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A Review of HVDC Circuit Breaker

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Abstract: ***The increasing interest in development, operation and integration of large amount of renewable energy resources like offshore wind farms and photovoltaic generation in deserts leads to an emerging demand on development of multi-terminal high voltage direct current (MTDC) systems. Due to preformed studies, voltage source converter based HVDC (VSC-HVDC) system is the best option for realising future multi-terminal HVDC system to integrate bulk amount of energy over long distances to the AC grid. The most important drawback of VSC -HVDC systems is their need for fast HVDC circuit breakers. This paper aims at summarizing HVDC circuit breakers technologies including recent significant attempts in development of modern HVDC circuit breaker. A brief functional analysis of each technology is presented. Additionally, different technologies based on derived information from literatures are compared. Finally, recommendations for improvement of circuit breakers are presented.***

Keywords: HVDC, HVDC fault current, Solid-state DC circuit breaker, Hybrid circuit breaker**.**

1. Introduction

Nowadays, it is well-known that renewable energy resources have many attractive advantages in comparison with fossil fuels for meeting increasing energy needs.

Among various types of sustainable energy resources, wind power has being widespread concerned from all the countries in the world for renewable energy development projects. With extend of the wind power technology gradually from land to the sea, the world's renewable energy developers are more interested in offshore wind power [1].

As a matter of fact, the average capacity of installed and planned offshore wind farms increases permanently and also they are being constructed in locations more far from the coast [2]. The necessity of development, operation and integration of large amount of renewable energy resources to the AC grid and also the need for management of intermittence inherent of wind energy leads to an emerging demand on development of multi-terminal HVDC systems.

The main barrier against the implementation of an HVDC power grid is a high vulnerability of such grid against the DC line short circuit faults. In system fault condition, interruption of a DC fault current becomes more complex than an AC fault current. In addition to absence of current zero crossing point, because of small inductance of DC side of the system
the rate of rise of DC fault current is considerably high and it demands for very fast interruption technology [3].

So as key technology to make the HVDC multi-terminal systems safely operational and to pave the way for integration of bulk amount of offshore wind energy to AC grid, more attention should be attracted to development of HVDC circuit breakers. DC circuit breakers, namely for high voltage applications, are not commercially and widely available today [4].

In this paper, firstly, the origin of need for HVDC circuit breaker is explained and the main requirements of an HVDC circuit breaker are introduced. Thereafter, HVDC circuit breaker technologies including mechanical circuit breakers with snubber, hybrid circuit breakers and also pure solid -state circuit breakers are reviewed and functional analysis of each topology is performed. Additionally, a comparison between different topologies based on results from literatures is presented. Finally, recommendations for improvement of circuit breakers are presented.

2. VSC-HVDC based multi-terminal grid

It is obvious that many of the planned offshore wind farm projects will have a large power capacity and also they will be constructed very far from shore. Consequently, there will be a need for considerable cable length for delivering power to a receiving onshore grid [2]. Considering the distances and plants capacity, transmitting power over conventional AC cables is not feasible [3].

HVDC transmission technology was practically demonstrated in 1954 for enabling transfer of bulk amount of electrical power at high voltage over long distances. Not only HVDC transmission lines are attractive from technical point of view but also they are economically reasonable [3].

Nowadays, there are two major HVDC technologies which practically are being used for point to point power transfer and interconnection of asynchronous electrical networks; current source converter (CSC) based and voltage source converter (VSC) based technologies [5].

In CSC systems it is necessary to install filters and additional capacitors on the ac sides and also the power flow is unidirectional and the reversal of the power-flow direction requires a change in polarity of the system, which could be problematic [5], [6].

On the other hand, VSC systems are designed based on Insular Gate Bipolar Transistors (IGBT). Active and reactive power flows are independently controllable in VSC systems and also by employing multilevel VSCs it is possible to increase the voltage and power rating of system. In VSC systems the presence of harmonics are limited to hig frequency and this will lead to considerably smaller size of the filters. Moreover, VSC-HVDC technology transmits active power and can provide the required amount of reactive power at both the power sending and the power receiving end. This also again makes designers possible to reduce the size of filter [5], [6]. Additionally, use of VSC offers the following advantages:

- Avoidance of commutation failures due to disturbances in the AC network.

- Possibility to connect the VSC-HVDC system to a “weak” AC network or even to one where no generation source is available, and naturally, the short-circuit level is very low.

- No need of transformers to assist the commutation process of the converter’s fully controlled semiconductors.

In recent years, authors agreed on VSC-HVDC as the enabling technology for realisation of future offshore multi-terminal HVDC grid [7]-[11]. Only a few authors suggest hybrid configurations employing both CSC and VSC for development of multi-terminal HVDC networks [10].

3 Requirements

As it is mentioned before, use of VSC-HVDC for developing multi -terminal HVDC systems is ultimately advantageous but there are a few drawbacks in realising multi-terminal systems based on VSC-HVDC. One of the concerns about the VSC systems is the power losses. Switching valves inside the VSC are responsible for large part of losses. Research activities are being carried out to reduce the losses to [4].

As a matter of fact, the main barrier against the implementation of VSC based HVDC system is a high vulnerability of such system against the DC line short circuit faults. In VSC-HVDC system when a short-circuit fault in DC side is occurred the interruption process is much more complex and difficult than interruption of an AC fault current. The conventional AC circuit breakers interrupt the fault currents with help of zero crossing point. Since there is no zero crossing point in DC fault current so the conventional circuit breakers are incapable of interrupting the current [12]-[15].

Additionally, the anti-parallel diodes integrated with IGBT modules in VSC act as an uncontrolled rectifier even when IGBTs are turned off. For this reason the VSC becomes defenceless against a DC short-circuit fault and the fault current is only limited by AC side of VSC [16].

Moreover because of small inductance of DC side of the VSC-HVDC systems the rate of rise of DC fault current is considerably high and even in some faults the capacitors of DC link of VSC discharge and contribute to the fault current and increase rate of rise of it [17], [18].

Considering aforementioned conditions, in a multi-terminal HVDC system it is critical to interrupt the fault current and isolate the faulty line from the system. DC circuit breakers, namely for high voltage applications, are not commercially and widely available today. There are many significant requirements for design of efficient and operational HVDC circuit breakers. The most important requirements of an HVDC circuit breaker with capability of operation in future multi-terminal HVDC system can be listed as following:

- Create a current zero crossing to interrupt the current (In case of conventional hybrid and mechanical circuit breakers).
- Very fast breaking action (Because the rate of rise of DC fault current is very high and delay in interruption will lead to a destructive fault current in system.)
- Minimal conduction losses (a small voltage drop across the terminals of circuit breaker should appear and the normal operation losses in comparison to other elements of system should be reasonable.)
- Reliable and efficient protection against all types of faults (including pole to ground and pole to pole faults)
- Repetition of switching operation (be capable to reclose after a fault clearance)
- Prevention of excessive overvoltage (be able to suppress the switching overvoltage and demagnetizing the system inductance).
- Minimal arcing after contact separation to reduce contact erosion (in case of mechanical or conventional hybrid circuit breakers)
- Provide enough isolation capability due to system ratings.
- Long lifetime
- Less need for maintenance and in case of need be capable of bypassing the current to prevent the service interruption.

4 HVDC circuit breakers

In this section different HVDC circuit breakers are classified and a brief functional analysis of each topology is presented.

4.1 Mechanical HVDC circuit breaker

A) Mechanical passive resonance CB

The mechanical HVDC circuit breaker with passive resonance circuit is an old technology and initially was developed for CSC-HVDC systems [19]. Fig.1 shows a simplified diagram of mechanical circuit breaker.

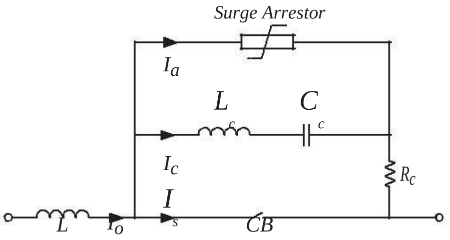

Figure 1: Mechanical HVDC circuit breaker

Typically, CB is an air blast circuit breaker with several interrupter units. During normal operation current flows through the CB and during interruption it is commutated into commutation path. For understanding the interruption process it is necessary to analyse the current equation during the process. The differential equation of during interruption can be written as below:

\

$$L_c\frac{d^2 i_s}{dt^2}+\left(R_c+\frac{\partial u_{arc}}{\partial i_s}\right)\frac{di_s}{dt}+\frac{1}{C_c}i_s=\frac{I_o}{C_c} \qquad (1)$$

An approximate solution for this this equation is:

$$i_s=I_o\left[1+e^{-\frac{1}{2L}\left(R_c+\frac{\partial u_{arc}}{\partial i_s}\right)t}.\sin\omega_c t\right] \qquad (2)$$

where $\omega_c=\sqrt{1/L_cC_c}$. If $\left(R_c+\frac{\partial u_{arc}}{\partial i_s}\right)<0,$

thw I_s will oscillating with increasing amplitude. The first zero crossing of current will be enough for breaker to interrupt it.

B) Mechanical active resonance CB

In the active mode, a current oscillation provided by the pre-charged commutation capacitor will arise instantly and it will grow to oppose the current in the main when the current is commutated into the branch. In some texts, this scheme is also introduced as hybrid interruption method.

Generally, in these types of circuit breakers thyristors are employed to act as commutator and disconnector switches. This concept is also known as two-stage interruption method. Although there are several variants for this concept, here two basic topologies are presented [20], [21]. Fig.2 depicts the first variant of mechanical active resonance circuit breakers.

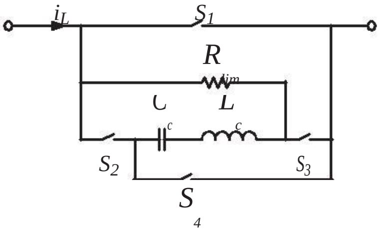

Figure 2: The first variant of active resonance circuit breakers

In the first topology and under normal load conditions, only the main breaker is closed while the other switches , and are in open state. The capacitor is pre-charged with a negative initial voltage . As soon as a fault current is detected is opened and simultaneously and are closed. Then the reverse current arising through branch opposes the fault current and when it reach the equal amount of fault current a zero crossing will happen and the current will be commutated to the parallel branches. After charging the , current inside the will fall to zero and it opens. Subsequently, the switch closed discharging the capacitor

into the loop - - - - . When a current-zero occurred in , it turns off and the main current commutated

again into the path including - - - . The switch opens when a current-zero is created resulting in a new

energy balance in which the capacitor is fully charged.

Interrupting the nominal rated current could be realised for the second variant by closing only the switch . Fig.3 shows the second topology of conventional hybrid circuit breakers.

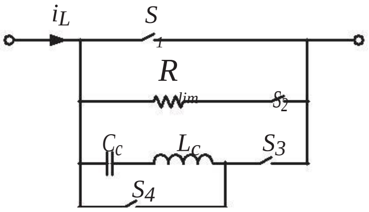

Figure 3: Variant 2 of active resonance circuit breakers

After fault detection in the second variant, the main breaker , is opened and simultaneously is closed to create a zero current inside the main breaker. Finally will naturally open after capacitor is fully charged.

4.2 Hybrid Technologies

Integrating controllable solid-state devices with a mechanical breaker or disconnector in a combined configuration is called the hybrid switching technique. Generally, within a hybrid circuit breaker, the commutation path is introduced by solid-state switches and only operates during the interruption process. All the switches are controlled by electronic circuits. Recent developments in semiconductor switches and improvements in their characteristics such as break-down voltage, conduction losses, switching time and reliability, bring about the possibility of using these devices as the main interrupters in circuit breakers. There are several possible topologies for hybrid circuit breakers, but in practice, two main structures attract more attentions. Fig.4 shows the first basic hybrid topology.

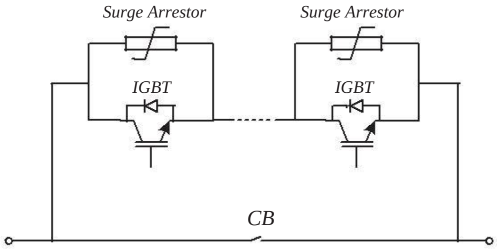

Figure 4: Topology 1 for hybrid circuit breaker

In this topology a fast mechanical breaker is equipped with a set of solid-state switches in the parallel path. This topology combines low losses of a pure mechanical breaker with fast switching response of a pure solid-state device. Since the arc chamber must only create sufficient voltage for commutation and not artificial current zero crossing point, this topology is faster than conventional circuit breakers. Application of this topology has been developed for medium voltage grids [22], [23], [24].

Another topology which has been introduced in [14] employs a fast solid-state device in the main path of current and in series with a fast mechanical disconnector. The parallel path is built by series connection of solid -state switches. The fast solid-state device in the main path can be an IGBT. ThisVIGBT needs only to create a sufficiently high voltage for the commutation of the current to the parallel full IGBT breaker so it has lower rating than the parallel path breaker. Typically, it can be realised by connection of a few number of IGBTs in series so the conduction losses and voltage drop will be low enough.

During the normal operation, the current will only flow through the bypass and the current in the main breaker is zero. When a DC fault occurs, the auxiliary DC Breaker immediately commutates the current to the main DC Breaker and the fast disconnector opens. With the mechanical switch in open position, the main DC breaker breaks the current. The mechanical switch opens with zero current and low voltage stress. The fast disconnector will be exposed to the recovery voltage defined by the protective level of the arrester banks first after being in open position while the main DC breaker opens. A simplified schematic of this topology is depicted in Fig. 5.

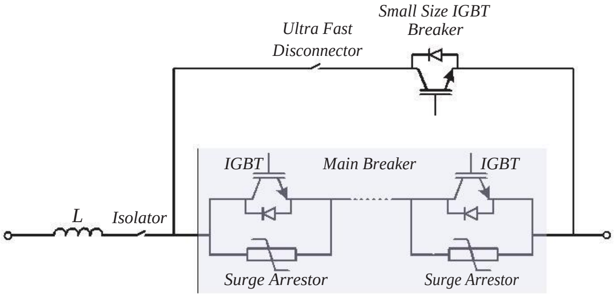

Figure 5: Topology 2 for hybrid circuit breaker

4.3 Pure solid-state circuit breaker

Fast and ultra-fast switching time of semiconductor devices make them a very strong candidate for DC fault interruption. A pure solid-state circuit breaker can be faster than all other topologies. Design of pure semiconductor based circuit breakers is possible by different combinations of solid-state switches and ancillary circuits. Considering proposed topologies in literatures there are two major topologies for this type of circuit breakers and other structures can be classified within one of these topologies. Generally, in pure solid-state circuit breakers many IGBTs, IGCTs or other semiconductor based switches are connected in series and parallel to support the voltage and current of system during normal and fault conditions. Researches with aim to optimize and improve the behaviours of solid-state circuit breakers are on-going and new contributions are also reported [25], [26].

A) CB paralleling a surge arrestor

Fig. 6 depicts a typical circuit configuration of a solid-state dc circuit breaker [25]. The semiconductor switch acts as the main breaker and a surge arrestor is connected in parallel with it. During normal operation is in on-state and conducts the current from source to the load. As soon as a short-circuit fault is detected will be turned off. Then the load current commutates to the surge arrestor . Surge voltage across is limited to the clamping voltage of the surge arrestor . The clamping voltage of surge arrestor is assumed as and also it is assumed that the impedance of the fault point is negligibly small. When turns off at time ,

is applied to so the inductor current can be calculated as follows:

$$i_L = I_0 - \frac{V_{margin}}{L_{dc}} t \qquad (3)$$

where is amplitude of the fault current at . The time to turn off the fault current is derived as follows

$$T_{open} = \frac{L_{dc}}{V_{margin}} I_0 \qquad (4)$$

and the energy absorbed in can be given by:

$$W_R = \left(\frac{V_{dc}}{V_{margin}} + 1 \right) \frac{1}{2} L_{dc} I_0^2 \qquad (5)$$

is usually much smaller than in high power applications in order to suppress the voltage across and to reduce 's conduction loss. In such case, the term in the parenthesis of equation (4) becomes large, and is much greater than the stored energy in at , which is
_ . The more voltage across is suppressed, the more capacity the surge arrestor needs [25].

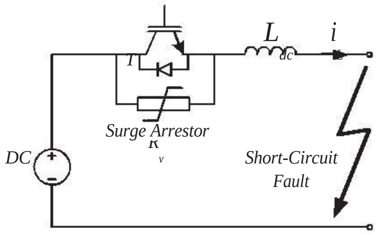

Figure 6: Topology 1 for solid-state CB

B) CB with freewheeling diode

As another topology of hybrid circuit breakers, a freewheeling diode and a varistor are connected across the DC line. The circuit reduces the energy absorbed in the breaker with suppressing the surge voltage across the valve device . A circuit configuration of the solid-state dc circuit breakers using a freewheeling diode is shown in Fig.7.

During normal condition, remains on and leads the load current . When turns off at after detecting a fault, the fault current is commutated to . Hence, the current flowing through immediately decreases to zero. The inductance is gradually demagnetized by , and the fault current decreases. When the clamping voltage of is expressed in , the surge voltage across is which is the sum of nominal DC voltage and the clamping voltage of . Because does not supply any power after turning off , the energy absorbed in the DC breaker at turn-off operation is equal to the energy stored in by the current . So the energy is given by:Since in (6) is smaller than *WR* in (5), the rating and volume of can be reduced by applying the freewheeling diode. Because the clamping voltage does not affect to , the surge voltage across can be suppressed without increase of by choosing a low value for .

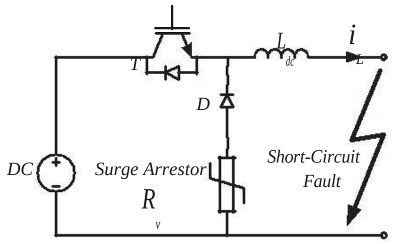

Figure 7: Topology 2 for solid-state CB

5 Comparison of technologies

In this section, different technologies are compared in terms of interruption time, power losses, voltage and current rating.

5.1 Interruption time

As it is expected the mechanical circuit breakers have the snappiest switching response up to 60ms while the pure semiconductor based circuit breakers are expected to reach the interruption times below than 1ms. Between these two topologies, hybrid circuit breakers with disconnection time of 2~30ms also represent attractive characteristics for application in high power systems [14]-[26].

5.2 Power losses

The mechanical circuit breakers and the hybrid ones with no semiconductor devices in main path of current have the lowest power losses among all configurations. The reason for this is a very low voltage drop on the metal contacts of main circuit breaker. The power losses for these topologies are less than 0.001% of the VSC station power losses. Additionally, the hybrid topologies with low rating semiconductor switches in the main path of current also represents reasonable power losses. In this type of circuit breaker, the power losses are no more than 0.1% of power losses of a VSC system. On the other hand pure solid -state configurations suffer from high power losses. Since there are many IGBTs or other semiconductor devices in main path of current in these topologies the total voltage drop of circuit breaker is relatively high. The power losses for this technology in comparison with a VSC station can reach to 30% [14]-[26].

5.3 Voltage rating

Nowadays, mechanical HVDC circuit breakers with nominal voltage up to 550kV are available. Hybrid circuit breakers also have been verified by experimental tests up to voltage rating of 120kV and it is expected that to reach up to 320kV level. Pure semiconductor circuit breakers are not available in high voltage and power ratings and only have been designed and implemented for operation in medium voltage applications. But considering the developments in semiconductor devices it is anticipated that 800kV voltage rating is achievable [14]-[26].

5.4 Current rating

Mechanical HVDC circuit breakers are able to interrupt currents up to 4kA with passive resonance system while they can interrupt up to 8kA with active resonance circuit. For hybrid circuit breaker topologies, current interruption level of 9kA has been proved experimentally and in theory levels up to 16kA is achievable. Considering the expected high voltage rating for pure semiconductor circuit breakers, 5kA current interruption rating is reasonable for them [14]-[26

6 Conclusion and recommendations

Nowadays, the main obstacle against the realisation of HVDC grids is lack of mature HVDC fault current breaking technologies. In this paper the present technologies of HVDC circuit breakers were summarised and compared. All of presented breaking schemes have limited capabilities in interruption of permanent fault current and need to be significantly improved.

In terms of mechanical circuit breakers as the basic devices for fault current interruption, attempts should be concentrated in optimization of size of resonance circuit’s elements . Also the behaviour of arc chamber needs to be improved to reach higher current rating.

Since hybrid circuit breakers present more efficiency and acceptable interruption speed, the development of faster mechanical switches with high surge voltage withstand and low concoction losses can lead to more improvements in this area.

In terms of solid-state circuit breakers, application of new wide-band-gap semiconductors like SiC or GaN based switches should be investigated. Also active gate driving technologies can improve the performance of semiconductor switches in pure solid-state circuit breaker. Moreover, accurate dynamic models for semiconductor switches with validity in high voltage and high currents to be used in designs and simulations are necessary to be implemented.

In order to provide the possibility of distinguishing the permanent faults from transient grid events applications of DC fault current limiters in HVDC networks can be interesting to study.

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