Feasibility of DC Transmission Networks

Dragan Jovcic, Dirk van Hertem, Kerstin Linden, Jean-Pierre Taisne and Wolfgang Grieshaber

***Abstract*—This paper examines the current status of technology and discusses technical options for developing DC transmission grids. The fast advances in VSC HVDC, the recent offshore VSC projects, the experience with multiterminal HVDC and recent development of fast DC circuit breakers bring large meshed DC grids closer to reality. The most important and most difficult remaining technical challenge is the system level protection of DC grids. The article further discusses some of the ongoing research directions like the use of travelling wave detection for fast protection or deployment of DC/DC converters for isolation of DC faults. One of the main work packages in EU funded Twenties project studies the major prerequisites for operation of DC grids. This project has delivered some major studies of DC grids and two hardware demonstration systems are under development: a mock-up DC grid at University of Lille and fast DC Circuit Breaker at ALSTOM.**

***Index Terms*— HVDC transmission, HVDC Transmission Control, Power Converters, Circuit Breakers.**

I. Introduction

High-Voltage Direct Current (HVDC) links are well established in applications such as bringing offshore wind power to shore, supplying oil and gas offshore platforms, interconnecting power grids in different countries and reinforcing existing AC grids. As the number of these point-to-point HVDC connections increases, it is becoming apparent that it would be beneficial to connect them directly, rather than through the broader AC grid, as they are currently. After the development of low-loss VSC converters, there is now a break-through of VSC technology, where more projects are discussed with VSC technology than with LCC technology. This is giving rise to plans for HVDC supergrids.

The DC networks can be considered as technical advances from HVDC and multiterminal HVDC. A multiterminal HVDC would have taps along the DC line, however a DC grid is meshed and provides multiple power flow paths between two points. A DC grid may have a single or multiple DC voltage levels. The advantages of DC networks are in flexibility and security in addition to numerous capital and operating cost incentives. Many of the reasons for developing meshed AC grids at the beginning of *20th* century apply now for enhancing HVDC into DC transmission grids. We will only mention several crucial advantages of DC transmission over AC transmission: smaller cable size for given power level, no reactive power flow, no distance limitation with cable systems, and simpler cables.

The DC grids are particularly attractive with offshore systems because of issues with long AC cables. The European supergrid is proposed to interconnect North sea and Baltic sea countries, perhaps utilizing existing HVDC lines, and also to provide transmission access for offshore wins farms [1],[2]. The plans to connect remote renewable power resources, such as wind power in the North Sea, solar power in North Africa and connecting hydro power stations in the Nordic countries, have created interest in the possibility of an HVDC grid.

The value of an HVDC grid (offshore or onshore) is mainly in its role as a facilitator for power exchange and trading between regions and power systems. As such, it can introduce additional flexibility to power systems, and also provide features as additional power oscillation damping and emergency power. Moreover, an offshore grid will allow the aggregation and dispatch of power from offshore wind farms from different regions, resulting in power generation profiles of lower variability.

There are also numerous studies on converting existing AC lines into DC in order to enhance power transfer and to provide full power control [3]. Converting multiple AC lines into a DC network could significantly improve power trading.

A multiterminal HVDC with small number of terminals and accepting some sacrifice in reliability could be developed with the existing VSC technologies. In developing high power large DC grids we should aim to achieve similar level of reliability and performance as with AC grids. The stringing requirements on reliability/security will require high-performance and reliable grid-wide protection system and the existing AC system protection cannot be used. A DC circuit breaker enables isolation of a faulted line or a unit and constitutes essential protection component but these components have not been used so far.

High power DC/DC converters also need significant development but may not preclude development of DC grids. It is possible to develop a DC grid of a single DC voltage level, nevertheless there are many practical reasons which will require DC/DC conversion like: lack of standardization, system expansion, DC technology by different vendors, system flexibility and others.

It is becoming accepted that the cost of DC circuit breakers and DC/DC transformers will be considerably higher than comparable components in AC grids. These cost indicators together with the above advantages necessitate careful analysis of topologies for DC grids.

This article accompanies the panels session with 5 panelists from different corporations and with differing views. It consists of 4 sections and the individual panelists do not necessarily agree with all statements in the paper.

Dragan Jovcic is with University of Aberdeen: d.jovcic@abdn.ac.uk,
Dirk van Hartem is with KU Leuven, dirk.vanhertem@esat.kuleuven.be.
Kerstin Linden is with ABB: kerstin.linden@se.abb.com,
Jean-Pierre Taisne is with RTE: jean-pierre.taisne@rte-france.com
Wolfgang Grieshaber is with Alstom: wolfgang.grieshaber@alstom.com

II. Technologies Available for DC Grids

A. Current technologies for HVDC grids

A reference project for constructing a regional grid with a limited number of nodes is already in place. The Québec–New England project completed in the 1990s has clearly demonstrated the feasibility of three-terminal HVDC systems at 2000 MW. ABB is also delivering the world's first multi-terminal UHVDC link to transmit 8000 MW of clean hydroelectric power from the North-Eastern and Eastern region of India to the city of Agra across a distance of 1,728 km. 4 terminals, located at 3 converter stations will create power pooling points in North-Eastern region.

HVDC Light technology can provide even better capabilities for operating regional multi-terminal systems, as the direction of power flow is changed by changing the direction of the current, and not by changing the polarity of the DC voltage. The terminals can be connected to different points in the same AC network or to different AC networks, including wind farms, supporting the AC network with reactive power at each connection point.

During 2010, ABB was awarded the first HVDC grid enabled link, the "NordBalt HVDC Light connection", by the TSO's of Sweden, Svenska Kraftnät and Lithuania, LITGRID turtas. ABB is at this moment pioneering the development of the UK's multi-terminal offshore supergrid by starting technical design work on an HVDC Light project. This will be the first link to incorporate a hub for the connection of offshore wind farms – the 'socket in the sea' approach.

B. Developments for an inter-regional HVDC grid

For smaller regional grids, the HVDC technology is available and ready to go now. However, the lack of a suitable circuit breaker has presented a significant barrier to the creation of large inter-regional grids. This is because the relatively low impedance in the HVDC grid means that, should a short-circuit fault occur, the fault penetration is fast and deeper than in an AC grid. Fast and reliable HVDC breakers, capable of clearing a fault within a few milliseconds are therefore required to avoid a collapse of the common DC voltage, and thereby avoiding a major disturbance on the AC grid.

Existing mechanical HVDC breakers, capable of interrupting DC currents within several tens of milliseconds are too slow to fulfill the requirement of a reliable HVDC grid, and their breaking capability is too low. Furthermore, they are complex devices which include additional passive components to create the resonance circuit required to generate current zero crossing for successful breaking of the current once the contacts open.

Semiconductor based DC breakers can easily overcome the limitations in operation speed but generate large transfer losses. ABB has now taken the advantages of the mechanical and semiconductor designs and combined them in a *prototype hybrid breaker* [4] that offers both fast operation and negligible transfer losses.

ABB is also addressing a number of other technical issues relating to HVDC grids including, protection, power flow control and network topologies.

III. Technical Challenges for DC grids

A. DC Grid Topology

In order to develop DC grids we need to follow similar performance, security, reliability and cost aspects as with AC systems. However comparing with AC network, it is important to note some significant differences:

- The fault conditions are much more onerous implying that fast and decentralized protection is required.
- The cost of DC Circuit Breakers will be much higher. This implies that topologies that minimize number of lines (like radial) should be considered.
- The cost of DC/DC transformers will be much higher.
- In most cases it will be possible to control power in each DC line. DC cable thermal limit will determine power transfer level.
- Most large DC systems will be bipolar with metallic return (three cable system). A loss of DC cable implies that half power can be transmitted. With monopolar DC systems, a DC cable loss will bring down the DC line.

B. DC Circuit Breaker

There are three main approaches for isolating DC faults and they will be reviewed in this section.

1) Mechanical Switch

A mechanical DC Circuit breaker uses AC CB technology but it is more complex because of additional resonant circuit. A 500kV prototype has been developed by EPRI [5] and similar topologies are discussed in [6]. The basic structure is shown in Figure 1. The cost is reasonable since it has no semiconductors, and the on-state losses are negligible. On the downside, mechanical CB has very long operating times, in the order of *30-50ms*, which is unacceptable for DC networks.

2) Series electronic switch

This DC CB consists of an IGBT in current path typically located at the DC cable ends. The on-state losses are high but they can be reduced if hybrid topology is used [4], as shown in figure 2. The operating times are fast, generally within few *ms*. A series inductor is used to limit the rate of rise of fault current typically to within *3-10kA/ms*.

The IGBTs in electronic switch should be rated for full DC voltage and maximum fault current. The maximum fault current can be around *15kA* assuming 5ms clearing time. The total cost of series electronic switch will therefore be 20-30% of the cost of full VSC AC/DC converter of same DC voltage.

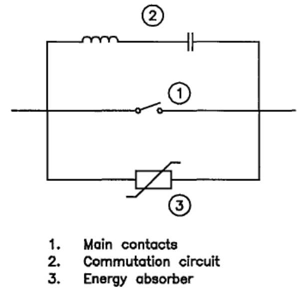

Figure 1. Mechanical DC circuit breaker from [6].

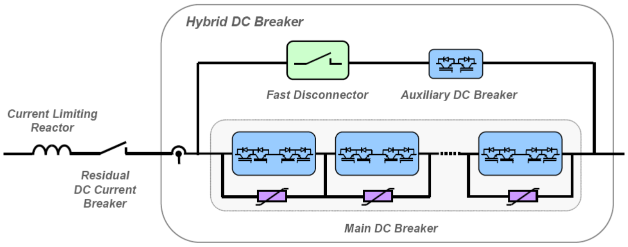

Figure 2. Hybrid DC circuit breaker from [4].

3) Interrupting DC faults using DC/DC converters

Some of DC/DC topologies have capability to interrupt DC fault current, like that in Figure 3 [7]. The advantage with this topology is that DC faults naturally reduce DC current without any control action and without causing any overvoltage. Another advantage is the capability of power flow control and interfacing different DC voltage levels.

On the downside, the on-state losses, and costs will be higher than a series electronic switch and probably somewhat higher than a full AC/DC converter.

C. DC/DC converters

The DC/DC converters have not been utilized at transmission levels but with DC grids there will be numerous applications. The primary function will be to interconnect two DC grids of different DC voltage levels.

DC/DC converters will be highly controllable units and this controllability can be utilized to support other functions in DC grids. In ideal case DC/DC transformers can achieve:

- DC voltage stepping,
- DC power or DC voltage regulation,
- DC fault isolation,
- Interfacing different DC technologies like current source with voltage source DC or monopolar with bipolar DC systems.

A single DC/DC converter can be viewed as replacement for multiple components in traditional AC systems. There is a wide range of possible technologies for DC/DC converters, including DC choppers, dual active bridge transformer isolated converter or resonant converters. It is difficult to clearly rank all available technologies and it is likely that different applications will favor different topologies.

The University of Aberdeen has demonstrated DC fault isolation capability of topology in figure 3 on a 30kW prototype. A 4-terminal DC grid with two DC voltage levels (900V and 200V) and two DC/DC converters is being built at Aberdeen.

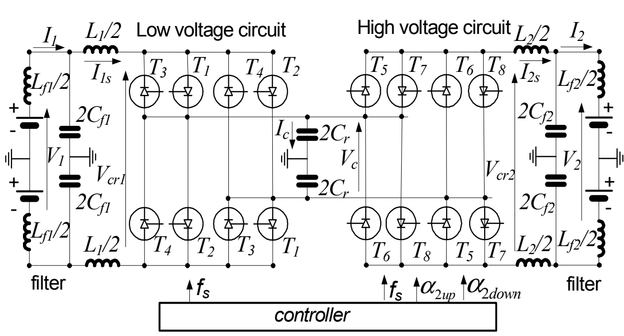

Figure 3. DC/DC converter with DC fault tolerance, from [7].

D. DC Grid Control

The operation and control methods of DC grids will be different from traditional AC systems, but this is not considered to be showstopping challenge. While AC systems are regulated through slow governors and generator exciters, the DC grids will have numerous fast acting converters. The time constants of DC grid response might be two orders of magnitude smaller, which brings opportunities for optimization, but also control complexity challenge.

Each of the AC/DC converters will have capability of DC grid control, and if utilised, DC/DC converters provide additional control channels. If there are more converters than DC lines we will be able to control power flow in each DC line. Otherwise power flow will depend on the line impedances, in the same way as with conventional AC systems.

It is essential to keep the DC voltage firmly controlled, similarly as it is important to regulate frequency in AC systems. The DC voltage in DC grids responds directly to system loading and therefore system adequacy can be instantaneously monitored using DC voltage measurements. However, while frequency is a global variable with identical value in all corners of AC grid, DC voltage will differ through DC grid. This complicates control design.

One converter in a DC grid will have DC voltage keeping function through integral control. While all other converters will control their local power, they will also respond to DC voltage variations. This is typically achieved through some algorithm of local DC voltage droop feedback [8].

IV. DC Grid protection systems

A. Introduction

Any protection system, AC or DC, must have the following properties [9]:

- Sensitivity: The protection system should detect every fault
- Selectivity: The protection system should only operate after a fault (not during normal operation), and only if the fault is in its own coverage domain
- Speed: The protection system should be fast enough to interrupt faults before they may damage equipment or can no longer be interrupted by the breakers
- Reliability: A good protection system is reliable and has a backup system in case the primary protection system fails
- Robustness: the protection system should have the ability to detect faults in normal mode as in degraded mode, and to discriminate faults from any other operation occurring (setpoint changes, operations,. . .)
- Seamless: after the fault clearance, the remaining part of the system should continue operating in a secure state

These general principles have consequences on each element of the detection and action chain. They also determine how the DC grid will look like. For instance, if it is necessary that individual line will be cleared in case a fault occurs (as is the case with AC grids), DC breakers are needed at both ends of each cable or overhead line.

B. Conventional protection means with AC systems

Overcurrent protection is based on devices trip whenever the current surpasses a certain threshold. They are simple yet not selective. A directional criterion based on current is required to improve the selectivity. However, the relay may also trip unnecessarily in case of a fault on a nearby line. Nevertheless, overcurrent protection, even fuses, might be useable as a secondary or final (backup) protection scheme.

Distance protection relays measure the distance to the fault by dividing the measured voltage value by the current. This method is very widely spread in AC grids. Distance relays cannot be directly used in DC grids because the complex impedance measured in a DC grid is of a fundamentally different nature compared to the AC system. Especially the influence of the fault resistance makes this device not suited for DC fault protection.

Differential protection schemes provide an intrinsic selectivity: the relays acts on the difference between the current at the sending and the receiving end of the transmission line. In case a fault occurs near one busbar, the fault at the other side of the line is only measured after a certain delay (which can take up ms on longer lines). Nevertheless, differential protection is very likely the best method in smaller links and to protect busbars against faults.

Cable Directional protection is an alternative method where each measurement device sends the direction of the current to the one at the other end or an aggregator. This method seems to be more robust than a line differential protection, because of the simplicity of information to be communicated (only a direction, instead of a current value), but the transmission issues are the same. This protection has to manage the fault wave propagation as well.

C. New protection means for DC protection

A new, to-be-developed, line protection methodology is necessary to protect the transmission lines in DC grids. This new device needs to be a fast and non-communicant protection (in case of failure on the communication device) and not sensitive to fault wave delays (difference with communicant line protections). This methodology can use alternative measurements to analyze whether a fault occurred and the location of that fault. Examples are the use of voltage or current derivatives, or traveling wave detection. Another approach is the use of signal processing to analyze the measurement signals, e.g. using wavelets, Fourier analysis or a derivative thereof [10]. In [11] a methodology is developed using wavelet transformation to determine which line was faulted within one *ms*. The traveling waves can also be used to find the faulted line in case of a DC grid using overhead lines.

HVDC converter support during transients now becomes a realistic feature for VSC converters. Up to now, voltage source converters lack DC fault current blocking capability, due to the existing path for the fault current flow through the anti-parallel diodes used in half H-bridges valves; yet, upcoming modules (e.g. as depicted in figure 4) based on full H-bridge IGBT arrangements are now expected in Modular Multi-level Converters (MMC) or Hybrid Converters (HC) [12]. This new kind of IGBT bridge makes it possible to limit the fault current, and even to block each valve for a short period of time and then deblock the converter at a glance. Used jointly with a DC breaker, the whole protection scheme of a DC grid could benefit from the dynamics of such a converter.

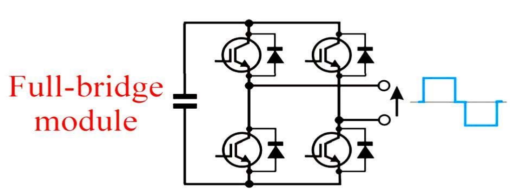

Figure 4: Example of a full-bridge module for VSC converters with current limitation

D. Other issues for protection systems

1) Robustness towards fault clearance

The direct consequence of a fault is the loss of a line. During fault elimination, the current rushes into the fault, which is fed through all connections. After successful clearing, the current in the remaining DC grid will be distributed to match the injections from the converters. As a consequence, a redistribution of the currents occurs. These transient phenomena can impact other protection devices that have to be robust against these events. The new repartition of currents can also cause overloads on other cables and converters and has to be managed quickly by the converter’s control. The interactions between converter’s control and the protection system have to be studied and simulated, for different topologies of the grid. Although the converter cannot be used to minimize the fault currents, they can be used to redispatch the power injections in a rapid and controlled manner so that there are no longer overloads [13].

2) Robustness towards HV architecture and evolutions

Depending on the substation architecture, additional operating devices other than breakers may be needed. In principle, the same busbar configuration as in AC power systems are possible, either on the AC grid or on the DC grid (e.g. breaker-and-a-half schemes). It is not unrealistic that multiple of them might be present in the same grid.

3) Selectivity and trip order

An efficient protection scheme is the one that trips only the necessary breakers to isolate the fault. As discussed before, some protection systems are intrinsically selective (such as differential protections), while others are not.

In short time limit constraints, avoiding that the protection system needs to make a choice between breakers would be better. In other words: each breaker shall have its own dedicated protection processing.

Some kinds of protection may not be able to discriminate the faulty element. In that case, a time lag shall be used to introduce a temporal selectivity between the protections. This temporal selectivity has to be compliant with the time limit constraints for fault clearance.

If some protections are too slow or temporized, based on a local criterion to move, it is possible to speed up the trip time by transmitting information between protection devices using acceleration schemes.

4) Backup protection

A protection system needs to be available and reliable. The grid must be protected even if the protection itself fails, due to internal or breaker failure or algorithm error. The additional time delays associated with the backup solution make the time constraints even more stringent. As such, it would be necessary to use DC CB of even higher capability or potentially even fuses to disconnect the faulted parts of the system.

V. Some advances of Twenties project

A. Introduction

TWENTIES is a collaborative research, development and demonstration project started in April 2010 and founded for three years within the European FP7 program, which aims at removing several barriers for welcoming large amounts of wind electricity into the European electric system and thus to help the EU to meet the 20/20/20 targets. Six different demonstration projects are included in TWENTIES. One of them is led by RTE and involves the University of Strathclyde, the University College of Dublin, RSE in Milan, Inesc Porto and Alstom Grid. This section will illustrate how three major prerequisites for the feasibility of HVDC meshed grids are addressed through two hardware demonstration systems. It is not intended to give a detailed overview of the work being done by each partner.

B. Definition of a reliable control strategy for the DC grid

This control strategy shall be robust enough to define a new setting point of operation after any event which may occur in the grid like a station trip or a cable tripping following a DC fault. This new operating point shall be inherent to the control strategy and shall not rely on a master control and on telecommunication links. The goal is to avoid loss of the energy transferred into the grid during the first seconds following the event since it would not be acceptable, for the AC systems connected to the DC grid, to sustain the shutdown of several GWs for hundreds of *ms*. New set points can be calculated afterwards by a coordinated power flow master control and sent to the converter stations with no high speed requirements to solve overloads in any segment of the grid which may result from the back up situation.

Several control strategies that can meet these requirements, like “the voltage margin method” or “the droop method”, are under investigation in the TWENTIES project. These investigations are led, at a first stage, with a modelling of the DC Grid, as well as the converter control system, based on state variables where the dynamic behaviour of the grid components is represented with differential equations. This system of equations is then linearized around the operating point. This type of modelling allows a modal analysis which is very efficient to study the small signal stability of the system and the influence of different parameters. Moreover, to validate the results obtained with this model, a comparison set of simulations has been made with an electromagnetic program (EMTP-rv) on a simple point to point DC link. The responses to transients like current order changes obtained with the two models were very similar both in the time domain and in the frequency domain.

The purpose of these simulations is to define a robust control strategy which could maintain a stable DC voltage on the whole grid, independently from wind generation variations, grid topology changes (converter tripping, cable disconnection,…). At a second stage (in 2012) this control strategy will be checked on a real time simulator where part of the DC grid will be represented by a reduced scale mock-up as shown on figure 5. Faults will be simulated on the DC grid and this will be also the opportunity to check protection algorithms combined with a mock-up of a DC breaker.

C. Development of a DC breaker prototype

When a DC fault occurs in an existing thyristor-based multiterminal DC link, the current is forced to zero by the converters control to allow fast disconnection to isolate the fault. Re-start of the poles can then take place and restoration of the energy transfer can be achieved in less than 500 ms with a three terminal link, but that time will increase with the number of converter stations to reconnect. As discussed above, this strategy will not suit for a DC grid. This strategy has been applied successfully with LCC converters which can control the DC fault current. The VSC converters which are mainly used nowadays to evacuate offshore wind power in DC, do not have this possibility up to now. The need for a DC breaker which can avoid the collapse of the DC voltage and big power swings on the grid is therefore very stringent. The first task within TWENTIES was to evaluate the duties that the DC breaker will have to face. It was not possible at this early stage of the project to have a comprehensive overview of all the grid topologies which could be met taking into account different converter topologies and control strategies for the grid. It was decided to evaluate the DC fault currents through Simpower Systems simulations (MATLAB environment). The grid topology chosen for these simulations is given in figure 6 and is similar to the topology considered in the CIGRE WG B4-52. The DC converters were grounded on one side hence the grid was monopolar and a simple control strategy was adopted: one station was controlling the voltage of the grid and the others control their current. Average and detailed models were taken for the VSC converters, the cables were modelled by T cells. Different faults were applied at different locations on the cables and at converter poles. The most severe fault current reached 60 kA in about 4 ms. The rate of rise would be smaller if the fault occurred in the middle of a long line or if smoothing reactors were inserted between the converters and the cables.

In order to have a better confidence in the results a second set of simulations were performed with EMTP where distributed parameters are available for the cables taking into account a frequency dependent damping. The topology chosen for this second set of simulations is described in figure 7 and each line was represented by two monopolar cables connected to the DC converter terminals. The topology changes were mainly justified by the possibility to represent a remote wind farm connected in "antenna" to the grid.

	Fault case	**Fault current (ampl. & peak time after fault inception)**
Cat I	**3**	**5 kA after 15 ms**
Cat II	**1**	**50 kA after 10 ms**
Cat III	**2**	**65 kA after 2 ms**

Table 1: Fault current categories

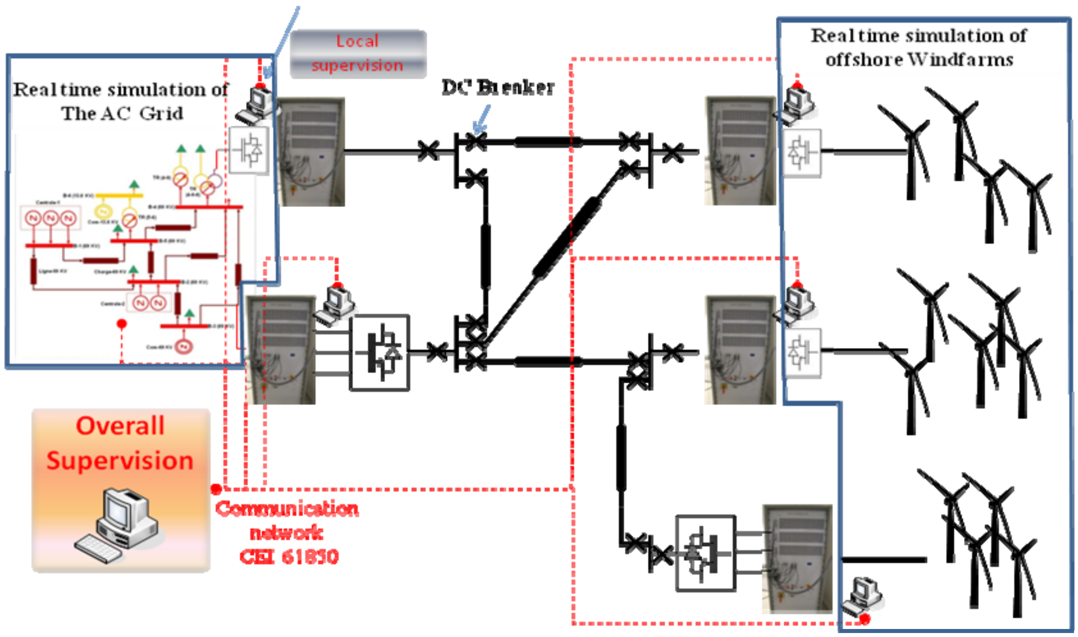

Figure 5 : Schematic of the DC grid that will be represented with the real time simulator

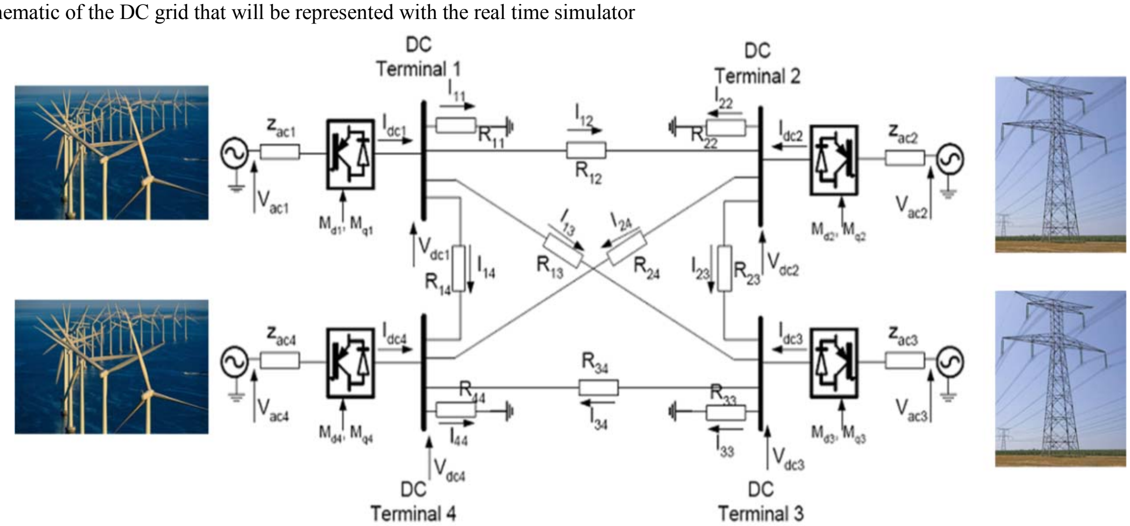

Figure 6. DC topology chosen for the MATLAB simulations

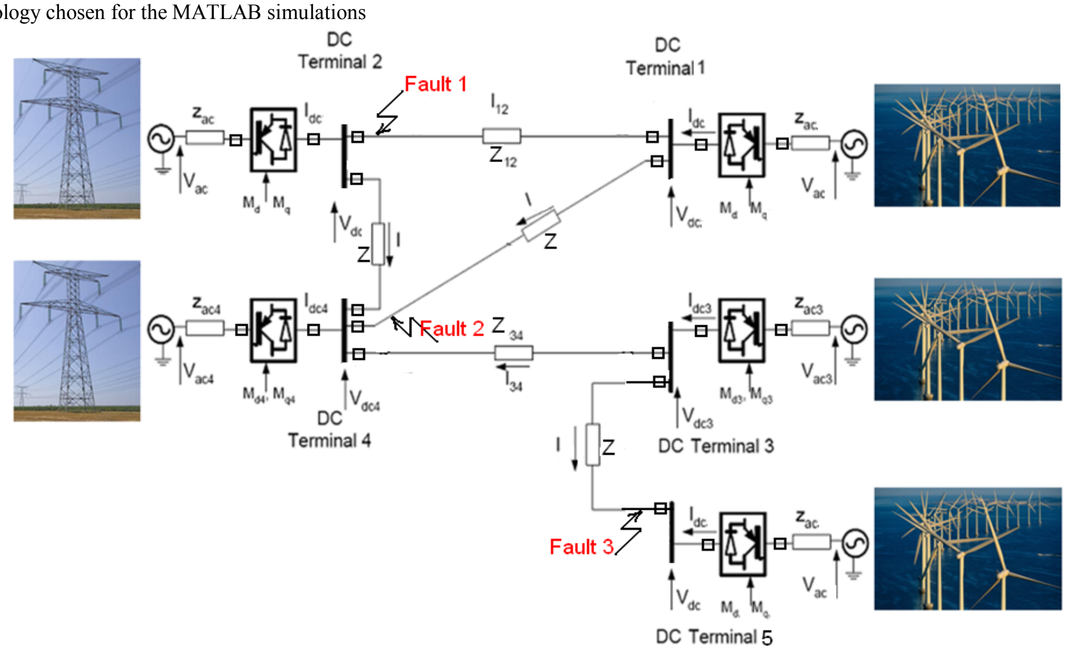

Figure 7 : Topology modelled for the simulations with EMTP

The control strategy adopted is the same as for the MATLAB simulations. The two stations on the left are connected to 2 strong AC networks and the other three being connected to offshore wind farms. DC fault currents were calculated for 3 locations as shown on figure 7 with different cable length from 10 to 100 km. Pole to pole faults are, by far, more severe in terms of amplitude compared to pole to ground DC faults. Therefore the results given below only refer to pole to pole faults. From these calculations three categories of fault currents were identified as shown in table 1. For these categories it is important to consider not only the magnitude but also the time to peak after fault inception. In the past decades DC breakers have been developed on the basis of electromechanical breakers combined with a parallel commutation circuit and a parallel arrester to absorb the energy (see figure 1 from [6], [14]). Once the main contacts are opening the commutation circuit will start to oscillate due to the voltage droop of the arc. 10 to 20 ms after the contacts opening a current zero will appear allowing the arc extinction between the main contacts and the rise of the voltage through the charge of the capacitor limited by the arrester protection voltage. Taking into account 20 ms between the order sent by the protection and the separation of the contact such a breaker would interrupt the current in 30 to 40 ms.

Compared to the characteristics given in table 1 it is clear that, with such a breaker, the fault current has already reached its peak value before the separation of the contacts and the DC voltage has collapsed which is not satisfactory for a DC grid.

A survey of the different type of DC Circuit Breaker is presented in table 2. From this survey it has been decided to develop a fast switch prototype within the TWENTIES project since it provides a small voltage drop in permanent load and it allows up to category II fault current interruptions. To avoid the DC voltage collapse of the complete grid and taking into account the breaking performances of the DC breakers, it is necessary to interrupt the DC fault current before it exceeds a limit (≈ 10 kA) which means a breaking time of about 1 ms.

To generate a current zero the DC breaker must switch a component (like capacitors and or arresters) into the circuit that opposes a voltage larger than the source voltage. The interruption time and the energy rating of the arrester depend on the ratio between the opposed voltage and the source voltage [15].

The ratings chosen for the DCCB prototype, developed by Alstom Grid, are the following:

- DC network voltage : 120 kV
- Prospective current to be interrupted : 7.5 kA
- Load current : 1500 A
- Rate of rise of fault current : 10 kA/ms

This prototype is now under manufacturing and should be sent to a test laboratory during the last months of 2012.

D. Development of a DC protection algorithm

As seen in the previous section it is necessary to interrupt the fault current while it is still raising and before it reaches a maximum value. This means to detect and to interrupt the fault current in the two first *ms* after the fault inception if the rate of rise is around 5 kA / ms (category II).

The time left for the protection in that case is only in the order of one ms and this has to be achieved with a high degree of reliability and a good selectivity. The fastest protection relays available today for differential protections in AC grids will give a minimum tripping time of about 20 ms which is too long. Some DC overcurrent protections which are built in the control cubicles of converter stations may have a tripping time of a few *ms* since they do not need any communication link with the valves control. In the case of the DCCB similar integration of the protection relays inside the control cubicles of the DCCB may be required and innovative signal analysis algorithms have to be developed and implemented in order to meet the global tripping time requirement.

Due to the short time responses required, it is necessary to look at the transient phenomena through signal processing (derivative, second derivative, wavelets, …), the challenge in a meshed grid being to define the correct localization of the fault. For this purpose it is likely that several algorithms will have to be combined in order to have a robust detection. This work is going to be continued with the aim to be able to check these algorithms on the DC mock-up. At least we shall point out that such algorithms need a sample frequency ranging from 10 kHz to 1 MHz which means not only powerful and quick protection relays but also wide band CTs and VTs.

Criteria	Super MRTB	Solid State Switch CB	Fast switch	Solid State Circuit Breaker without auxiliary circuit
arc / power electron.	arc chamber	arc chamber + power electronics	power electronics	power electronics
development needed	synchronous making switch	synchronous switch, capacitor load circuit	new concept	new concept
foreseen smallest break time	27ms (to 41ms) i.e. 19ms for contact separation + 8ms (to 22ms) arcing time.	27ms i.e. 19ms for contact separation + 8ms arcing time	< 2ms	~0.2ms
foreseen on-state losses	<1 mOhm	<1 mOhm	<~5 mOhm (estimated)	~100 mOhm (estimated)
foreseen max break current	~4kA, (possibly 8kA)	5 kA (possibly 10kA)	6 kA (possibly 12kA)	To be further investigated (~6 kA)
scalability	yes	yes	yes	yes
complexity	low	medium	high	high

Table 2: Survey of the different types of circuit breaker

VI. Conclusions

This paper presents the current technology status with DC transmission grids and discusses the main technical challenges.

The ABB has made significant advances in VSC HVDC technology and it is accepted that small-scale DC grids are currently technically feasible.

The central technical challenge with large scale meshed DC grids is protection system and technology for fast DC CB. The recent announcements on laboratory testing of fast and low-loss hybrid DC CB bring DC grids closer to reality. Nevertheless the protection development at grid level is still a challenge. In the meantime research is progressing on other components like DC/DC converters which can very effectively isolate DC faults.

The Twenties project involves leading EU stakeholders in DC technologies and addresses all major challenges with DC grids. The first simulation results have developed benchmark models with conclusions that performance requirements for DC CB are beyond current technology levels. A fast DC CB prototype of around 7.5kA breaking capability is under development and testing is expected in 2012.

Small scale DC grids of 10-30kW and 200-900V DC are under development at University of Aberdeen and under the Twenties project.

VII. Acknowledgement

RTE is indebted to PhD students P. Rault (L2EP, Lille, France) for making available his results of his ongoing work on DC grid control strategies and to J. Descloux (G2E-Lab, Grenoble, France) for fruitful discussions on protection algorithms.

VIII. References

[1] G.W.Adamowitsch, “Connection to Offshore wind power in northern Europe”, EU coordinator’s report, Brussels, 2008, http://ec.europa.eu.

[2] D. Van Hertem and M. Ghandhari, “Multi-terminal VSC HVDC for the European supergrid: Obstacles,” Renewable and Sustainable Energy Reviews, vol. 14, no. 9, pp. 3156 –3163, 2010.

[3] L.O. Barthold, D.E. Douglass and D.A. Woodford, “Maximizing the Capability of Existing AC Transmission Lines.” CIGRE 2008, Paris, France Paper B2-109

[4] JÜRGEN HÄFNER, BJÖRN JACOBSON "Proactive Hybrid HVDC Breakers - A key innovation for reliable HVDC grids", CIGRE symposium, Bologna, September 2011.

[5] Pauli, B. Mauthe, G. Ruoss, E. Ecklin, G. Porter, J. Vithayathil, J. “Development of a high current HVDC circuit breaker with fast fault clearing capability” *IEEE Transactions on P.D.* Volume 3, Issue 4, Oct. 1988 pp: 2072 - 2080

[6] CIGRE brochure 114, “Circuit Breakers for Meshed Multiterminal HVDC systems” 1997

[7] D Jovcic and B.T Ooi, “Theoretical aspects of fault isolation on DC transmission lines using resonant DC/DC converters” *IET Generation Transmission and Distribution, Vol. 5, Issue 2, 2011, pp 153-160.*

[8] Johnson, B.K.; Lasseter, R.H.; Alvarado, F.L.; Adapa, R. "Expandable multiterminal DC systems based on voltage droop" IEEE Transactions on power delivery, Volume: 8 , Issue: 4 , 1993, Page(s): 1926-1932

[9] P. Anderson, Power system protection. Wiley-IEEE, 1998.

[10] K. De Kerf, “Protection Strategies for DC Faults in Multi-Terminal VSC HVDC Systems,” Master’s thesis, K.U.Leuven, Belgium, May 2009.

[11] K. De Kerf, K. Srivastava, M. Reza, D. Bekaert, S. Cole, D. Van Hertem, and R. Belmans, “Wavelet-based protection strategy for DC faults in multi-terminal VSC HVDC systems,” Generation, Transmission & Distribution, IET, vol. 5, no. 4, pp. 496–503, 2011

[12] M. Merlin, T. Green, P. Mitcheson, D. Trainer, D. Critchley, and R. Crookes, “A new hybrid multi-level Voltage-Source Converter with DC fault blocking capability,” 9th IET International Conference on AC and DC Power Transmission, 2010. ACDC, oct. 2010, pp. 1 –5

[13] D Van Hertem, M. Ghandhari, J.B. Curis, O. Despouys, A. Marzin, “Protection requirements for a multi-terminal meshed DC grid”, in Cigré symposium: The electric power system of the future, Bologna, Sept 2011

[14] Christian M. Franck, "HVDC circuit breakers: a review identifying future research needs", IEEE Transactions on Power Delivery, Vol26, No2, April 2011, pp 998-1007

[15] Wolfgang Grieshaber, Jean-Pierre Dupraz, Michel Collet, "Direct current during commutation and interruption: relation between interruption duration, insulation level and energy in the transmission means", in print at MatPost11, 23&24 November 2011, Lyon-France

IX. Biographies

Dragan Jovcic (SM’06, M’00, S’97) obtained a Diploma Engineer degree in Control Engineering from the University of Belgrade, Yugoslavia in 1993 and a Ph.D. degree in Electrical Engineering from the University of Auckland, New Zealand in 1999. He was a visiting professor with McGill University in 2008. He started academic career in UK in 2000, and currently he is a Reader with the University of Aberdeen, Scotland. His research interests lie in the areas of FACTS, HVDC, control engineering and power electronics.

Kerstin Lindén was born in Tranås, Sweden 1963 and graduated as M.Sc.E.E. and Tech.Lic.E.E. at Chalmers University of Technology, CTH, Gothenburg, Sweden in 1988 and 1992, respectively. Since 1993, she has worked for ABB/HVDC, STRI (former Swedish Transmission Reasearch Institute) and Malardalen University. She is most experienced in power systems and HVDC/HVAC-interaction and is currently working as an R&D Project Manager at ABB/HVDC. Member of IEEE.

Dirk Van Hertem (SM IEEE) was born in 1979, in Neerpelt, Belgium. He graduated as a M.Eng. in 2001 from the KHK, Geel, Belgium and as a M.Sc. in Electrical Engineering from the K.U.Leuven, Belgium in 2003. In 2009, he has obtained his PhD, also from the K.U.Leuven. In 2010, Dirk Van Hertem was a member of EPS group at the Royal Institute of Technology, in Stockholm, Sweden where he was the program manager for controllable power systems for the EKC² competence at KTH. Since spring 2011 he is back at the university of Leuven. His special fields of interest are power system operation and control in systems with FACTS and HVDC and building the transmission system of the future with large penetration of renewables and DC Grids. He is an active member of both IEEE and Cigré.

Jean-Pierre Taisne was born in France in 1957. He received his dipl-Ing degree in Electrical Enginering from Ecole supérieure d’Electricité in 1980 and he joined EDF Research Division where he was involved in the studies, HV equipments and site tests of the Corsica tapping on the SACOI HVDC link between Sardinia and Italy mainland. In 1990 he moved to the Transmission Division, which became RTE in year 2000, and took part in the development of power transformers, phase shifters and static var compensator. He is currently deputy head of the substation department in charge of the converter stations for the new DC interconnections with Spain and Italy.

Wolfgang Grieshaber studied physics at the University of Karlsruhe, Germany (now KIT) and specialized in solid state physics and optical spectroscopy. After several years of optical characterization of semiconductors (PhD in Grenoble, France; post-doc in Boston, USA) and prototyping of optical amplifiers (Alcatel-Alstom Research in Marcoussis, France) he moved to the high voltage division of Alstom where he has been developing high voltage switchgear (from mock-up to product) for AC and DC applications over the last 10 years. He is member of the CIGRE working group A3.06, and inventor of over 10 patents.