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Zoning in High Voltage DC (HVDC) Grids using Hybrid DC breaker

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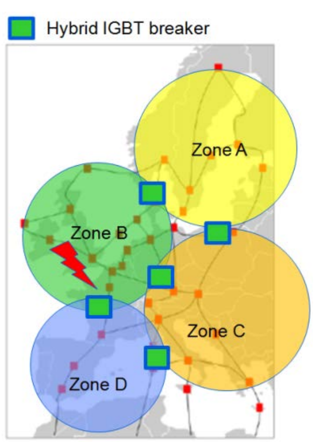
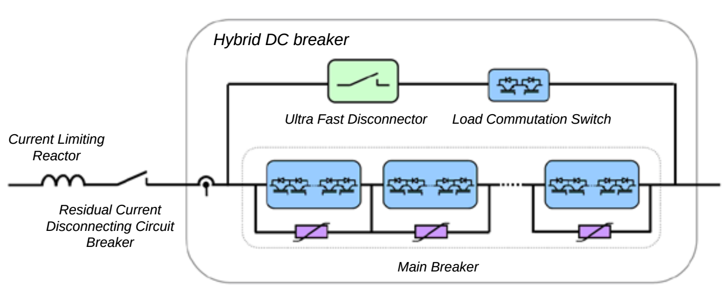
Abstract

Inter-regional DC grids can be defined as systems characterized by multiple protection zones. The build-up and operation of large DC grids will require isolating healthy sections or zones of the network from zones with faults. The rapid collapse of the dc voltage in case of faults requires components with very fast response times. ABB's hybrid DC breaker technology boasts of response times of ~2 ms which will enable the operation and protection of large DC grids. From the hybrid breaker principles towards an 11 terminal system with control and protection details, the feasibility of the zoning concept is demonstrated.

Introduction

The recent advances of the voltage source converter technology makes it possible to build high voltage dc grids with many terminals [1]. One of the main challenges in dc grids is to handle dc faults due to the low impedance in dc grids. The remedy is to apply fast and reliable HVDC breakers to isolate faulted parts in order to avoid a collapse of the common DC voltage in large DC grids. The scope of this paper is to investigate if the hybrid DC breaker can be used for dc grid zoning, also having in mind various system sizes. Zoning is a protection feature to be implemented in larger – interregional dc grids – by using the hybrid dc breaker having arresters in the line for current limitation [2]. The principle is that when a fault occurs in a certain zone, the hybrid dc breaker protects the other surrounding zones as illustrated in Fig.1. Thus, these protected zones will be operated as normal.





(a) (b)

Figure 1: (a) Inter-regional DC grid, (b) ABB's hybrid DC breaker technology

An important criterium is that the dc voltage of the protected zones should be kept constant, since a fault may not lead to cascaded outages or other operating disturbances. Usually 90% values are used. The design considerations and operation of the hybrid breaker have been the central object of the study in a system having various sizes, meshed and radial. If a fault is cleared a new power flow will occur which gives disturbances and that need to be controlled by the primary controls of the dc grid. These higher level controls are not in the scope of this study, rather only basic controls will be used i.e. one slack bus controlling the dc voltage whereas the remaining stations operate in power control.
This paper is divided into the following sections. First the hybrid dc breaker principle will be explained followed by the current limitation feature. Then the hybrid dc breaker operation will be discussed as used for zoning followed by a description of the 11 terminal simulation model used for the zoning studies. Finally a simulation example of the zoning study will be presented followed by the conclusions.

Principle of hybrid dc breaker

The hybrid dc breaker consists actual of three parallel current paths. One path carrying the current in normal operation consist of a fast disconnector and an auxiliary IGBT switch having few IGBTs. The other path consists only IGBTs and is called the main breaker and last one path consisting of arrester banks. The auxiliary switch, in series with a fast disconnector, is conducting during the normal operation, but the IGBTs in the main breaker are also in on position, Fig.2. Regarding to greater resistance in main breaker branch there is almost no current flowing through it, in the contrast, whole current is going through auxiliary switch. The maximum load current is assumed to be 2kA in steady state.

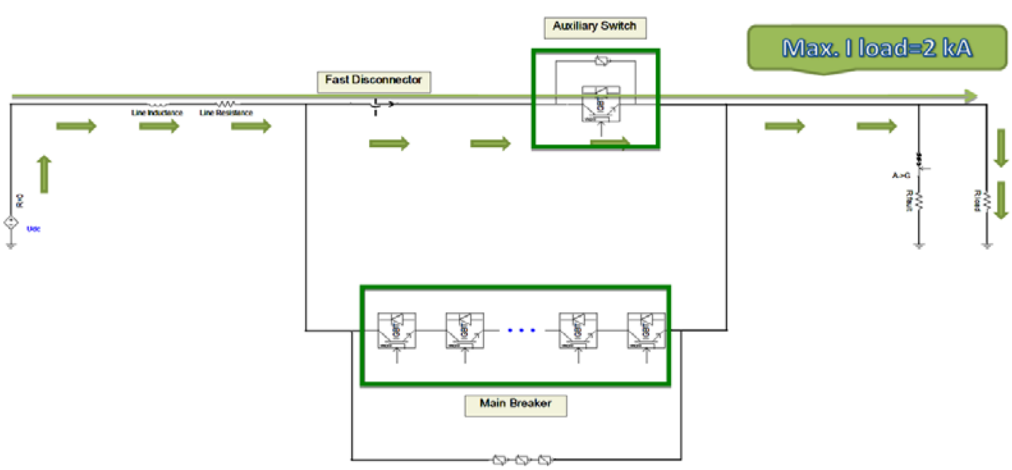


Figure 2: DC-breaker in normal operation

Upon an abnormal situation which causes the current to reach 2.4kA in t0, the control system needs some time to decide whether it is an absolute fault which needs to be interrupted or not, so 100us after t0 is deciding time period and no change is happening in the circuit, Fig.3.

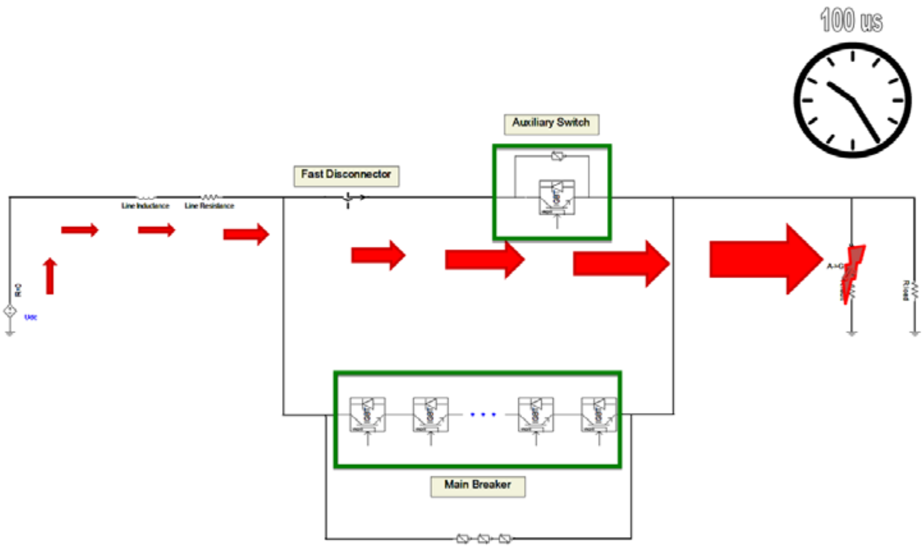


Figure 3: DC-breaker t0 to t1

While the short circuit fault is assured, the auxiliary switch starts to be turn off (t1=t0+100us). The current is commutating from the auxiliary branch to the main one, but it takes a certain period of time because of stray inductance in the circuit, Fig.4. In this study, the stray inductance is assumed to be 40uH and the commutating time is assumed to be 50us.

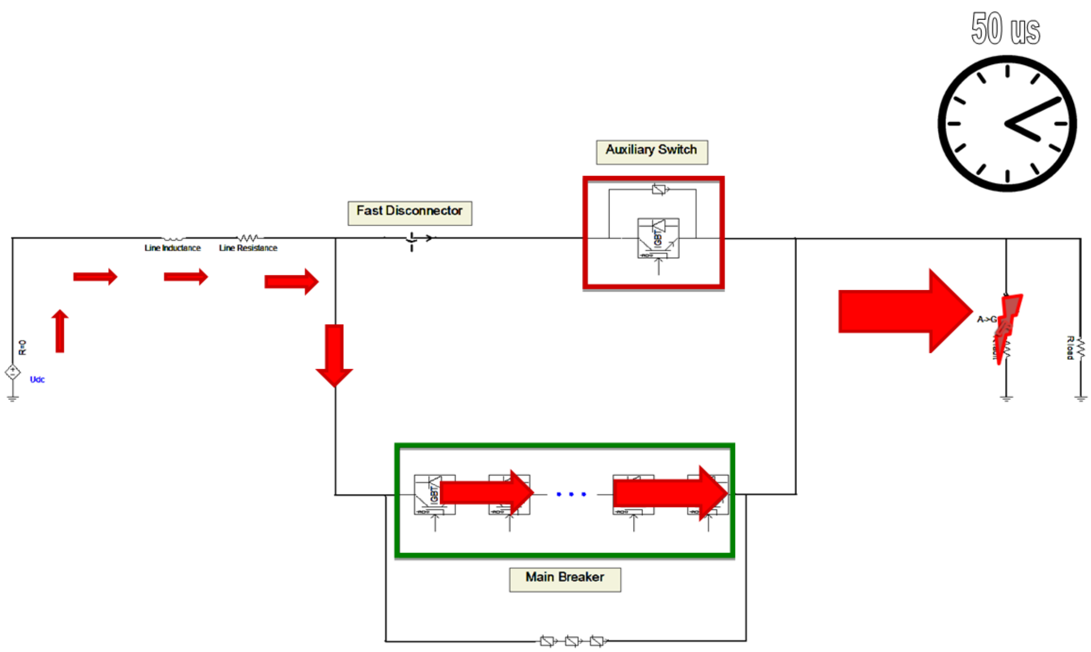


Figure 4: DC-breaker commutating time

After the commutation time, it is the time for fast disconnector to act and separate the auxiliary switch from the other part of the circuit and make the situation ready for main breaker to interrupt the current. The action time requirement for the disconnector is 2ms.

The hybrid dc breaker provides fast protection without time delay if opening time of the ultra-fast disconnector is within delay of selective protection (<2ms). The hybrid DC breaker will facilitate the isolation of faults, and protection of the healthy parts of the system. The focus of this paper is to illustrate the operation of the hybrid DC breaker in a large DC grid (ie. 11-terminal), where the breaker is used as a fault current limiting device and protection device. The capability of the breaker to provide both functionalities allows for the protection of the healthy section of the DC grid from the faulty section.

Current limitation of the hybrid dc breaker

Zoning is a protection feature to be implemented in interregional dc grids, through the use of the hybrid dc breaker as a fault current limiter. The goal is to have the protected zones unaffected during the fault. This means that the dc voltage of the protected zones should be kept constant to prevent operating disturbances leading to system-wide collapse of the DC grid.
Demonstration of the ability to provide limitation of fault current, while maintaining constant DC voltages is explained in Fig.5.

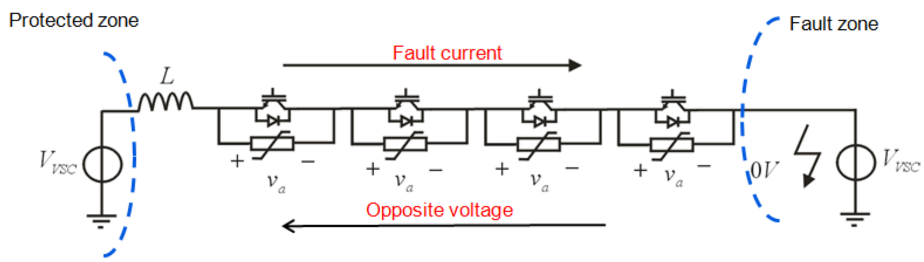


Figure 5: Principle of operation of the breaker as a fault current limiter

The hybrid DC breaker has been shown to have ability to limit fault currents [2]. The hybrid DC breaker is a component comprised of multiple sections. Fault current limitation is achieved by controlling the switching 'in' and 'out' of the sections of the breaker based on the value of the current. The basic principle is shown in Fig.5. In view of Fig.5, it is assumed that in normal operation a dc current of $I_{dc,nom}$ flows from the left region to the right region. If a fault occurs at $t = t_{fault}$ the voltage in the fault zone reduces to zero causing the current to rise rapidly limited by the impedance between the two zones X_L as,

$$I_{fault} = I_{dc,nom} + \frac{V_{dc}}{X_L} l(t - t_{fault}). \qquad (1)$$

Here is l(t) a switch function and equal to one for t>0. To limit the fault current and to keep the dc voltage in the protected zone constant arresters will be switched in the current path as,

$$I_{fault} = I_{dc,nom} + \frac{V_{dc} - v_{br}}{X_L} l\left(t - t_{fault}\right), \tag{2}$$

were the breaker operation can be simplified as,

$$v_{br} = v_a \left(p_1 + p_2 + p_3 + p_4 \right) \tag{3}$$

were

$$p_i = \begin{cases} 1, & IGBT\,\sec tion\,switched\,off \\ 0, & IGBT\,\sec tion\,switched\,on \end{cases} \tag{4}$$

Considering that the 4 arrester voltages in this case equals the nominal dc voltage as $V_{dc} = 4v_a$ we can conclude that all 4 arrester need to be inserted in the fault current path in order to keep the dc voltage in the protected zone constant. As the voltage at the terminals of the breaker varies the arresters need to be controlled and selected accordingly. The breaker will thus be operated in different so-called switch states.

Considering 4 sections having binary states give redundant states for 1,2 or 3 arresters inserted as follows,

normal state; all main IGBTs closed,

$$0 \quad 0 \quad 0 \quad 0\,,\ v_{br} = 0\,, \tag{5}$$

And the redundant switch states,

$$\left.\begin{matrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{matrix}\right\} v_{br} = v_a\,, \quad \left.\begin{matrix} 0 & 0 & 1 & 1 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 \end{matrix}\right\} v_{br} = 2v_a\,, \quad \left.\begin{matrix} 0 & 1 & 1 & 1 \\ 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 \\ 1 & 1 & 1 & 0 \end{matrix}\right\} v_{br} = 3v_a \tag{6}$$

And using full limitation, which means that all main IGBTs are open,

$$1 \quad 1 \quad 1 \quad 1\,,\ v_{br} = 4v_a\,. \tag{7}$$

During the current limitation the states can be selected properly in order to minimize the arrester energies. A sorting algorithm is used that switches in those arresters that have a lowest energies.

Breaker operation

The hybrid breaker combines two features as current breaking and current limitation. For current breaking all arrester sections are switched in at the same time to provided full reverse voltage, after the fault current declines to zero. For current limitation the hybrid breaker is controlled as such that a sorting function sorts the arrester in order.

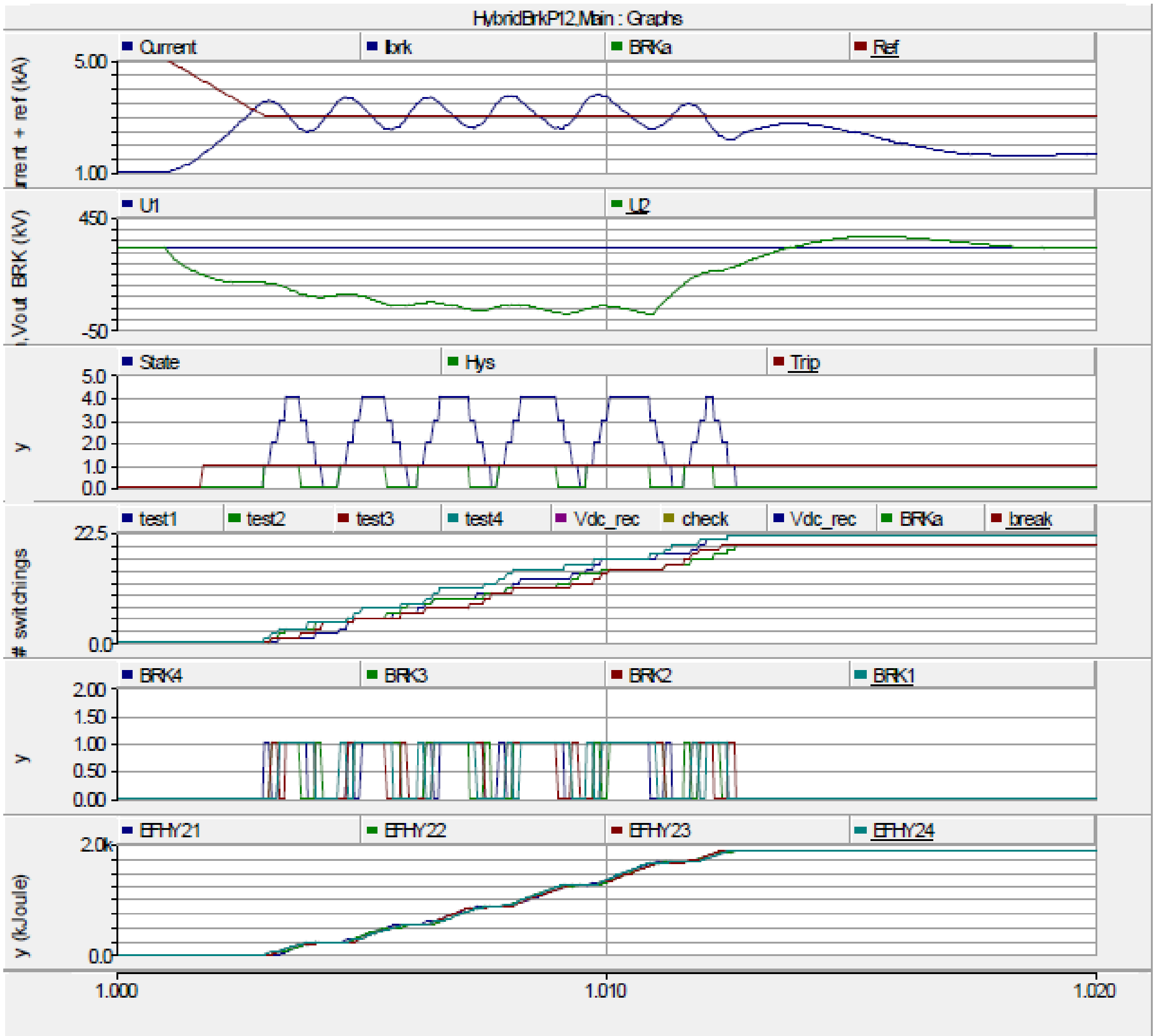


Figure 6: 11 Breaker operation, trace 1: Fault current limited within bounds, trace2: breaker terminal voltages, trace 3: breaker trip signal and control reference signal, trace 4: number of switching actions per section, trace 5: switching instants per section, trace 5: arrester energies

This is shown in Fig. 6 for the operation of the hybrid dc breaker as current limiter. In the first trace one can observe the fault current controlled within two bounds. There are different scenarios thinkable on which level one wants to limit the current ie. a high level or a low level. When it concerns a breaker in the pole of the converter once could limit just below the blocking current rating of the converter and use the voltage source converter to support the ac network with reactive power during the disturbance. Also the dc voltage in the faulty zone shows faster recovery times. Limiting at a lower current could be beneficial for the line breakers between the zones if the power exchange between them is little.

In the second trace the terminal voltages of the breaker are shown. In the third trace a state selector signal is shown deciding which arresters are switched in. In the fourth trace the number of switching actions per section are shown with the switching instants in trace five. Trace number 6 shows the energy absorbed by the arrester banks per section. The arrester energies are equally distributed over the sections, due to the sorting algorithm, reaching and energy level of a bit less than 2MJ in the simulation case shown in Fig.6.

11 terminal meshed radial system

A meshed-radial 11 terminal system has been implemented in PSCAD using bi-pole converters. The system layout is shown in Fig.7. It can be observed that the 11 terminal system is divided in two zones. VSC stations 1,3 and 5 will form zone A and the other stations will form zone B as indicated. Hybrid dc breakers (HB) are located in the pole of VSC 1, 3 and 5 and in the line towards zone B. The line breakers are there to protect zone B from a voltage collapse when a fault occurs in zone A.

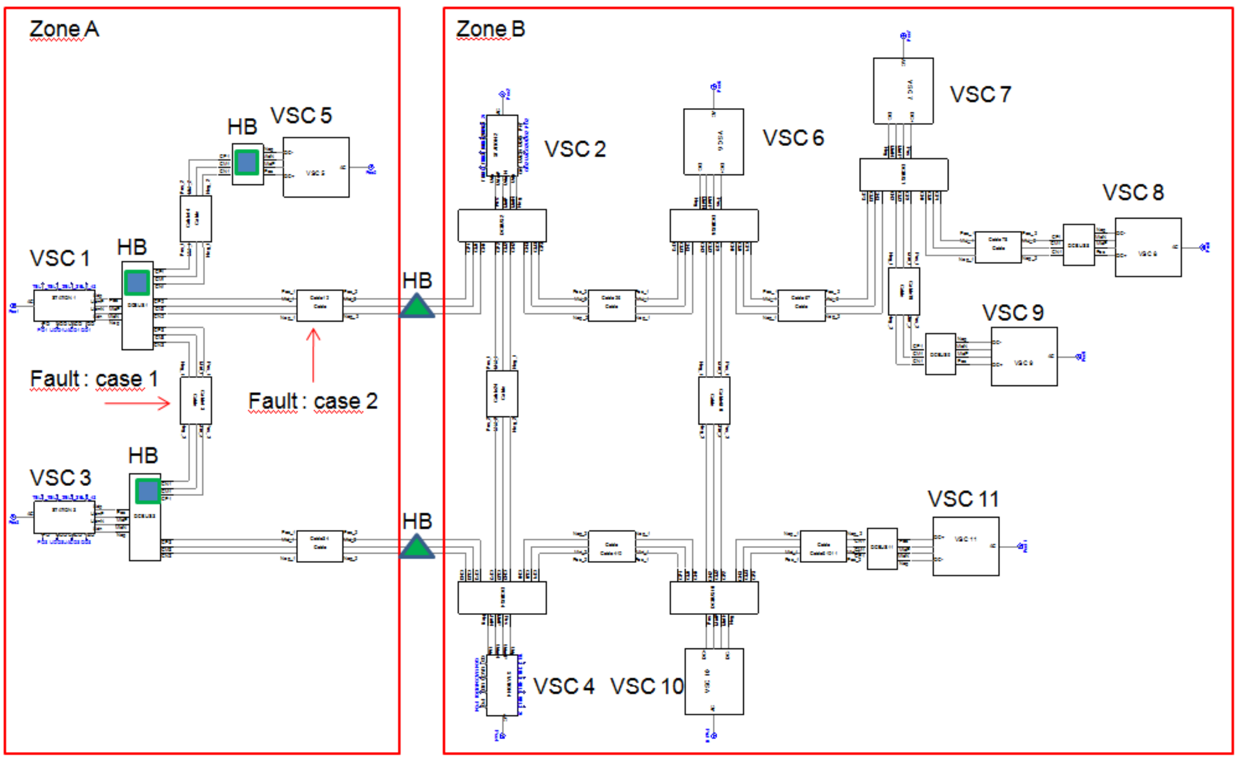


Figure 7: 11 terminal meshed radial system in pscad

Typical cable lengths for the system shown in Fig.7 are given in Table 1 but they have been varied during the studies to explore worst cases. One worst case is for instance to have many outgoing short cables from one DC yard, to mention one.

Table 1 Cable sections

Cable 1-5	400 km	Cable 4-10	400 km
Cable 1-3	400 km	Cable 6-10	40 km
Cable 1-2	20 km	Cable 6-7	400 km

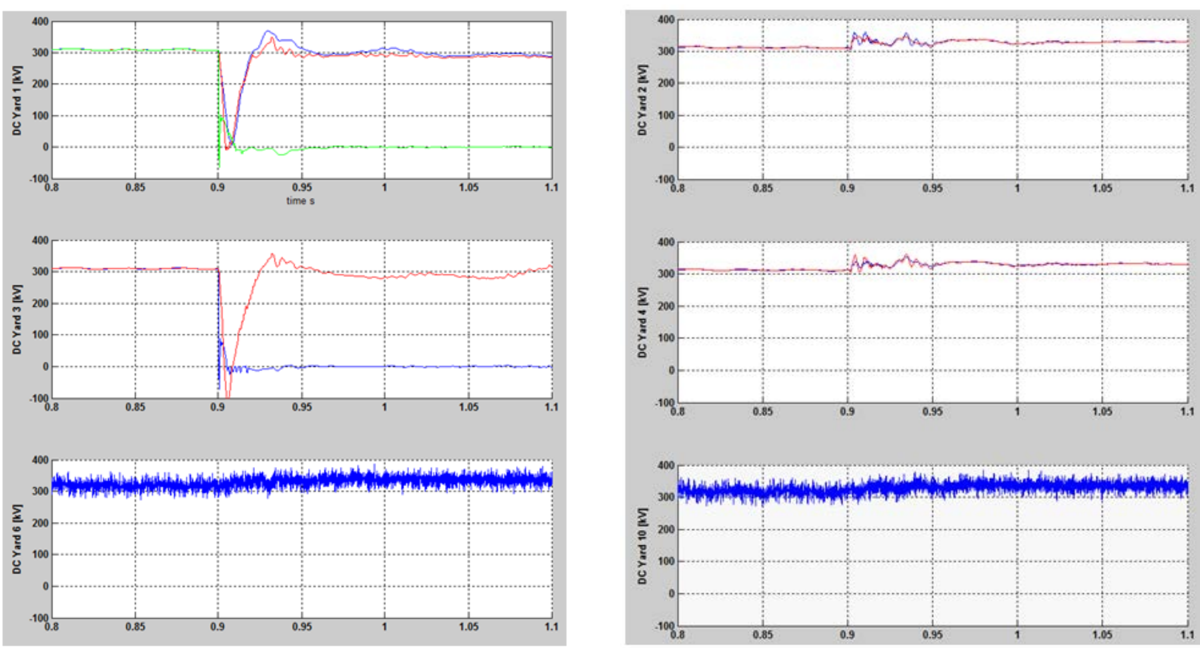
Cable 3-4	20 km	Cable 7-9	200 km
Cable 2-4	100 km	Cable 7-8	100 km
Cable 2-6	400 km	Cable 10-11	400 km

Stations VSC 1, 2, 3 and 4 are detailed models of the CTL (Cascaded Two Level) converter including all control and protection details. The remaining stations are simplified models this to reduce the computation time.

Zoning simulation results

In the system study many cases have been simulated for different fault locations, different system sizes and different power flows. The main objective is to keep the dc voltage of the protected zone constant. One example is therefore shown in Fig.8 showing the dc voltages in several dc yards in zone A and B. The results illustrated in Fig.8 show the DC voltages at the HVDC stations in Zone A and some in zone B. A fault occurs in Zone 1 at t = 0.9 sec leading to a voltage collapse in zone A, Fig.8 trace 1 and 2 (the faulty cable equals zero). The hybrid dc breakers start to respond and limit the fault current in dc yards 1,5 and 3 and the line breakers are controlled as such that they limit the fault current from zone B. The faulty cable is cleared and the dc voltage in zone A starts to recover of the remaining system.

The impact of the fault can be clearly seen in zone A and virtually unaffected zone 2 (Fig.8a trace 3 and Fig.8b trace 1-3).



(a) (b)

Figure 8: (a) trace: dc voltages dc yard 1, trace 2: dc voltages dc yard 3, trace 3: dc voltages dc yard 6, (b) trace 1: dc voltages dc yard 2, trace 2: dc voltages dc yard 4, trace 3: dc voltages dc yard 10

Conclusions

The hybrid dc breaker has been presented and tested in a simulation environment to demonstrate zoning in larger interregional dc grids. The breaker with 4 sections has been evaluated and shows quick response time. The current limitation feature relaxes the requirement on other systems components while the VSC has the ability to support the ac network with reactive power during the disturbance. The main requirement of zoning can be fulfilled by as the arrester sections of the breaker maintain a relative constant voltage in the protected zone.

Acknowledgements

References

[1] E. Koldby, M. Hyttinen “Challenges on the Road to an Offshore HVDC Grid” (Nordic Wind Power Conference, Bornholm, Sept. 2009)
[2] Jürgen Häfner, Björn Jacobson, Proactive Hybrid HVDC Breakers - A key innovation for reliable HVDC grids, Cigre Bologna 2011, paper 264