further awards for Rounds 2 and 3 plus Round 1 and 2 extensions and the Scottish Territorial Waters, has identified development sites with a total combined capacity of close to 50 GW.

In its *UK as a net electricity exporter scenario*, the *Offshore Valuation report* [4] states that the UK has the largest potential offshore renewable resources in Europe. Many of these renewables are also within fairly close distances from major energy markets in France and Germany. Power transmission links from these resources can be designed as connections that can also be used for power exports or imports.

This scenario calls for a total installed offshore generating capacity of 169 GW by 2050, utilizing 29 percent of the practically usable renewable resources – with the major part being wind generation. However, a development on this scale would require a large, controllable, power transmission grid interconnecting the offshore generation schemes and the land-based AC grids.

3 Large scale wind generation necessitates flexible grids

Renewable sources, including wind energy, have a variable output which can be predicted fairly accurately on a long term basis, but with a much higher level of skill required on a short term basis. Adding renewable generation and at the same time phasing out fossil fuel generation is also a shift from a limited number of large, predictable production units to a large number of units with a variable output. Thus, the increasing dependence on renewable energy sources necessitates both the use of new technologies and changes in the planning, design and operation of the power systems and grids.

Grids and procedures have to be adapted for rapid variations in renewable power production. Although present AC grids will remain the backbone of the transmission system, new transmission links must be able to cope with the operational properties of renewable generation, as well as being compatible with the existing main AC grids.

The links between generation based on renewables must allow rapid, efficient and reliable control of power flows, grid voltages and also of the back-up generation.

4 HVDC power transmission technology

For well over a century, High Voltage Alternating Current (HVAC) was seen as the natural choice for electrical power transmission. However, the capacitance per unit length makes AC cables impractical for transmitting large amounts of power over distances greater than 50–70 km: a significant amount of reactive power is generated, and low-frequency resonances may result in instability.

While Classic High Voltage Direct Current (HVDC) technology has been commercially available since the mid 1950s, it has mainly been used for point-to-point, high-capacity bulk power transmission links over long distances or for the interconnection of asynchronous grids. Its active components are high power thyristors.

The past 12 years has seen the emergence of a new generation of VSC (Voltage Source Converter) technology, based on series-connected power transistors – a commercial example is ABB's 'HVDC Light' [5]. VSC-based HVDC is of particular interest for use with submarine cables, underground cables or back-to-back transmission links ranging from a few MW up to over 1,000 MW.

4.1 Fast control of active and reactive power flows

VSC-based HVDC uses series-connected IGBTs (Insulated Gate Bipolar Transistors) that enable VSCs to be connected to networks at high voltages that were previously unattainable. Such solutions can be used for

power transmission, reactive power compensation and harmonic/flicker compensation. With fast vector control, this converter solution enables independent control of active and reactive power while imposing low levels of harmonics, even in weak grids [5].

PWM (pulse width modulation) is used for the generation of the fundamental voltage, with both the magnitude and phase of the voltage controlled freely – and almost instantaneously – within certain limits. This allows independent and very fast control of active and reactive power flows. In this way, a PWM-based VSC is a close to an ideal component in the transmission network. From a system point of view, it acts as a zero-inertia motor or generator that can control active and reactive power almost instantaneously. Furthermore, it does not contribute to short-circuit power, as the AC current can be controlled.

VSC-based HVDC enables fully independent control of both the active and the reactive power flow within the operating range of the design. Normally each station controls its reactive power contribution (both inductive and capacitive) independently of the other station. The active power can continuously and almost instantaneously be controlled from full power export to full power import. However, the flow of active power in the DC cables must be balanced, which means that the active power entering the HVDC system must be equal to the active power leaving it. A difference in power would mean that the DC voltage in the system would rapidly increase or decrease, as the DC capacitance increases its voltage with increased charge (and vice versa). With a normal design, the stored energy is equivalent only to the power that would be transmitted by the system for around 2 ms [5].

To achieve this power balance, one of the stations has to control the DC voltage. This means that the other station can adjust arbitrarily the transmitted power within the power capability limits for the VSC-based HVDC system design, in which the station that controls the DC voltage will adjust its power to ensure that the balance (that is, constant DC voltage) is maintained. The balance is achieved without telecommunications between the stations: it simply requires the DC voltage to be measured.

4.2 Low power and power reversal

Unlike conventional HVDC converters, VSC-based HVDC converters can operate at very low, and even zero, power. The active and reactive power are controlled independently, and at zero active power the full range of reactive power can be utilized.

A VSC-based HVDC transmission system can transmit active power in any of the two directions. This means that power transfer can be reversed quickly, without any change of control mode and without any filter switching or converter blocking. The power reversal is obtained by

changing the direction of the DC current and not by changing the polarity of the DC voltage as for conventional HVDC. Depending on the network, it is possible for the converter to reverse to full power in milliseconds if required.

4.3 Black start capability

VSC-based HVDC provides the voltage and frequency support essential to aid grid restoration.

When the AC grid connected to one end of a VSC-based HVDC link experiences a blackout, the control and protection system detects and identifies the disturbance as an AC blackout. Then the converter is blocked and the AC breaker opens, immediately followed by switching the converter control into black start control mode. The converter then deblocks, and the AC voltage starts to build up to the predetermined reference level – see Fig. 1. [6]

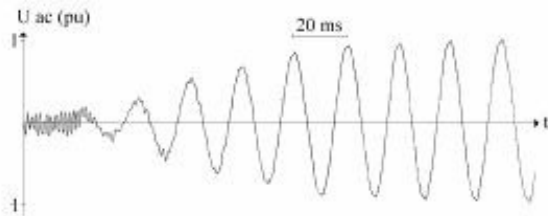


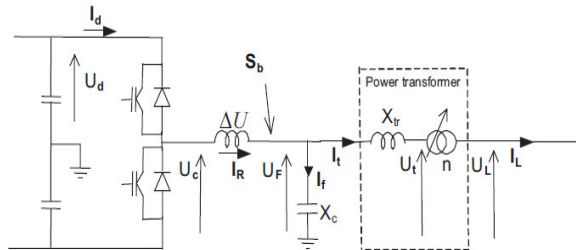
Fig. 1. AC voltage at start-up of an isolated network

It should be noted that by ramping up the voltage and eventually energizing the AC grid, the slow ramping doesn't cause any inrush currents in equipment such as transformers or motors.

During the build-up of the AC grid after a blackout, AC generation doesn't have to match AC consumption, since the DC link can compensate for the imbalance by injecting or absorbing active and reactive power.

During a black start, the converter control and protection systems have no need for large amounts of power; low power batteries are sufficient.

4.4 VSC-based HVDC – the theory



Simplified circuit diagram
Fig 2 Simplified Circuit Diagram

The fundamental base apparent power at the filter bus between the converter reactor and the AC filter is defined as follows:

$$\dot{S}_b = P + jQ = \sqrt{3} \times \dot{U}_F \times \dot{I}_R^*$$

The active and reactive power components are defined as:

$$P = \frac{U_F \times U_C \times \sin \delta}{\omega L}$$

$$Q = \frac{U_F \times (U_F - U_C) \times \cos \delta}{\omega L}$$

Where:

δ = phase angle between the filter voltage U_F and the converter voltage U_C

L = inductance of the converter reactor

Changing the phase angle controls the active power flow between the converter and the filter bus and consequently between the converter and the AC network.

Changing the amplitude difference between the filter voltage U_F and the converter voltage U_C controls the reactive power flow between the converter and the filter bus and consequently between the converter and the AC network.

With the OPWM (Optimized-Pulse- Width-Modulation) control strategy, it is possible to create any phase angle or amplitude (up to a certain limit) by changing the PWM pattern. This offers the possibility of controlling both the active and reactive power independently.

The typical P/Q diagram, which is valid within the whole steady-state AC network voltage, is shown in Fig. 3. The P/Q diagram shown is for a back-to-back, i.e. with no distance between the two stations. The 1st and 2nd quadrants represent the rectifier, and the 3rd and 4th the inverter. A positive value of Q indicates the delivery of reactive power to the AC network. It should be noted that the reactive power can be controlled independently in each station.

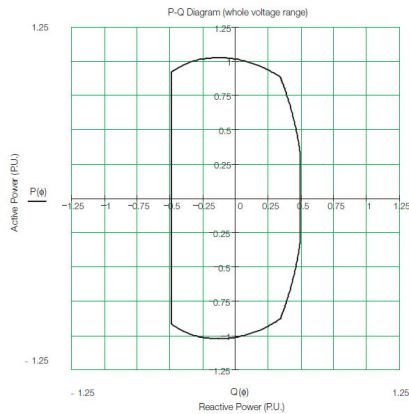


Fig 3 Typical P/Q Diagram

5 The East-West Interconnector

A good example of a VSC-based HVDC scheme is the East-West Interconnector that will connect the Irish and UK power systems. The link is scheduled to be in operation in 2012 and will be operated by EirGrid, the independent Transmission Systems Operator (TSO) in Ireland, and the Market Operator in the wholesale electricity trading system. The converter stations will be located at Woodland, County Meath, Ireland and Shotton, Flintshire, North Wales, UK.

The design reasons for choosing VSC-based HVDC technology for the East-West Interconnector encapsulate the specific demands on power transmission systems required to handle a substantial amount of wind generation, present or future:

- electricity trading between Ireland and the UK, or with the EU mainland markets via the UK

- ensuring security of supply to Ireland by utilising import capability from the UK when the renewable generation is insufficient for the load
- promotion of competition and trading
- black start capability
- active AC voltage support
- all cable transmission due to environmental factors
- ability to cope with the variable production from renewable generation
- ease of building – modular approach, compact terminals, minimal cable corridor width.

5.1 Sea and land cable transmission

The main technical details of the East-West Interconnector are:

- VSC-based HVDC technology
- Cable transmission with a pair of parallel cables with a total length of 262 km
 - 76 km land cable path, 46 km in Ireland and 30 km in the UK
 - 186 km submarine cable path
- DC voltage ± 200 kV
- AC voltages 400 kV at both terminals
- Power rating 500 MW

The arrangement of the main circuits of the East-West Interconnector is shown in Fig. 4.

5.2 Compact installation profile

VSC-based HVDC eliminates the need for a number of components required by conventional HVDC converter stations, such as AC filters and shunt capacitors. The result is a very compact installation footprint – see Fig. 5.

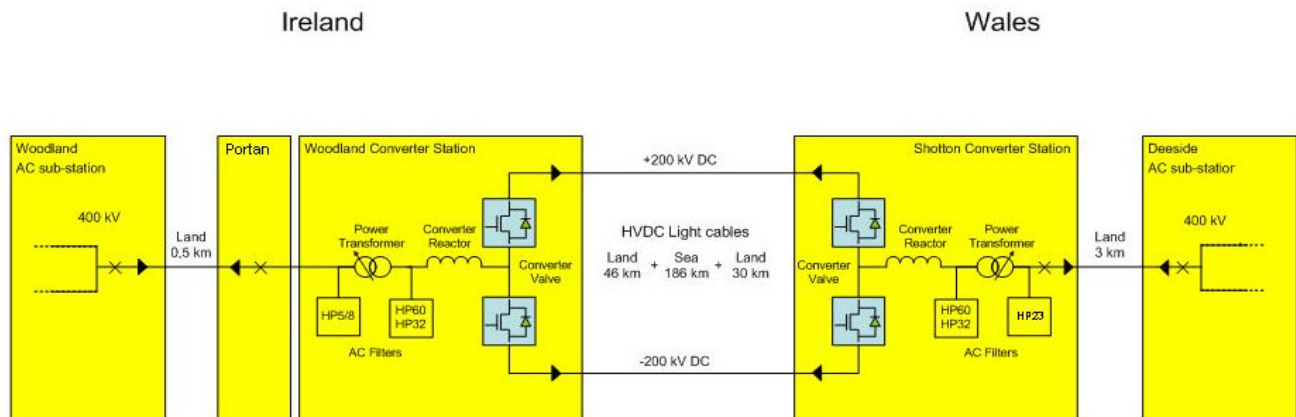


Fig. 4. Simplified single-line diagram of the East-West Interconnector between Ireland and Wales.

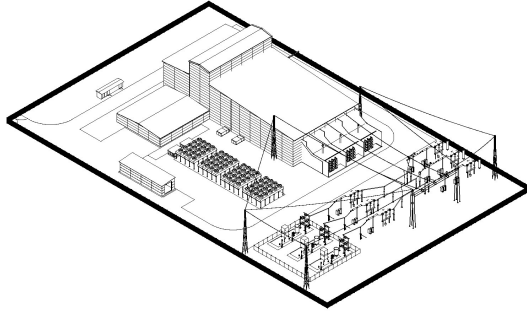


Fig. 5. The Shotton HVDC Light converter station, on the Welsh side, has a footprint of 180 m x 115 m.

6 Interconnections increase security of supply

Connecting two AC grids via VSC-based HVDC transmission results in increased security of supply for both grids. The power flows can be controlled in both magnitude and direction with great speed and accuracy, which facilitates trading.

These were major objectives for using VSC-based HVDC technology for the East-West Interconnector, and also for the Estlink transmission. The 350 MW, ± 150 kV Estlink connects the Finnish 400 kV main grid with the Estonia 300 kV main grid over a distance of 105 km, of which 74 km are submarine cables across the Gulf of Finland.[7]

VSC-based HVDC is also being used for the BorWin1 project to connect the BARD Offshore 1 wind farm, 125 km offshore in the North Sea, to the German grid. The BorWin1 transmission has a rating of 400 MW, and a voltage of ± 150 kV DC. The submarine and land cable have lengths of 125 km and 75 km respectively, and the AC grid voltage is 380 kV. [5]

7 HVDC cables for both submarine and land transmission links

The cables are key components in VSC-based HVDC systems. They are manufactured from cross-linked polyethylene (XLPE), a polymeric insulating material. These cables are very compact compared to conventional, three-phase HVAC cables. The cable is designed around a central conductor, several layers of insulation and a protective shield of steel armour around the isolation. These cables are very robust, yet light and flexible. They are also environmentally sound, containing no oil or any other hazardous materials. [8]

To see how these cables compare with conventional AC cables, consider the requirements for a 550 MW subsea connection over a distance of 75 km. For an AC scheme, three 220 kV XLPE cables would be required with a copper conductor cross-section of 1600 mm² and copper wire tensile armour. The weight of the three cables is 3 x

60 kg/m = 180 kg/m. However, a VSC-based HVDC link would require only two 150 kV cables with a copper conductor cross-section of 1400 mm² and steel wire tensile armour. The weight of the two cables is 2 x 32 kg/m = 64 kg/m i.e. around one third of the AC scheme

The DC magnetic field associated with HVDC Light cable pairs is very low, even compared to the Earth's magnetic field. Since the cables are operated in bipolar mode, and run side by side, with one cable with negative and the other cable with positive polarity, the residual magnetic field is reduced almost completely.

Submarine HVDC cables are laid directly on the sea bottom and then buried approximately 1 meter under the sea bed. Land cables can be deployed by a ploughing technique that requires a very small corridor, this is especially useful when negotiating rights-of-way.

8 Conclusions

VSC-based HVDC is a state-of-the-art technology, developed over more than a decade of operating experience for interconnections between AC grids. It offers a number of important features that can contribute to the successful development of renewable energy as an integral part of the generation mix. Among these are long low-loss submarine cable transmission links, the ability to cope with rapidly variable generation and black start capability.

The combination of their unusually rich renewable resources and strong and experienced offshore and energy industries puts Ireland and the UK in an excellent position to become leading nations in renewable power production. HVDC transmission technology makes it possible for even the most distant resource to be developed with power transmitted to the main grids, and then exported to the large energy markets on the EU mainland.

References

- [1] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources (amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC).
- [2] www.dcenr.gov.ie
- [3] Delivering a Sustainable Energy Future for Ireland, (IRE) Government White Paper, 2007.
- [4] The Offshore Valuation. A valuation of the UK's offshore renewable energy resource. First Published in the United Kingdom 2010 by the Public Interest Research Centre on behalf of The Offshore Valuation Group, an informal collaboration of government and industry organizations.
- [5] It's time to connect - Technical description of HVDC Light technology, Rev. 6, 2010; ABB Grid Systems, Sweden.
- [6] HVDC with Voltage Source Converters; A Powerful Standby Black Start Facility, by Bernt Abrahamsson, Hugo Duchon, Ying Jiang-Häfner, Michael Karlsson, Leif Ronstrom., IEEE PES T&D conference in Chicago, USA, April 21-24, 2008

- [7] The Estlink HVDC Light® Transmission System, by M.L. Hoffstein (ABB Sweden), M. Lahtinen (Fingrid, Finland), R. Pajo (Eesti Energia, Estonia) and L. Ronström (ABB Sweden).
- [8] HVDC with Voltage Source Converters and Extruded Cables for up to ± 300 kV and 1000 MW, by G. Asplund, B. Jacobson, M. Bergkvist, A. Gustafsson, M. Jeroense, P. Rey and Y. Yiang-Häfner (all from ABB, Sweden); Cigré Conference 2006 in Paris, France