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The limitations of Hybrid DC Circuit Breakers used for VSC-HVDC Transmission System

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Abstract — **In order to maximize the utility of renewable energy resources, voltage source converter based high voltage DC (VSC-HVDC) transmission has become an attractive option. The protection of VSC-HVDC based transmission systems against faults is still considered a major hurdle to practice it widely. In this context, hybrid HVDC breakers are considered a reliable option to protect the system against line-to-ground (L-G) faults on the DC side of the converter. However, these breakers are not suitable for higher voltage and increased fault-current interruption requirements. In this paper, firstly, working principle of hybrid DC circuit breakers is explained with the help of MATLAB/SIMULINK based simulations. In subsequent parts of this study, capacity restraints of such breakers are explained.**

Index Terms— **ABB, ALSTOM, Hybrid DC Circuit Breaker, Renewable Energy, and VSC-HVDC.**

I. INTRODUCTION

In the recent years, different nations have willfully focused on generating electrical energy from renewable resources, to avoid the harmful effects of hydrocarbon fuel. The emission of CO_2 share by different counties is given in [1], whereas, the effect of these gases on the environment are given in [2-3]. Unfortunately, at times remote areas are affluent in terms of green energy-resources, thereby, to utilize these resources successfully, effective, efficient, and economical transmission network is undisputedly required. In this context, the VSC-HVDC transmission has become an attractive option. Because it allows the independent control of active and reactive power [4]. The comprehensive comparison between different HVDC topologies is given in [5].

Although, VSC-HVDC have distinct advantages, however, such systems are more vulnerable to the L-G faults because of DC-link capacitors and their discharge current. So, protecting the system against the frequent fault is bit challenging. In this context, DC circuit breakers (DCCBs) are considered the most reliable option. The DCCBs have gone through the different developmental ages. In principle, these are broadly classified into three major categories, and those are shown in Fig. 1.

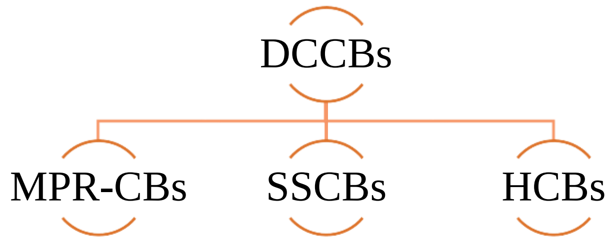

Fig. 1: Different types of DCCBs

The functional details of these three types of DCCBs, i.e., mechanical passive resonance circuit breakers (MPR-CBs), solid-state circuit breakers (SSCBs), and hybrid circuit breakers (HCBs) are briefly given in [6].

There are many topologies of HCBs available in the literature, but the fundamental concept of HCB for 320 kV was first introduced by ABB in 2012 [7-8]. The fault interruption current was 2.2 kA within few milliseconds. Soon after ABB, ALSTOM also introduced their design in 2014. The schematic diagram for both state-of-the-art topologies is given in Fig. 2 and Fig. 3 respectively. The detailed critical evaluation of both state-of-the-art topologies is given [9]. Some topologies of HCB for DC and AC, with fault-current limiting capacity are given in [10-13].

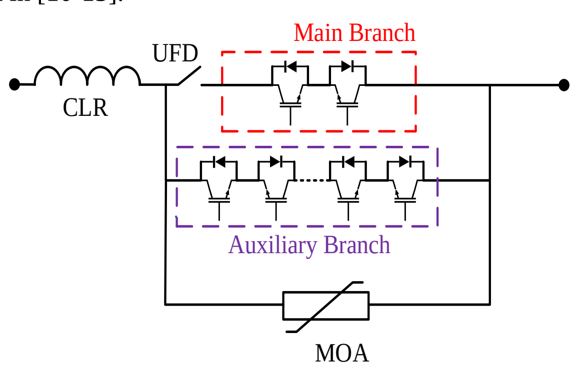

Fig. 2: The schematic layout of ABB's HCB

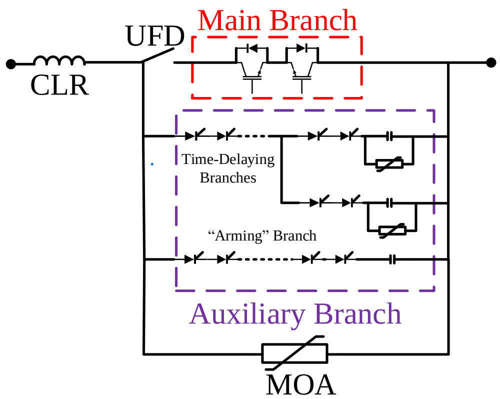

Fig. 3: The schematic layout of ALSTOM's HCB

The HCBs enjoy good characteristics in comparisons with other topologies, therefore, these days such breakers are considered as the best option to guard the system against L-G faults. From the list of HVDC projects available in [14], it is observable that the rating of VSC-HVDC projects have increased significantly with the passage of time, thereby, HCBs have shown some limitations with increased voltage and fault-current handling capability. In this study, the working principle of ABB's HCB is explained. Later on, four different case studies are presented with simulation results to understand, how the increased ratings of the system, influence the performance and cost of such breakers. The rest of the paper is organized as follows. In section-II**,** working principle of HCB is explained, considering the design of ABB as an example. Section-III of the paper contains the simulation-based analysis, followed by Section-IV which drives the conclusions.

II. Fundamentals of Hybrid Circuit Breaker

In this section, the working principle of HCB considering the example of ABB's design is explained. From the schematic diagram of ABB's HCB in Fig.1, it can be observed that there are three branches of this circuit breaker, namely: the main branch, which is constituted by IBGTs and a mechanical switch called ultra-fast disconnector (UFD); the auxiliary branch, which is composed of IGTBs; and lastly the energy absorption branch, which contains metal oxide arrester (MOA). These three branches form three different current paths; the details are given in Fig. 4. The working principle is divided into three time intervals.

- For interval $0 \le t \le t_1$

This interval is the normal operating period, during this time the system carries the rated current, which is defined according to the requirement of the system. Current during this interval is defined as I_{normal}.

- For interval $t_1 \le t \le t_2$

This interval is transient time, at t_1 fault in the system is suspected, and the current start to increases from the rated value to I_{trip}.

- For interval $t_2 \le t \le t_3$

Once fault in the system is confirmed at t_2, the switches associated to the main branch of breaker open completely, and transfer the fault-current to the auxiliary branch. At this stage, fault-current gains the value of I_{peak}. I_{peak} is the maximum value of the fault-current system can tolerate.

- For $t > t_3$

This case is the final stage, after t_3 the switches associated to auxiliary branch open, and fault-current is transferred to MOA and eventually isolated from the system. Energy absorbed by the MOA can be calculated by using the following equation [15].

$$E = \int V(t) I(t) dt \quad (1)$$

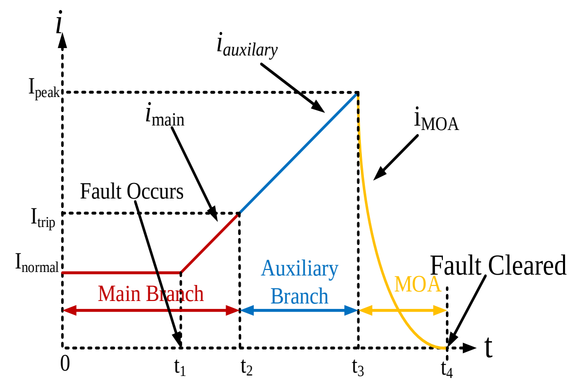

Fig. 4: The overall response of DC current explaining the working of ABB's HCB

III. Simulation Results and Discussions

The generalized model for simulation for different cases is given in Fig. 5. For simulation-based analysis, four different case studies are presented, with different voltage ratings. For case-I, the simulation model was built for 132 kV voltage; likewise, for case-II, case-III and case-IV simulation models were built for 200 kV, 320 kV and 400 kV. It is essential to observe that, for all these simulations fundamental model of ABB's HCCB is considered so that it is analyzed how the increased voltage ratings can influence the design requirement of the beaker. ABB experimentally validated this breaker for 320 kV, and ideally, this breaker is recommended for 320 kV configuration or voltage rating even less than 320 kV.

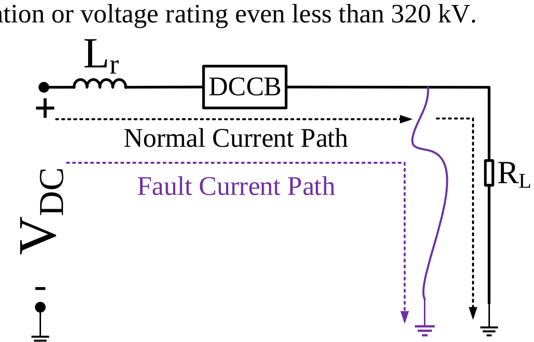

Fig. 5: Generalized model for simulation

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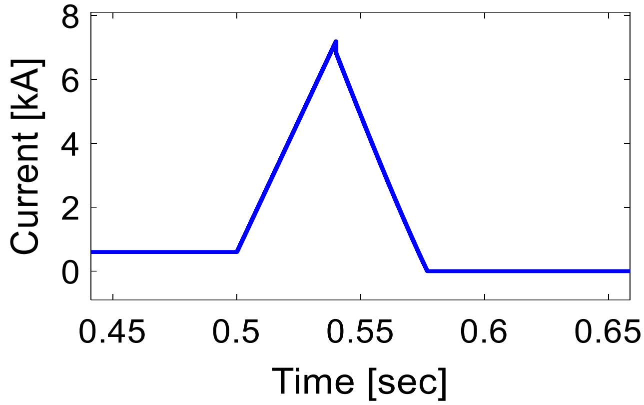
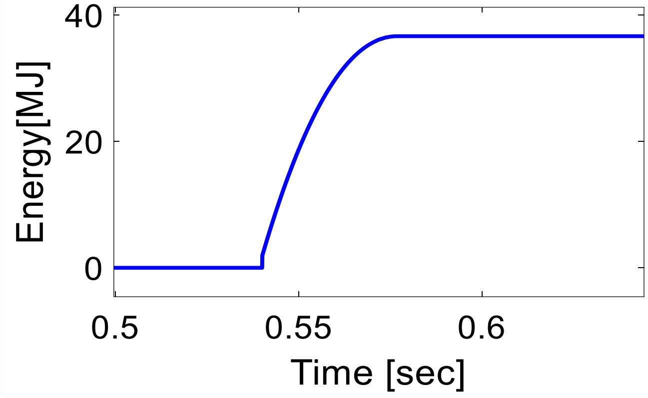
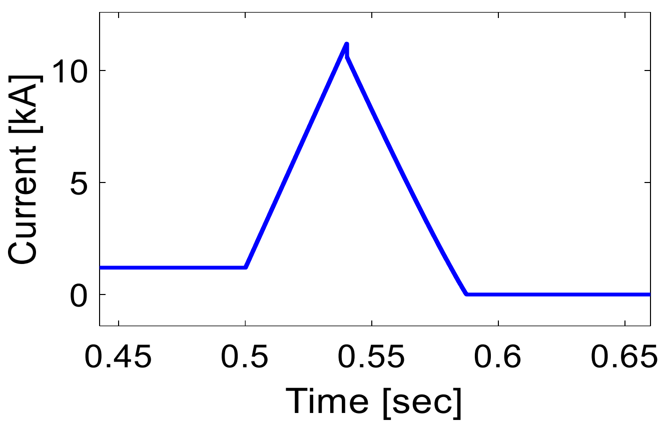


(a)

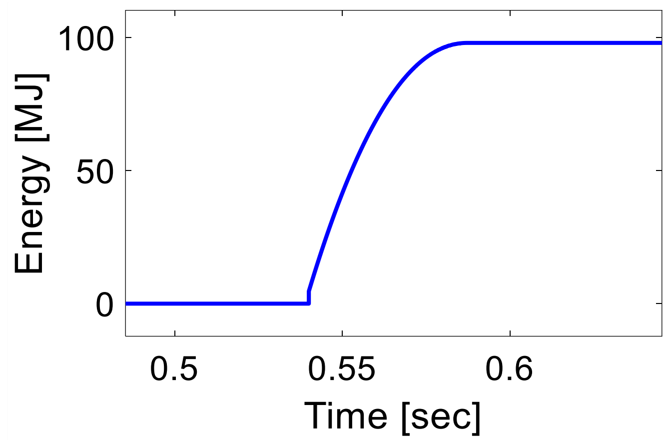


(b)

Fig. 6: Result for case-I considering 132 kV (a) overall response of DC-current; and (b) energy absorbed by MOA

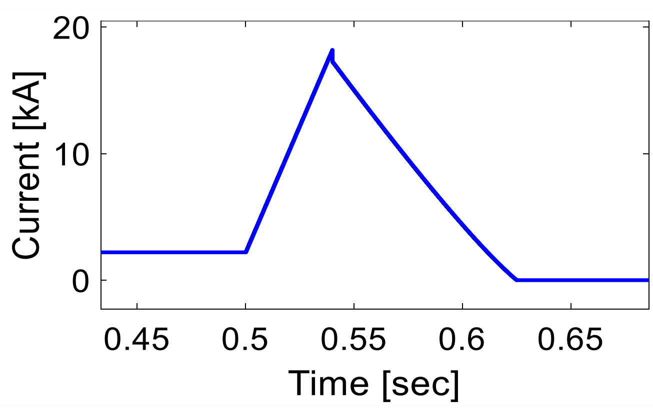


(a)

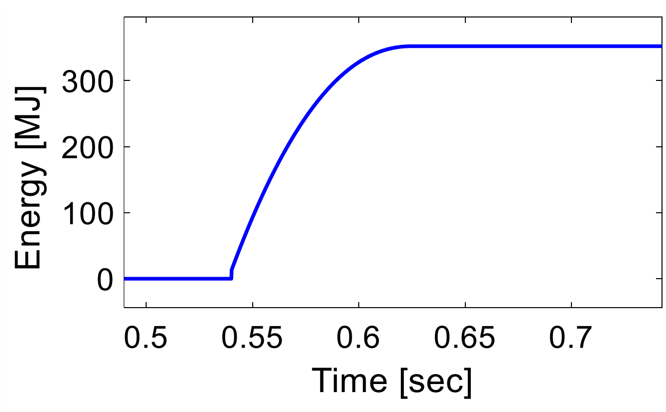


(b)

Fig. 7: Result for case-II considering 200 kV (a) overall response of DC-current; and (b) energy absorbed by MOA



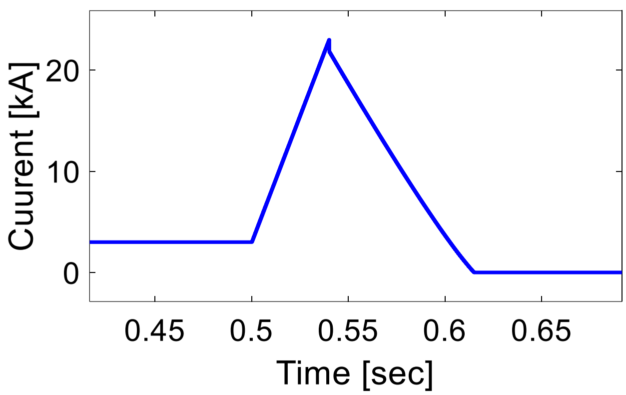
(a)



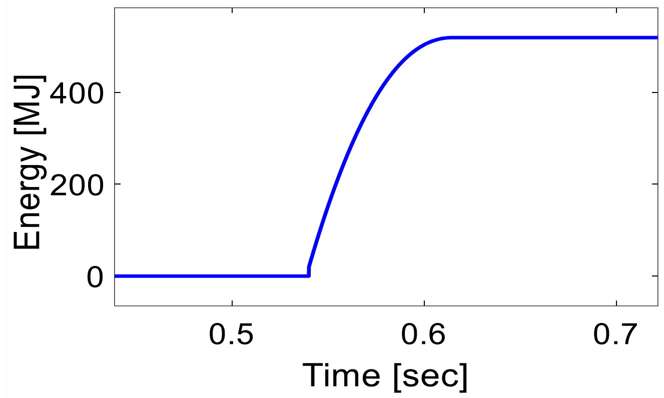
(b)

Fig. 8: Result for case-I considering 320 kV (a) overall response of DC-current; and (b) energy absorbed by MOA

The details of results given in Fig. 6, Fig. 7, Fig. 8 and Fig. 9 is as follows. From 0 to 0.5-sec system is allowed to operate under normal condition. Current during this interval is regarded as normal current, which flows through the main branch of the breaker. At 0.5-sec L-G fault in the system is introduced, and current starts to increase, for few milliseconds current continue to flow through the main branch of the breaker. Because few milliseconds are required to confirm the existence of the fault. When fault-current reaches the level of I_{trip}, the switches associated to the main branch of the breaker open, and transfer the fault-current to auxiliary branch, this time in the simulation is set as 0.502-sec. After 0.502-sec, the fault-current starts to flow through the auxiliary branch, till it reaches the level of I_{max}, at 0.504-sec the switches associated to the auxiliary branch of the breaker open and shift the residual fault-current to MOA, at this stage fault from the system is isolated.



(a)



(b)

Fig. 9: Result for case-IV considering 400 kV (a) overall response of DC-current; and (b) energy absorbed by MOA

The result of each case is divided into two parts, (a) and (b). The results highlighted in part (a) represent the overall response of DC-current when the system is subjected to L-G fault, whereas, the results in part (b) indicate the energy absorbed by MOA. From all the results, it can be observed that when voltage ratings of the system increases, the required level of fault-current interruption also increases, and thus energy required to be absorbed by MOA also increases. In Table I, the detailed summary of the result is elaborated, with exact statistics. The stats presented in Table I shows that when the voltage rating of the system increases, the expected peak current (required to be interrupted) also increases from 7.2 kA to 20 kA for different voltage levels. As a result, more IGBTs are required to withstand the voltage and current. Another fact is required to be stated at this juncture, each branch of the breaker should be capable enough to tolerate the 1.5 times of rated voltage [9], keeping in view this fact total number of IGBTs are selected. For calculating the estimated numbers of IGBTs, the IGBT model 5SNA 2000 K450300 by ABB is considered as a consideration. The voltage rating of the model discussed is 4.5 kV and 2000 A [16]. Keeping in view the security margin, the voltage rating of this model is considered as 3 kV, so by considering all these aspects the total number of IGBTs for the bidirectional configuration is estimated. Table II represents the required IGBTs for different voltage levels.

TABLE I: Representing the summary of results with quantified stats

Case	Rated DC Voltage (kV)	Rated DC Current (kA)	Interrupted Current (kA)	Energy Absorbed by MOA (MJ)
I	132	0.6	7.2	36
II	200	1.2	11.0	92
III	320	2.2	18.0	352
IV	400	3.0	20.0	519

TABLE II: Representing the required IGBTs for different voltage levels

Case	Rated DC Voltage (kV)	IGBTs required for Bidirectional configuration
I	132	140
II	200	200
III	320	320
IV	400	400

IV. Limitations of HCBs Based on Case Studies

Based on the results of different case studies, the limitations of HCBs can be explained. For example, when rated DC voltage increases, the requirement for the breaker to handle the fault-current also increases. Moreover, the increased fault-current require the large size of MOA to dissipate energy, and more time is required to force the fault-current to zero. To handle large fault-current, the number of IGBTs in each branch of HCB are required to be increased, which results in more cost. To overcome these challenges, the additional circuit (namely fault current limiter) can be used with HCB, to resolve the capacity issues of the breakers, one solution is discussed in [11].

V. CONCLUSION

In this paper, four case studies for different voltage levels are presented, for ABB's HCB. From the detailed analysis, it is concluded that if the voltage level is increased, the required level of fault-current which is to be interrupted also increases. Therefore, for higher voltage level, more IGBTs are required. The increased number of IBTs for designing the HCB increases the overall cost. Moreover, with increased voltage ratings, the requirement of MOA for energy absorptions also increases.

These problems of HCB can greatly be alleviated by using the external circuits to decrease the amount of fault current. Another option can also be considered that is the modifications in the design of HCB. It should be modified in such a manner, that it can reduce the intensity of fault-current. By opting these modifications, the design of HCB can be made useful for high voltage levels.

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