DC circuit breakers and their use in HVDC grids

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Table of Contents

Abstract 3

1. Introduction to High Voltage Direct Current 3

  1.1 HVDC compared to AC transmission 3

  1.2 HVDC converter comparison for use in DC grids 4

2. HVDC circuit breaker 5

  2.1 Circuit breaker basics 5

  2.2 Electromechanical Circuit Breakers 5

  2.3 Solid State Circuit Breakers 6

  2.4 Solid state breaker simulation 8

3. Breakers in DC grids 9

4. Conclusion 10

5. References 11

Abstract

Over the last 60 years High Voltage Direct Current (HVDC) power transmission has gained serious popularity; suggesting a valid alternative to the currently, almost exclusively used, AC power transmission. The technological innovations of the last 20 years on the electrical converters made HVDC an even more promising solution on energy distribution and transmission. A lot of work has been done on the area resulting in several examples of HVDC systems in the last three decades.

There are still a number of problems in the technology if we want to talk about DC grids. The main issue is the interruption of the short circuit current in order for the line to shut down when a problem occurs on the grid. DC breakers are the key factor for the accomplishment of a function DC grid. There are currently several types of circuit breakers under research but a lot of issues still arise when it comes to their implementation. This report will summarize the technological attempts on DC breaker on the last 20 years, trying to weigh the advantages and drawbacks and conclude to an optimal suggestion for the future of this project.

Index terms: HVDC, VSC, CSC, Sold-State DC breaker, Electromechanical DC breakers.

1. Introduction to High Voltage Direct Current

1.1 HVDC compared to AC transmission [3][1]

This project examines HVDC transmission and how this technology is used to create multi-terminal networks that can be used to connect different power stations in a more efficient way than AC transmission. HVDC circuit breakers are fundamental to the operation of such networks, due to their ability to prevent faulty situations. Research will be done on the operation of breakers, their limitations and how these can be used in DC grids.

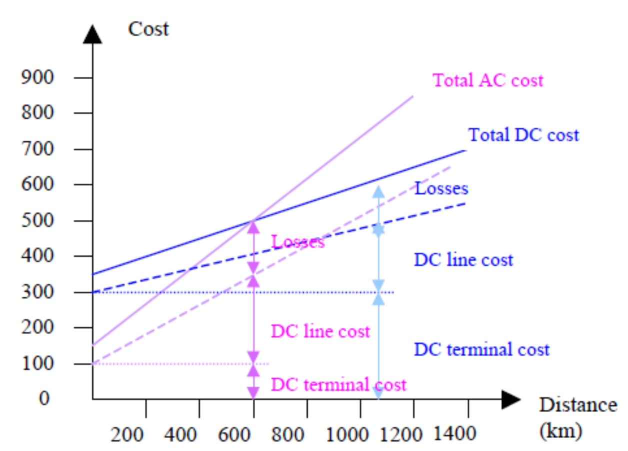


Figure 1: HVDC-HVAC cost comparison [3]

High Voltage Direct Current has been used for decades for transmission of power over long distances. The fact that capacitance in cables doesn't cause losses means that it makes up for drawbacks in the conversion process from AC, since HVDC conversion stations are more expensive than the AC ones. On the other hand, long distance HVDC lines cost in general less than the respective AC lines. As we can see from figure 1, above a certain distance HVDC transmission will have lower costs.

[1] [ ] will be used to refer to one of the sources from the reference last on the last page of the report

There are many HVDC point to point links in use today, often over international borders for trade of energy resources between countries. One natural progression for this industry would be the implementation of a HVDC grid linking multiple AC grids and transferring power in any direction between these points. A grid such as this promises huge savings on conversion facilities and the cost of lines. It would also be beneficial for the economic transmission of energy from areas where it is cheap, abundant and/or clean to regions where generation is more limited.

Although AC/DC conversion technologies have improved greatly recently, in order to operate a practical HVDC grid, circuit breaker technology still doesn't exist to satisfactorily isolate a single branch line of the grid, meaning that the whole grid would have to be shut down in the event of a malfunction. This means that development of a successful HVDC circuit breaker would be a significant breakthrough for the future of power transmission.

1.2 HVDC converter comparison for use in DC grids [5]

HVDC systems use electrical converters in order to switch from DC to AC and vice-versa. There are two main types of energy converters used, the Current Source Converters (CSC) and the Voltage Source Converters (VSC). Both of these converter types will be analyzed and ultimately we will conclude that VSC-HVDC is not only a competitor to CSC-HVDC, but it is the only possible solution for multi-terminal systems. Up until recently multi-terminal systems were not attractive for renewable energy interconnects or for energy distribution, but nowadays their use is being explored.

During the 20th century, HVDC systems used exclusively current source converters, while at that point VSC technology did not exist. Things changed in the 90s when insulated gate bipolar transistors (IGBT) which were a new type of self-commutation high power switches became available. IGBTs are three-terminal power semiconductor devices. They offer both high efficiency and fast switching, two factors which are of great importance for HVDC power systems. In addition, they allow the system to be much smaller compared to the use of other more conventional devices. CSC systems could not benefit from the new IGBTS and hence became inferior to VSC-HVDC.

Both converter types act differently on the AC and the DC side. More specifically, CSC act as voltage sources and requires major AC filtering in order to eliminate the harmonics which exists in the AC side of the system. VSC acts as a constant current source with no need for large filters and reactive power supply. Their roles are reversed when we move on to the DC side. VSC uses a capacitor to store energy and due to this capacitor no additional DC filtering is required. This is not the case for CSC.

Another advantage of VSC-HVDC systems is that the power flow in VSC-HVDC can simply be changed by changing the direction of the current, while in the case of CSC the DC voltage polarity had to be altered which is hard to achieve. Therefore it is clear that multi-terminal systems are only feasible with the use of VSC technology.

CSC point to point transmission does not require HVDC circuit breakers, since AC circuit breakers can be used instead. Multi-terminal systems though, which use VSC technology, will require HVDC circuit breakers so that the whole system does not have to shut down. We will next analyze circuit breakers and their use in DC grids.

2. HVDC circuit breaker

2.1 Circuit breaker basics [1]

Circuit breakers will be positioned on DC grids and act when a fault occurs. Breakers would have to fulfill some basic requirements. Current zero crossing should be created to interrupt the current once a fault occurs. At the same time the energy that is stored in the system's inductance should be dissipated and the breaker should withstand the voltage response of the network.

There are two types of HVDC circuit breakers: electromechanical and solid-state. Electromechanical can be grouped into three categories: (1) inverse voltage generating method, (2) divergent current oscillating method, and (3) inverse current injecting method. Only the inverse current injecting method can be used in high voltage and current ratings. In this type of breaker, current zero can be created by superimposing an inverse current (of high frequency) on the input current by dis-charging a capacitor (that was pre-charged) through an inductor. (Explained on next section) The cost of components required for an electromechanical DC circuit breaker would not be significantly higher than that of an AC circuit breaker.

Electromechanical HVDC circuit breakers are available up to 500 kV, 5 kA and have a fault-clearing time of the order of 100 ms. [1]

Solid-state circuit breakers are the second type of HVDC breakers. These breakers can interrupt current much faster (which is required in some cases) than electromechanical circuit breakers, having an interruption time of a few milliseconds. They are based on Integrated Gate Commutated Thyristors (IGCT), which compared to IGBT (bipolar thyristors) have lower on-state losses. Current flows through the IGCT and in order to interrupt, the IGCT is turned off. Once that happens, voltage quickly increases until a varistor (that is in parallel to the thyristor) starts to conduct. The varistor is designed to block voltages above the voltage level of the system. The main disadvantages of these types of circuit breakers are the high on-state losses and the capital costs.

Typical ratings of solid-state circuit breakers in operation are 4 kV, 2 kA, although in ratings of up to 150 kV, 2 kA were considered. [1]

2.2 Electromechanical Circuit Breakers [1]

On the figure we can see a basic electromechanical circuit breaker. The breaker consists of three parts:

- The **nominal current path** is where DC current passes through and the switch is closed during normal operation
- The **commutation path** consists of a switch and a resonant circuit with an inductor and a capacitor and is used to create the inverse current
- The **energy absorption path** consists of a switch and a varistor

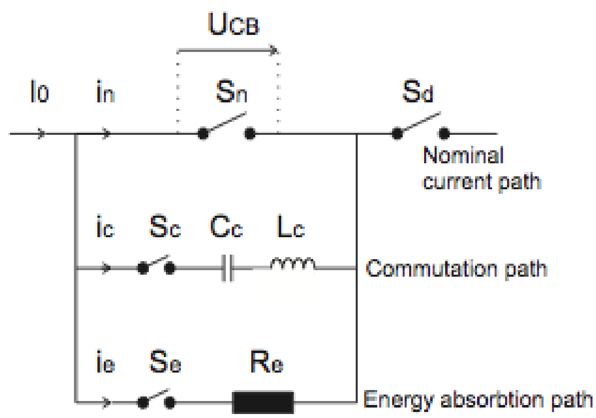


Figure 2: Electromechanical Circuit Breaker [1]

The commutation path has a series resonance. When interruption is required, current oscillation can occur between the nominal and the commutation path at the natural frequency (1/LC). If the amplitude of the oscillating current is larger than that of the input current then zero crossing occurs and the switch can interrupt the current in the nominal path. Current (Io) will continue to flow and will charge the capacitor. If the capacitor voltage exceeds a given value, which is chosen to be the voltage capability of the circuit breaker, the energy absorption path will act causing the current to decrease.

This is a basic circuit that would need further implementations to be efficient in high voltages. Reduction in cost and better use of the costly components (varistor, capacitor) will be required. Also, the optimum capacitance value would minimize the breaker's interruption time and improve the whole interruption performance. Furthermore, current oscillations grow when the arc resistance (dU/dt) of the switch on the nominal path is negative. Growing oscillations can lead to faster current interruption. At the same time a large C/L ratio can help maximize the breaker's interruption performance.

2.3 Solid State Circuit Breakers [4]

The second type of circuit breaker we will be analyzing is the solid-state circuit breaker. In the following figure we can see that a solid-state circuit breaker uses gate-commuted thyristors instead of integrated gate-commuted thyristors for semiconductor devices, this is due to the fact that in this topology our immediate concern is lowering the on-state losses.

When there is no circuit failure detected current flows through the GCTs. Once it is detected, the semiconductors are switched-off. This leads to the rapid increase of the voltage until the varistor begins to conduct. Any voltage higher than the grid voltage is blocked due to the design of the varistor. This in turn, leads to the demagnetization of the line inductance. In this topology, parallel connections are unnecessary; hence we have a total of fourteen devices.[4]

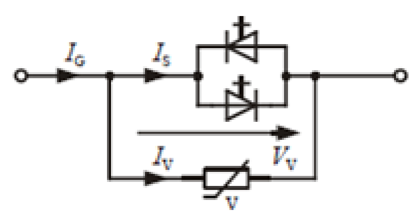
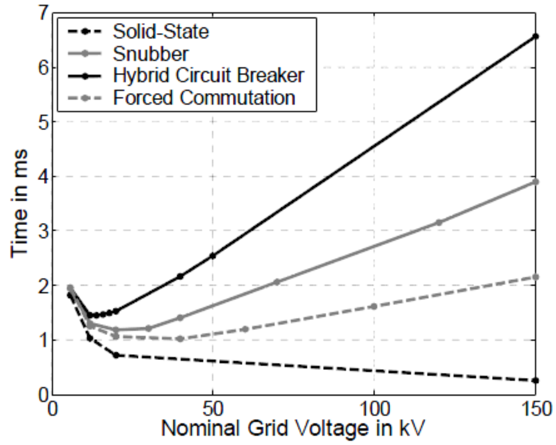


Figure 3: Solid State Circuit Breaker [4]



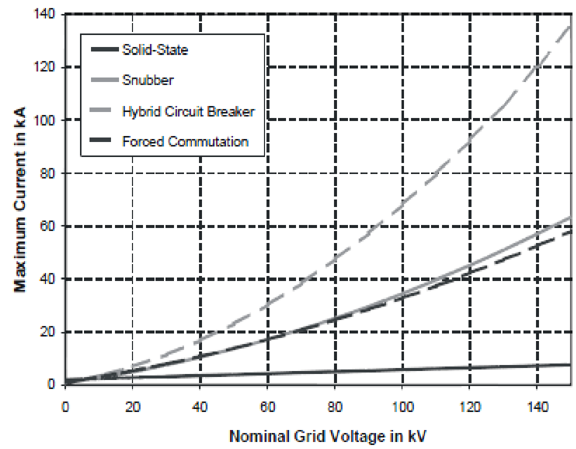


Figure 4: Grid Voltage vs. Time [4]

Figure 5: Grid Voltage vs. Maximum Current [4]

In the above diagrams as we can see the maximum current in solid-state circuit breaker has almost no dependence on the grid voltage and at the same time the higher the voltage the lower the turn-off time.

Voltage	Solid-State	Mechanical with Snubber circuit	Conventional Hybrid	Forced Commutation
6kV	6000	5400	8100	11400
12kV	9000	8800	27500	21200
20kV	21000	18000	47500	34800
150kV	300000	4450000	54544000	2602000

Figure 6: Cost comparison for four different circuit breaker models [4]

The solid-state circuit breaker model has many advantages compared to the rest of the circuit breaker topologies. First of all, because of the lack of any mechanical components the solid-state circuit breaker is much more responsive, which leads to a reduced turn-off time. Furthermore, the higher the voltage across the inductor the higher the overvoltage which allows the demagnetization process to be performed faster as we can see on figure 4. This fast turn-off process limits the peak current to low levels compared to the rest of the circuit breaker topologies. Hence, for the same grid voltage the power losses per circuit breaker are very low in the solid-state case.

With all this in mind, one would assume that the solid-state circuit breaker is the better choice due to the low component cost, low turn off time and low peak current regardless of grid voltage or cable length. This however is not the case because of one significant disadvantage; the high on-state losses. As we can conclude from figures 4, 5 for low to medium grid voltages the low turn-off time and low peak voltage are not low enough to counter the power losses during the on-state. In high voltage grids however, the solid-state topology has an advantage since the power saved per circuit break is sufficient to make them more economic compared to the other circuit breakers, even when the on-state losses are taken into consideration.

2.4 Solid state breaker simulation

We decided to simulate a solid state circuit breaker using an HVDC model provided by MATLAB. The model represents a point to point VSC based transmission at 230kV. In our attempt to simulate the fault, both cables were connected to a switch, which when opened both cables became grounded. Our breaker consists of an IGBT and a varistor in parallel. The IGBT is used instead of a GCT because that was available from MATLAB and their difference is only on the on state losses. The model is presented below.

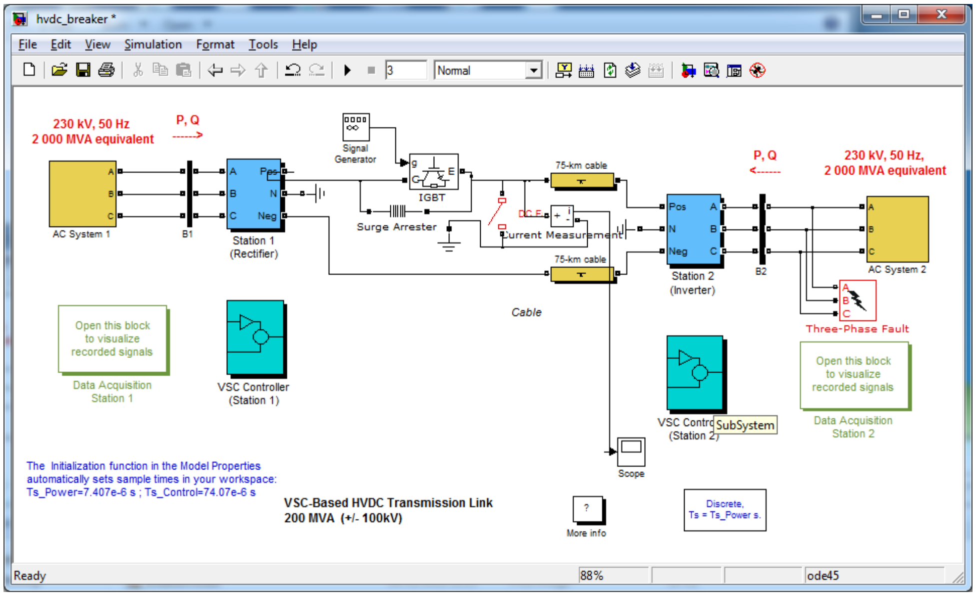


Figure 7: HVDC MATLAB model

At first we tested the power changes when the fault occurred. The fault occurred at 0.3s while the IGBT interrupted at 0.5s. From figure 8 we can see that even though power should be zero, during 0.1-0.3s there are some on state losses due to the use of IGBTs. Furthermore, once the DC fault occurs power increases rapidly, which is normal since current increases until the interruption occurs. Power though continues to oscillate even after the interruption has occurred.

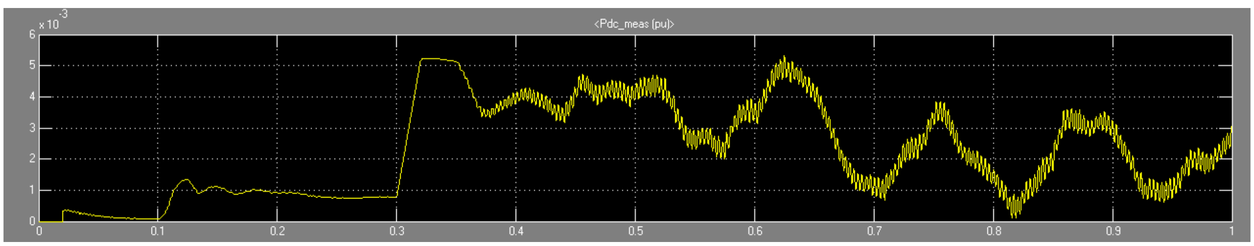


Figure 8: Power vs. time graph

Then we tested the current response of the model. We modeled the DC fault to occur at 0.3s and turned on the IGBT for current interruption at 0.65s. It is clear that once the fault occurs the current increase is rapid, though the breaker response is immediate and current drops back to its original value.

Our simulation showed that solid-state circuit breakers have rather high on-state losses which can be a clear disadvantage. On the other hand, it's very small interruption time and its functionality at 230kV is very promising.

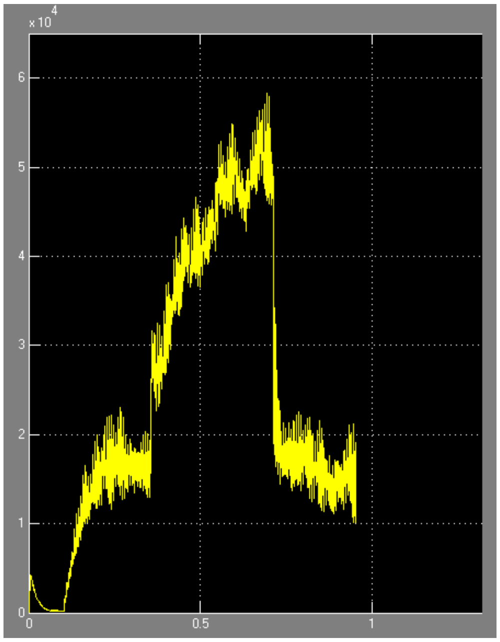


Figure 9: Current vs. Time

3. Breakers in DC grids [2]

We previously compared two technologies, CSC and VSC and saw that VSC is the ideal technology for multi-terminal networks. In CSC technology (point to point transmission) once a fault occurs the whole station is shut down. That cannot happen in a DC grid and that is why DC breakers that can interrupt one part of the network are required.

We will examine the interruption process in three different DC grid topologies. Large offshore wind farm grids will be used as an example.

1. Point to point topology

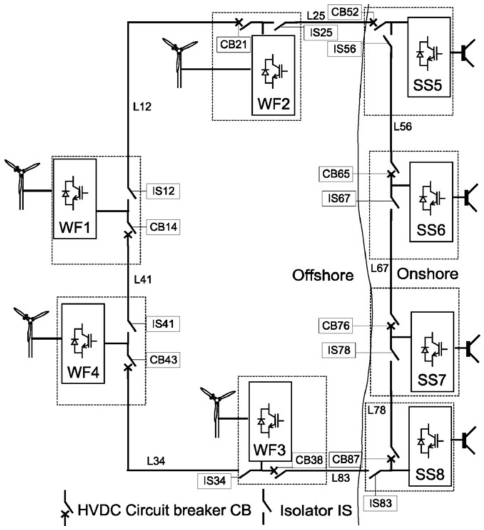
In a grid with multiple point to point connections, once a fault occurs a single line can be disconnected by simply using the AC circuit breakers on the converter side for each station.

2. Ring topology (figure 10)

The stations are connected in a ring. Once a fault occurs the two HVDC circuit breakers that are connected to the fault are opened. When the fault current is interrupted and reaches zero the isolators can isolate the faulted station and then the circuit breakers can close again. The advantage is that if AC breakers were used all the stations will have to turn off.

3. Star topology (figure 11)

The stations are all connected to a central node. Once a fault occurs the line with the fault can be disconnected using the HVDC circuit breakers, compared to CSC where both the faulty station and the central node would have to disconnect.



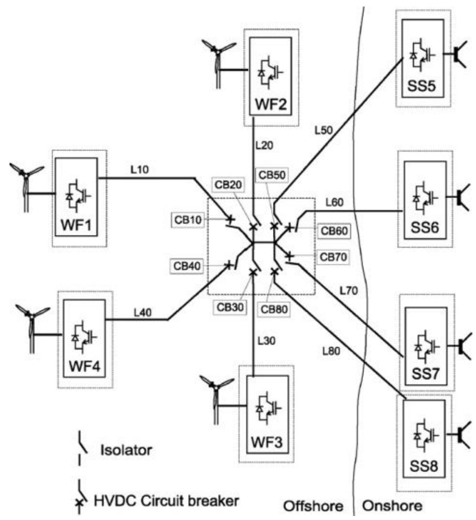


Figure 10: Ring topology

Figure 11: Star topology [2]

Multi-terminal HVDC networks can offer some clear advantages. With the use of a DC grid, the number of converters required is less than that of multiple point to point HVDC links and that decreases investment costs and AC to DC conversion losses. Furthermore, energy trade is made much easier with the use of a grid and power imbalances can be handled more efficiently. On the other hand, compared to an AC grid, DC grids are much more efficient, less costly, stations are much smaller than the respective AC ones and even though installation costs are high, these costs will balance out with time. [6, 8]

4. Conclusion

HVDC is a technology with continuous advancements and it is going to be dominant in the next few years. The potential change from CSC to VSC is going to make HVDC much more efficient, since VSC can offer higher efficiency, faster switching and by using less components make systems smaller and cheaper. Also, given the fact that VSC can make the change in power flow much easier, it will allow the creation of HVDC grids, multi-terminal networks that are much more efficient than point to point HVDC transmission and AC grids.

The creation of such grids depends on the development of HVDC circuit breakers that can efficiently handle fault situations in such high voltage ratings and currents. Electromechanical breakers can work up to a few hundreds of kilo-volts, but changes are required so that they can cost less and interrupt faster than they do at the moment. On the other hand, solid-state circuit breakers are much faster than the electromechanical ones, but can work up to 150kV and their on-state losses are too high.

We can see that the creation of appropriate circuit breakers can lead to great changes in the area of energy transmission. Dr Uhlmann's statement that "It can be safely stated that a DC circuit-breaker will be available at the time the need for such arise"[7] has become much more relevant today, since with the advancements in the HVDC field and the uprising need for energy transport, circuit breakers are the only thing that stops the creation of HVDC grids which can change the way power is transferred all over the world.

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