Service Operation of UHVDC Systems with Emphasis on Switching Phenomena

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***Abstract*—The presented paper is aimed at the topic of UHVDC systems with emphasis on switching and breaking techniques both for nominal and non-standard cases of service. The topic of HVDC is very actual and demanding amongst challenges being dealt with within the professional public and power engineers. The first part of the paper contains introduction, assessment and evaluation of the state-of-the-art technology of UHVDC transmission systems and the definition of the greatest challenges within the switching and breaking operations. The second part of the paper is aimed at comparison of conventional and hybrid DC circuit breakers with the detailed explanation of crucial advantages of hybrid technology. The model of hybrid DC circuit breaker is shown in the last part of the paper and its functionality is discussed within exemplary scenarios. The paper concludes with the evaluation of DC breaking techniques and their current and future demands.**

***Keywords*—HVDC; circuit breakers; hybrid technology; short-circuit; solid-state; transmission lines; breaking process**

I. Introduction

The power transmission using HVDC technology is becoming much more used and utilized way of transmission at the whole specter of grid types and voltage levels. Most of the HVDC links consists of changing power station to convert alternating current (AC) to direct current (DC). Using direct current to transmit power has many advantages which are going to be described in the upcoming chapter. HVDC systems are and efficient alternative to transmit electric power over long distances and allows the operator to quickly manage power and energy flows in the grid. The HVDC technology joints together many of the most challenging areas of state-of-the-art electrical engineering sector, such as service operation and maintaining of the large transmission lines, overhead lines and cable traces construction and maintenance, solid state technology and switching phenomena within circuit breakers. Circuit breakers are the only device capable of switching the circuits off both in nominal and nonstandard cases of operation. And the switching phenomena in DC grids are the most critical issue, because there is no current zero, in which the circuit is naturally, which creates on of the most challenging thins in the HVDC grids – to successfully design fast, secure and reliable circuit breakers.

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II. Advantages and Disadvantages of AC and DC Transmission

With relation to the massive emerge of the HVDC grids, it's possible to mention technical and economical comparison of DC and AC systems. One of the greatest advantage of AC system is its historical evolution and adopted practices with generating, transforming, transmission and distribution, maintaining and utilizing the AC energy. AC system has more than a century lasting evolution that allows us to easily and reliably maintain power grid in terms of voltage and frequency stability and control and cost demands. On the other hand, disadvantages of AC transmission grids are well known for many years and some of them, such as energy and power losses, frequency stability in emergency states, reactive power flows and long-distances transmissions, might be reduced by properly designed HVDC grids. Main advantages of HVDC transmission are: [1, 3, 4]

- Ability to control values and direction of the power flow.
- No effect of inductive and capacitive parameters of the transmission lines, compared to AC.
- Shorter insulating distances – no need to design for the amplitude of the sinusoidal waveform.
- Economically more effective and lower investments for longer distances.
- Possible to use only 2 wires, instead of 3.

On the other hand, disadvantages of HVDC grids are the greatest challenges that slows down their spread:

- Difficult conversion to the high voltage levels.
- Large cost demands for convertor stations (economically viable only for long distances).
- Great losses in the convertor stations (semiconductors)
- Possible to connect only two locations – each other branches increases the investments.
- Generating harmonics in the connected AC system.

The transmission losses, the greatest advantage of the DC transmission will be explained in the next chapter.

III. Losses comparison for AC and DC Transmission

The power losses in transmission lines are caused mainly by passive parameters of the lines, whereas the most decisive is the resistance of the line. For a true evaluation of losses it's necessary to take RMS values of AC transmission into account and evaluate losses for the same transmitted power P_{trans}. Regarding the unipolar DC system, its power losses are:

$$\Delta P_{dc} = 2 \cdot R \cdot I_{dc}^{\ 2} = 2 \cdot R \cdot \frac{P_{trans}}{U_{dc}} \qquad (1)$$

Similar approach can be observed for single-phase AC circuits, where *cos(φ)* makes an addition, which gives information about active and reactive power in the transmission.

$$\Delta P_{1ph} = 2 \cdot R \cdot I_{1ph}^{\ 2} = 2 \cdot R \cdot \left(\frac{P_{trans}}{U_{1f} \cdot \cos\varphi} \right)^2 \qquad (2)$$

Different situation appears for the three-phase systems, where we obtain different coefficient in the denominator part. Regarding the relations between line-to-ground and line-to-line voltage, the total losses can be written as eqns. (3) and (4).

$$\Delta P_{3ph} = 3 \cdot R \cdot \left(\frac{P_{trans}}{3U_{ph} \cdot \cos\varphi} \right)^2 = R \frac{P_{trans}^{\ 2}}{3U_{ph}^{\ 2} \cdot \cos^2\varphi} \qquad (3)$$

$$\Delta P_{3} = 3 \cdot R \cdot \left(\frac{P_{trans}}{\sqrt{3}U \cdot \cos\varphi} \right)^2 = R \frac{P_{trans}^{\ 2}}{U^2 \cdot \cos^2\varphi} \qquad (4)$$

Comparing the losses for DC and 1-phase AC transmission, we obtain the following ratio in eqn. (5). We can observe conditions, in which the ratio equals 1 – when the power factor is 1 and the RMS value of AC voltage equals the DC voltage. These conditions are not always met. Similar can be observed from eqn. (6) that shows the same comparison, when we assume three-phase AC system. [2, 4]

$$\frac{\Delta P_{dc}}{\Delta P_{1ph}} = \frac{U_{ph}^{\ 2} \cdot \cos^2\varphi}{U_{dc}^{\ 2}} \qquad (5)$$

$$\frac{\Delta P_{dc}}{\Delta P_{3ph}} = 6 \frac{U_{ph}^{\ 2} \cdot \cos^2\varphi}{U_{dc}^{\ 2}} = 2 \frac{U^2 \cdot \cos^2\varphi}{U_{dc}^{\ 2}} = \frac{2}{3} \cdot \frac{U_{ac}^{\ 2} \cos^2\varphi}{U_{dc}^{\ 2}} \qquad (6)$$

Regarding the most used technology at AC transmission, 3-phase with line-to-line voltages, we can obtain the loss ratio 2/3 of total AC losses for the DC losses, as shown in eqn. (7). This makes an important point in the whole power transmission issues at AC and DC lines.

$$\frac{\Delta P_{dc}}{\Delta P_{ac}} = \frac{2}{3} \cong 0.66 \qquad (7)$$

Critically limiting the efficiency of the DC transmission are the converter stations, which not only they are very expensive unit, but also have a great thermal losses due to the semiconductors installed. The overview is shown in the Tab. 1.

TABLE I. Percentual comparison of losses in the converter stations

[%]	**Rectifier**	**Invertor**
Ventil	35,44	35,57
TR	52,49	51,42
C	0,32	0,42
AC filter	4,83	4,52
DC coil	6,50	7,59
DC filter	0,08	0,10
PLC filter	0,33	0,39

IV. Common HVDC Systems

One of the most progressive companies in the HVDC construction has been historically considered ABB, which started with the construction near the Gotland island. With the historical evolution of technology the approaches evolved as well and currently we are distinguishing multiple systems.

A. *HVDC Classic*

HVDC Classic is the most classical approach. It uses thyristor converters and it is used for universal purposes. It can be constructed as an overhead line or cable under the sea. It is mostly used as the interconnection between two incompatible AC systems (such as the connection between Norway and Netherlands).

B. *HVDC Light*

The HVDC Light System has been introduced in 1997 with the transmission capability up to 2.500 MW. It uses IGBT transistors which allow to continuously set the power flow through semiconductors. HVDC Light system have been utilized mostly for the connection of large off-shore wind farms and oil platforms with the continental grid. Thanks to easy and quick setting of power and effects of the reactive power flows in the connected AC grids it can be also used for the specific connection of two AC grids, such it is in the case of connection between Ireland and Great Britain. [6, 8]

C. *HVDC Ultra*

HVDC Ultra System is the newest approach related to the new technology of ABB to upgrade the voltage levels up to ±1100 kV. The evolution of this system has been conditioned by the evolution of equipment sufficient to withstand such a voltage stress. This voltage levels have the main purpose to minimize the losses over long distances. HVDC Ultra is constructed this time in China within several projects at voltage levels ±800 kV to connect the inland with the coastal areas.

V. Current interruption in DC circuits

The phenomenon of current interruption in DC circuits is quite challenging because of the lack of current zero, which makes a great disadvantage of DC grids. Let's assume standard circuit with resistive and inductive parameters, which is in accordance to the real lines. The layout can be observed in Fig. 1. The continuity of the current through the inductive must be preserved.

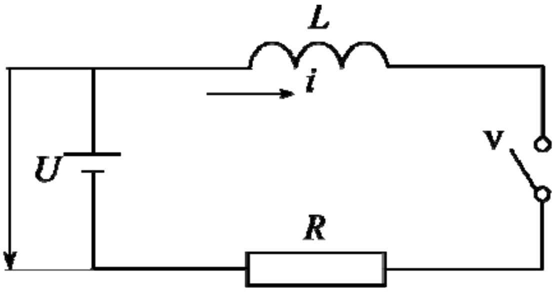

Fig. 1. Simple DC circuit with inductive character

Regarding the instantaneous operation of the mechanical breaker (in the Fig. 1 as V), we need to provide a parallel branch to the contacts, in which the energy is absorbed. The approach differs with the different DC circuit breaker applications. The historically verified and most used technology at low voltage levels represents the contacts with quenching chamber with ribbings, in which the electric arc is being extinguished. Unfortunately, this technology can't be used at HVDC levels because of the large energy amounts. That is why the new techniques has been developed, mostly using **a)** the resonant RLC circuits and **b)** the semiconductors. This will be explained in the next chapter. The circuit topology varies a lot regarding the accounted and neglected parameters, but we can state the fact the parameters R and L are the most important for the current interruption.

VI. Circuit Breakers for DC Circuits

It is necessary for the circuit breakers to be able to interrupt nominal service currents as well as special conditions such as short-circuits and other faults. The main motivation is to interrupt the current as quickly as possible and to easily transform and dissipate the energy stored in L.

The very first type of the DC breaker is the electromechanical breaker. The principle stands in the mechanical disconnecting in the nominal current path and electrical dissipation of the energy and lowering the current to the zero, using three different approach: (1) generating the inverse voltage, (2) oscillating divergent current or (3) injecting the inverse current. Comparing these three approaches, only the third one can be used at the high voltage levels with the appropriate current load. The current interrupting is reached by layering the inverse current of discharging capacitor, which has been charged in the nominal, closed operation. The electromechanical breaker is shown in the Fig. 2 and it contains three paths. First one is the nominal current path which carries the nominal current when the breaker S_n is closed. The second path consists of the series resonant LC circuit to create the commutation and to create the inverse current. When the impulse for an interruption comes, the commutation injects the current to the nominal current path. When the amplitude of the oscillating current is higher than the cleared current, zero crossing comes and the breaker S_d turns off and the operation is over. If the voltage across the capacitor overcomes the voltage abilities of the breaker, the energy absorption path consisting the nonlinear resistance dissipates the overvoltage energy.

This diagram in Fig. 2 represents the basic layout of the electromechanical breaker. Optimal value of the capacity ensures the shorter breaking time and improves the whole process, also higher oscillations might lead to the shorter breaking time. The total length of the process is in milliseconds.

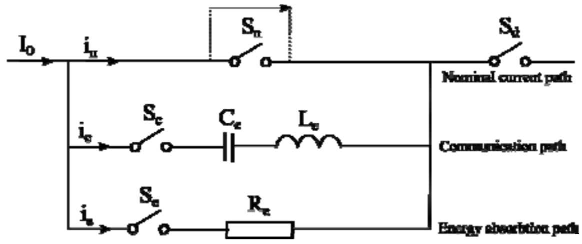

Fig. 2. Electromechanical breaker

The second type of the DCCB is the solid-state breaker, which can interrupt the current faster than the electromechanical breaker. The basic layout of the solid-state DCCB is in the Fig. 3. The main current path consists of two antiparallel IGCT thyristors. Using the solid-state components, we are limited by the allowed voltage and current stressing. The principle stands in the fast regulation and control of the IGCT voltage. The overvoltage caused by the current continuity is then absorbed in the parallel branch with the varistor capable of minimize the overvoltage effect.

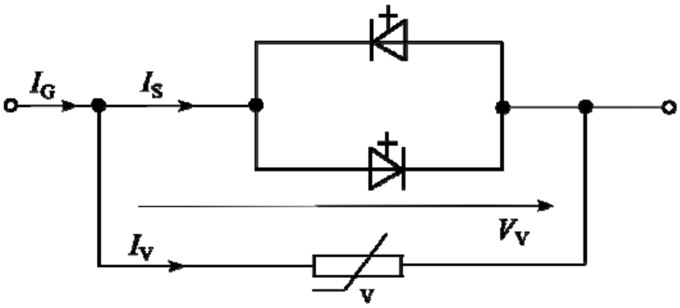

Fig. 3. Solid state breaker

Thanks to the voltage and current limitations of the solid-state components, it is necessary to create cascades of mentioned layout.

Another possibility is to combine electromechanical and solid-state breaker together which leads to the hybrid DC circuit breaker technology (HDCCB). HDCCBs basically consist of the main branch with the mechanical breaker and a commutation component, auxiliary branch contains the solid-state components and the overvoltage limiters – metal oxide varistors (MOVs). The HDCCBs combines advantages of both principles, such as low losses in the closed state and fast interruption of the circuit. On the other hand, hybrid technology also brings many challenges for the manufacturers and operators. These will be introduced and explained in the next chapter. [9]

VII. Hybrid Circuit Breaker Technology

A. ABB's Hybrid DCCB

The ABB's HDCCB consists of two branches. The main branch with ultrafast disconnector (UFD) and load commutation switch (LCS). The additional branch is the semiconductor-based branch separated into several sections with arrester banks, which need to be dimensioned for the full voltage and current breaking capability, whereas the LCS matches lower voltage and energy capability. LCS and the auxiliary branch are both created of IGBT transistors. IGBT transistors in the main branch must be in the anti-series to be able to commute current of both polarities. Also the auxiliary branch has multiple cells of anti-series IGBTs with the parallel MOV arrester banks. The total count of cells is given by the rated voltage level of the breaker. [7]

The main purpose of the auxiliary branch is to carry the high current when the UFD operates, which lowers the stressing of the main branch. The parallel MOV arrester is for dissipation of the energy as well as for the overvoltage protection of the semiconductors.

The Fig. 5 shows the breaking process of the ABB's HDCCB in each step. In the beginning of the operation, breaker is in the nominal service operation, current flows through the main branch and partially also through the auxiliary branch, thanks to the non-infinite impedance of the semiconductors. It's shown in the part **a)** of the Fig. 5. In the second step, **b)**, a fault appears and the current quickly increases to the value of cleared current of the LCS. Reaching this value, the signal is sent on IGBTs in LCS and it leads to the current commutation to the auxiliary branch and the UFD operates. In the third step, **c)**, the high current flows through the IGBTs in the aux branch, which need to withstand such a current loading. Rate of increase is defined by the actual fault. When the UFD successfully opens (which takes approx. 2ms), turn-off signal is sent on the aux branch and the current commutes to the MOV branch, where thanks to the inverse voltage the current decreases and energy dissipates. This is part **d)** of the Fig. 5. When the current falls to zero, RCD opens which protects the MOV units from thermal overload caused by residual currents. After the RCD is successfully opened, the operation ends and the fault is cleared.

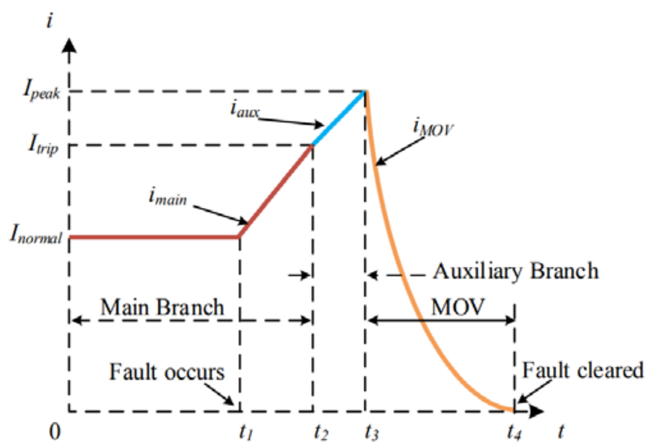

Fig. 4. Current interruption in ABB's HDDCB

Fig. 4 shows the current performance in the process. The first part is the time interval of the fault detection and current commutation to the aux branch. The second part is the UFD operation and total fault current commutation, third part is the fault clearance.

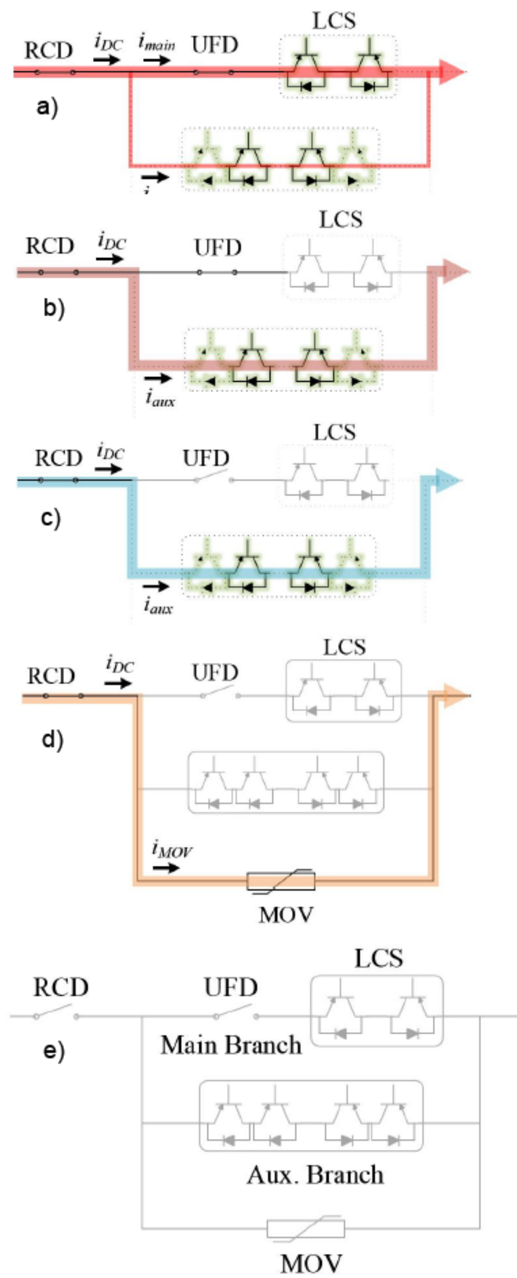

Fig. 5. Current interruption process in ABB's Hybrid DCCB

It's possible to mention that the ABB is a pathfinder in the whole HVDC technology industry and their HDCCB allowed such a massive development of HVDC grids mainly in Asian continent. Nevertheless, multiple issues appeared, which had been subsequently encountered and solved by the Alstom Grid and their modification of HDCCB.

B. Alstom Grid Hybrid DCCB

The breaking capability and rate of operation of IGBTs are quite high, the UFD operation is much slower than IGBT cells, therefore the total time of system's protection needs to be longer. Alstom Grid decides to solve such a thing and designed the hybrid DCCB with similar function and topology, but different process in the aux branch. The aux branch in the Alstom's breaker installs pulse power thyristors PPT. Aux branch consists of time delaying branch and parallel arming branch.

In the Fig. 7, part a), breaker is in nominal service operation, all thyristor groups in aux branches are off and current flows through LCS in series with UFD. When the operation due to a fault or any other input initiates, LCS obtains turn-off command and the first time-delaying branch with thyristor groups turns on. In part b), current commutes to time-delaying branch and it charges the capacitor. After LCS commutes all of the current, UFD breaks off. In the step c), before the UFD is fully opened, thyristor groups in the second aux time-delaying branch are opened. When the capacitors in the first time-delaying branch are fully charged, it's recharging into the parallel arrester bank, leading to the steady voltage at the branch and current decrease to zero. In this moment, thyristors of the first time-delaying branch are turned off and before the UFD is fully opened, current flows through the second time-delaying branch. After the UFD finished operation, current flows through the arming branch as it's shown in e) of the Fig. 7. Second time-delaying path operates with the capacitor similarly like the first one so the current completely commutes to the arming branch. Arming branch operates with the task to transfer the current to the main arrester bank. Then, similarly like with the ABB HDCCB, MOV decreases the current to zero and the residual current circuit breaker switches off. [10]

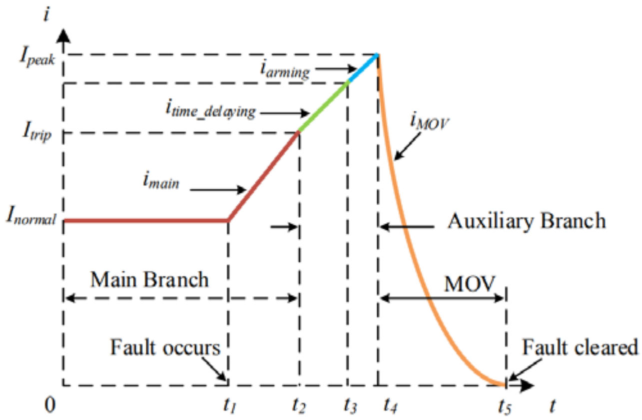

Fig. 6. Current interruption in Alstom's HDDCB [10]

The Fig. 6 shows the whole current interruption process over time. It's visible that comparing to ABB HDCCB, there is a time-delaying part and arming part leading to more significant increase of the current.

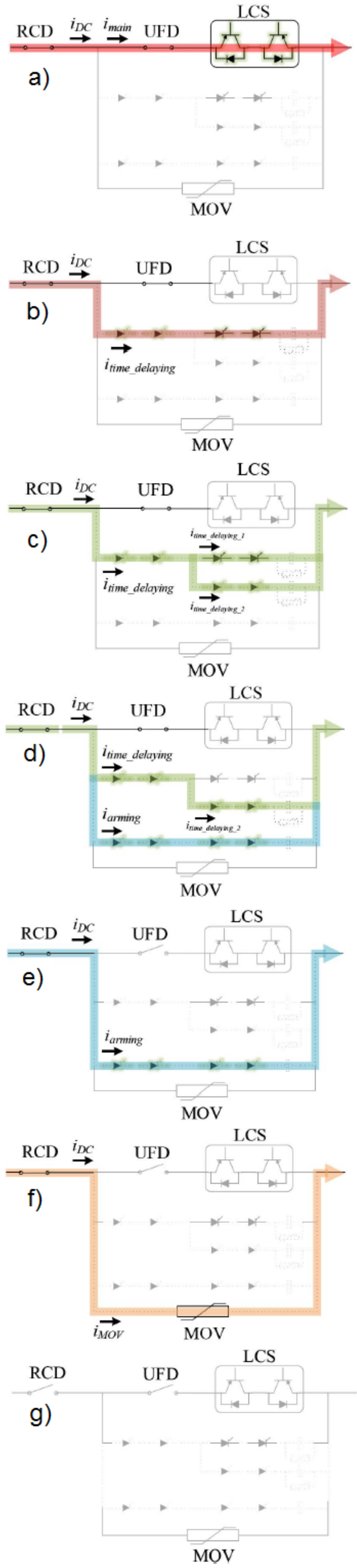

Fig. 7. Current interruption process in Alstom's Hybrid DCCB [10]

VIII. Comparison

It is visible that both of the mentioned HDCCBs are developed and designed to meet the state-of-the-art requirements and both decided to use such a positive features of the solid-state components in the commutation branches.

TABLE II. Comparison between HDCCB for multiple criteria

	ABB HDCCB	Alstom Grid HDCCB
Breaking method	Current commutation	Current commutation
Main branch components	Mechanical disconnector with 2 IGBTs in anti-series	Mechanical disconnector with 2 IGBTs in anti-series
Aux branch components	IGBT cells in series	Thyristor groups with capacitors in series
Component cost demand	Depends on the number of IGBT cells, more cells for higher voltage levels	Depends on the number of thyristor groups, larger capacitor for higher voltage levels
Advantages	Quick operation of IGBTs, easy control	Higher fault current abilities for thyristors
Disadvantages	IGBTS struggle with higher currents, needs for stronger protection	Problems with thyristor's turning off and on, requires capacitors
Losses	Higher than Alstom Grid HDCCB	Very low, severals of kW
Current interruption speed	Significantly high	Easily controllable by delaying branches
Applications	Preferred for MVDC and HVDC for the faster current interruption	Preferred for HVDC systems with more time delays for protection

Both circuit breakers have been modelled and their function simulated in the [10] with the following results of the cleared current. The most important conclusion about the simulation is the visible time delay of the Alstom model thanks to the time-delaying and arming branches. Thanks to this feature, Alstom Grid HDCCB gives the possibility to easily control time delays for the protection systems in the UHVDC grids.

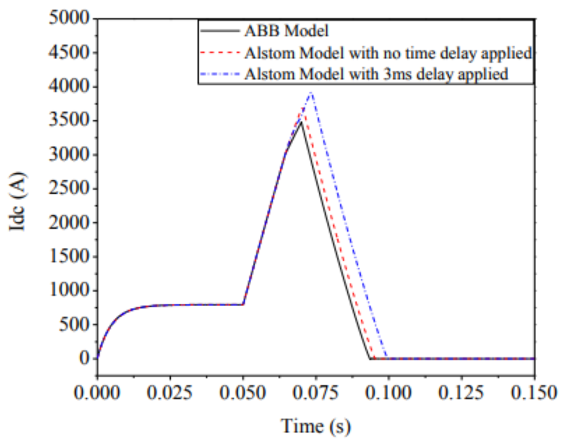

Fig. 8. Current interruption process simulated in [10] for both HDCCBs [10]

IX. Conclusion

The HVDC grids and their operations are one of the greatest challenge in the modern era of power engineering. It is a tool for the transmission system operators to deal with the slight changes in the character of electric power grid and help them to provide necessary reliability and stability to the system. HVDC grids might be the answer for the power grids of the future generations.

While breaking and interrupting the DC circuit still remains the issue, hybrid technology is a sufficient way to easily and reliably interrupt nominal and fault currents. The approach of different manufacturers slightly varies, but thanks to several similarities and thanks to different properties of components, it is possible to design a large portfolio of circuit breakers with tighter attachment to the final application, as it comes out from the ABB and Alstom Grid comparison.

Hybrid breakers and HVDC transmission lines in general are making a great feature leading to the sustainable and reliable mix of power system.

Acknowledgement

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