Transient system behaviour under DC fault conditions in meshed HVDC system

A. Yanushkevich, N.A. Belda

***Abstract*-- Nowadays, development of multi-terminal HVDC systems is driven by aim to connect remote loads, offshore wind power plants and increase of energy trading. Operation of meshed multi-terminal systems is hard to imagine without fault clearing devices. The aim of this paper is to investigate simulated system behaviour under fault conditions before switching device operation and after fault clearance system restoration. The paper presents results of simulations of the VSC based multi-terminal systems with embedded fault clearing devices under fault conditions. The multi-terminal system is presented by CIGRE B4 DC Grid Test System. The main focus is the analysis of the switching process and evaluation of the stresses on the components of the system under short circuit conditions.**

***Keywords*: HVDC, DC fault, transient behaviour, meshed grid, DC circuit breaker, CIGRE B4 test system.**

I. Introduction

Growing demand and increase of renewable power generation are current and future challenges for transmission systems. Lack of control over production from renewable sources, such as solar and wind, is leading to unpredictable power flows in the grid. HVDC technology is a solution for flexible control of power flows in transmission systems. In case of long cable transmission and nonsynchronous systems interconnection with HVDC is the only solution. Started from point-to-point systems HVDC transmission is evolving into multi-terminal systems. As of today we can see examples of three-terminal systems around the world [1,2]. This is just a first step towards meshed systems or even DC grids overlaying continents [3].

For reliable operation of a meshed multi-terminal system a protection system with fault clearing devices is required. Thus, circuit breaker is a crucial element for future meshed multi-terminal HVDC systems. Several concepts for fault clearance in HVDC systems have been proposed and studied [4]. A circuit breaker could be a mechanical device with auxiliary active and passive circuits or fully semiconductor based, or a combined, so called hybrid solution. Each of these solutions has its advantages and drawbacks. However, the most promising concept nowadays is a hybrid breaker technology which combines low operational losses and fast fault clearing time.

In AC systems, because of prolonged operation of fault clearing devices, fault current could be considered as a steady state. Unlike in an AC system, in an HVDC system, where a fault clearing device is required to operate in very short time, system parameters and parameters of the device itself have strong influence on current and voltage behaviour under short circuit conditions.

A number of studies have been done investigating DC short circuit current development in multi-terminal systems [5]. However, DC voltage behaviour in the system before and after fault clearance is often neglected. Furthermore, there are papers describing operation and performance of HVDC circuit breakers in test circuits [6,7,8].

Simulation of HVDC systems with embedded circuit breakers allows study of system operation and the stresses applied to the equipment installed in the system during and after fault clearance. Understanding of the transient fault conditions is an important step towards developing requirements for system design and test criteria for switching devices applied in future meshed multi-terminal systems.

In this paper, simulations of DC fault conditions in HVDC systems with embedded models of different concepts of hybrid breakers are performed to investigate the conditions prior the DC fault and after fault clearance. These simulations are performed within the Simulink environment of MatLab.

II. HVDC technology

Voltage source converter (VSC) technology, due to easy power flow control, is proposed to be used to create meshed systems with more than three terminals. The half bridge converters, however, are not able to block flow of fault currents. Therefore, circuit breakers are required in order to clear a fault. Nowadays, only circuit breakers at the AC side of the converter stations are installed. Breaking current at the AC side is relatively simple, because the arc in the breaker can easily be extinguished during a zero crossing. The result of this approach, however, is a voltage collapse of the complete HVDC system. For large systems with many interconnected terminals this situation is undesirable.

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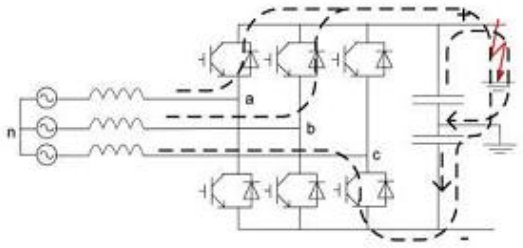

Fig. 1. Pole to ground fault in VSC system

Simplified diagram of pole to ground fault in VSC system is shown in Fig. 1. In case of a pole to ground fault, IGBTs in the converter are blocked within first millisecond after a fault occurs in order to protect IGBTs from overcurrent. Then uncontrolled short circuit current continues to flow through freewheeling diodes connected in parallel to IGBTs. In order to simplify and speed up model design and simulation, most of the control systems of the converter are neglected in following simulations. Converter is presented as a three arm diode converter with parallel connected capacitor bank. In this paper only pole to ground fault is investigated.

III. HYBRID HVDC CIRCUIT BREAKER

Hybrid breaker combines benefits of mechanical type by low operational losses and solid state type with fast fault clearing capability. Several manufacturers have come with their concepts for hybrid HVDC breakers and few of them have laboratory prototypes [6,7]. In order to investigate fault behaviour in meshed multiterminal HVDC system three concepts of proposed breakers were simulated in Simulink environment of MatLab.

A. Type I hybrid breaker

Simulation of type I hybrid breaker is based on the concept proposed in [6]. The model of type I hybrid breaker presented in Fig. 2 consists of four parallel branches.

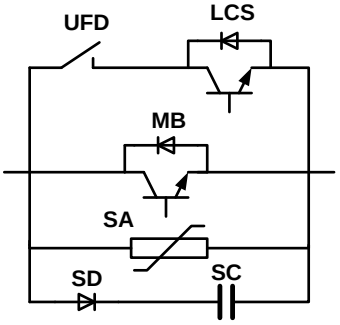

Fig. 2. Model of type I hybrid HVDC breaker

Nominal current branch includes ultrafast disconnector UFD and load commutation switch LCS for bypassing short circuit current into the main breaker branch. Main breaker branch sustains fault current till ultrafast disconnector is open to protect load commutation switch from overvoltage during voltage recovery when fault current is blocked. When disconnector is open main breaker MB blocks the current and magnetic energy stored in the system is dissipated in surge arrester SA. Snubber circuit consisted of diode SD and capacitor SC which is used to control rate of rise of voltage in order to protect power electronic components in the main breaker part.

Simulation model is tested in order to verify model performance. Behaviour of voltage and current of model verification is presented in Fig. 3. Achieved results are similar to presented in [6].

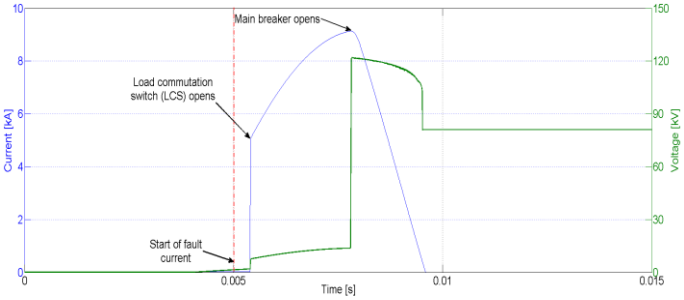

Fig. 3. Current (blue) through and voltage (green) across the breaker during breaking operation

B. Type II hybrid breaker

Simulation of type II hybrid breaker is based on the concept proposed in [7]. The model of type II hybrid breaker presented in Fig. 4 consists of four parallel branches. Nominal current branch includes ultrafast switch presented by vacuum breaker VB and power electronic switch PES for bypassing short circuit current into the second branch. Second branch consists of capacitor C1 and thyristor T1 which conducts when power electronic switch blocks the fault current. While capacitor C1is charging mechanical switch is open. When capacitor in the second branch is fully charged the thyristor T2 in the third branch is fired and fault current is charging capacitor C2. Voltage across the DCCB rises very rapidly towards the peak value. When voltage reaches protective voltage of surge arrester SA in the fourth branch the current flows through arrester and magnetic energy stored in the system is dissipated.

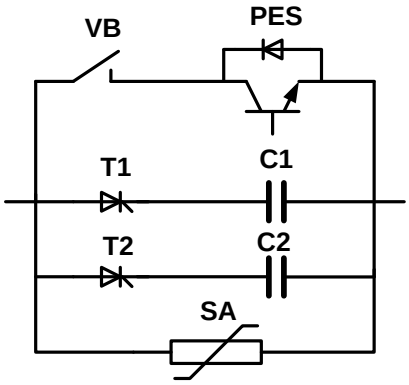

Fig. 4. Model of type II hybrid HVDC breaker

Simulation model is tested in order to verify model performance. Behaviour of voltage and current of model verification is presented in Fig. 5. Achieved results are similar to presented in [7].

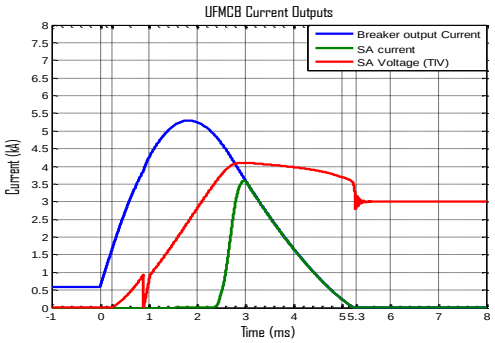

Fig. 5. Current (blue) through and voltage (red) across the breaker current during breaking operation; surge arrester current (green)

C. *Type III hybrid breaker*

Simulation of type III hybrid breaker is based on the concept proposed in [8]. During normal operation, the current is flowing through the main path of the circuit breaker. In this path, a mechanical breaker MB is located with very low losses. After a fault is detected, the mechanical breaker opens establishing an arc between contacts.

In following step, the thyristor Tpg is fired and the precharged capacitor Cpg starts to interact with the inductor Lpg, resulting in an oscillating output voltage. Because of the low impedance of the mechanical breaker, the voltage at the output terminal also oscillates. As soon as the output voltage of the circuit breaker becomes negative the protection voltage of surge arrester SAdb is reached and current flows through diode Ddb towards the mechanical breaker. The opposite current creates a zero crossing of the fault current and results in extinguishing of the arc.

After the arc is cleared, the thyristor Tpg is turned-off at the next zero crossing. The capacitor Cpg is quickly charged to nominal voltage level again. Finally, the remaining magnetic energy of the network is dissipated in surge arrester SApg. Diode Dpg prevents capacitor from discharging and Rpg represents internal resistance of the components

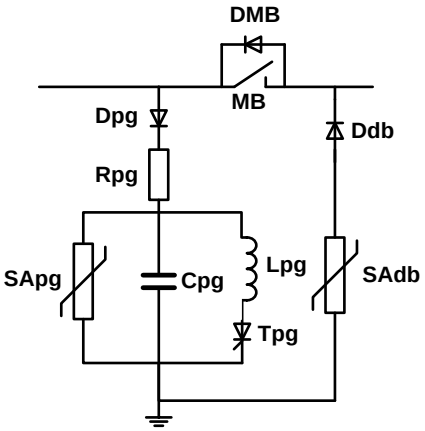

Fig. 6. Model of type III hybrid HVDC breaker

Simulation model is tested in order to verify model performance. Behaviour of voltage and current of model verification is presented in Fig. 7. Achieved results are similar to presented in [8].

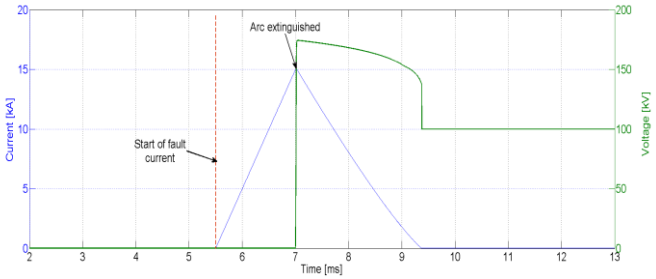

Fig. 7. Current (blue) through and voltage (green) across the breaker during breaking operation

IV. DC FAULT SIMULATION CASE

Transient bechaviour is studied using the CIGRE B4 DC Grid Test System as shown in Fig. 8. The details of this model are described in [9]. The test system is simulated in Matlab/Simulink, lines are simulated using distributed model. Reactors of 10 mH are installed in all converter stations. A pole-to-ground fault of 1 Ω is created in the middle of a 200km long line between Bb-B4 and Bb-B1. The line is protected by two circuit breakers installed on both sides. Voltages of two converter stations are observed: one 100 km away from the fault (Cb-B1) and one 500 km away from the fault (Cb-D1).

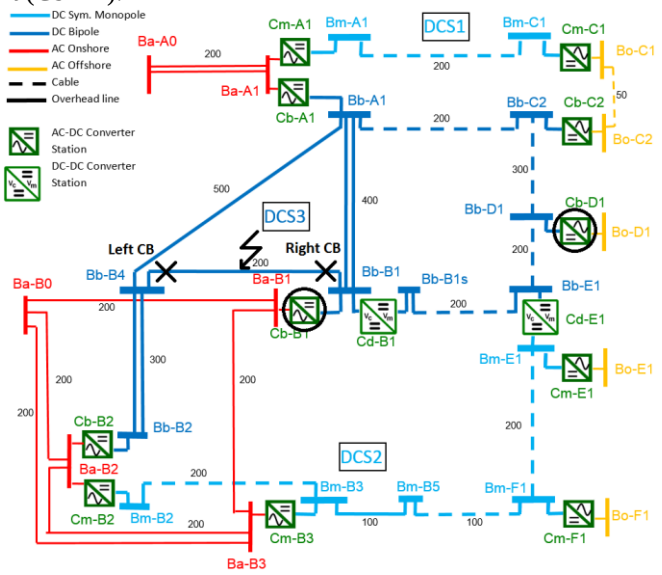

Fig. 8. CIGRE B4 DC Grid Test System

All types of hybrid breakers are installed in the test system. The time of 1 ms is chosen for fault detection and selectivity by protection relay. Therefore, triggering signal to the breakers is send 1 ms after fault occurs. Protection levels of circuit breakers' arresters are set at 50 per cent above nominal voltage level.

A. *Type I hybrid breaker fault clearance*

The results of the tested type I hybrid circuit breakers are shown in Fig. 9. Fig. 9-left shows that the maximum current is flowing through the right circuit breaker. This can be expected, as the line is directly connected to a converter station on the right side. Also, the right side is connected to other converter stations by relatively short cables/lines. Because of the short

connections to other converter stations, capacitor discharging currents will be much higher than for the left breaker. Furthermore, a strong AC network is connected to converter station Cd-B1 by a short line. This results in a low impedance path for AC network current through the right circuit breaker. Finally, the influence of line reflections can be observed as short current drops.

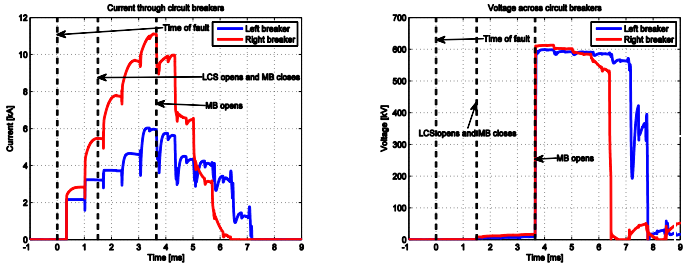

Fig. 9. Left: Current of the left (blue) and right (red) breaker;
Right: Voltage across left (blue) and right (red) breaker

Fig. 9-right shows the voltage across the circuit breakers. In this figure is shown that the protection value of 600 kV is reached very quickly after the IGBTs in the main breaker are blocked. The voltage is then slowly decreasing until the current through the breaker has become zero. Furthermore, it is shown that the voltage across the IGBTs of the load commutation switch is relatively low.

Fig. 10 shows the voltages at two converter stations: one near the fault and one 500 km away from the fault. Fig. 10-left shows that the voltage of terminal station Cb-B1 is almost immediately dropping to zero after a fault occurs in the case of an inactive breaker. If the breaker is activated, this voltage drop is reduced significantly and the voltage immediately starts to recover once the circuit breakers have cleared the fault. High frequency reflections and oscillations can be seen due to traveling waves.

Fig. 10-right shows the voltage of terminal station Cb-D1. In this figure can be seen that the voltage starts to drop after a delay of roughly 10 ms. This delay is caused by limited wave speed through the lines. Also, the drop of voltage is less severe due to higher impedance between converter and the fault. The long line parameters damp oscillations and prevent high frequency reflections to reach the far converter station. Therefore, the figures show that faults far from the converter station have reduced effects.

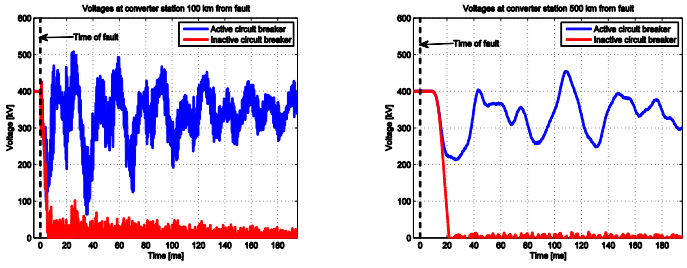

Fig. 10. Left: Voltage at Cb-B1, active (blue) and inactive (red) breaker;
Right: Voltage at Cb-D1, active (blue) and inactive (red) breaker

B. Type II hybrid breaker fault clearance

The results of the tested type II hybrid circuit breaker are shown in Fig. 11. Fig. 11-left shows that the highest current is again flowing through the right circuit breaker. Also, this results show that the reflections have very high impact on the current behaviour.

Fig. 11-right presents the voltage across the left and right breaker has a similar behaviour. The figure shows that the protection voltage of the surge arrester is reached steeply. Also, the figure shows that the voltage across the breakers is decreasing towards the nominal value.

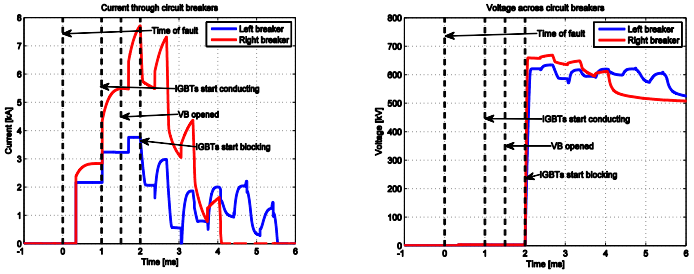

Fig. 11. Left: Current of the left (blue) and right (red) breaker;
Right: Voltage across left (blue) and right (red) breaker

Fig. 12 shows that the voltage at the converter stations is only dropping slightly and also recovers relatively fast. The voltage at the closest converter station shows a lot of oscillations/reflections, while the voltage at the converter station far away is affected much less preventing high disturbances in the system operation.

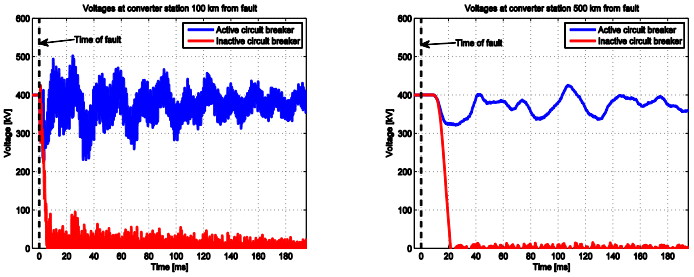

Fig. 12. Left: Voltage at Cb-B1, active (blue) and inactive (red) breaker;
Right: Voltage at Cb-D1, active (blue) and inactive (red) breaker

C. Type III hybrid breaker fault clearance

Fig. 13-left presents the current through the type III hybrid circuit breaker and the voltages across the breaker. For this simulation, the value of the pulse-generator capacitor Cpg is chosen to be 0.1 µF. Furthermore, the value of the pulse-generator inductor Lpg is chosen to be 40 nH. Results show that the mechanical switch is open 1.5 ms after the fault occurs. In this figure, also a large current pulse is shown at the moment of the arc extinguish. This current pulse has a maximum value of 10 kA lasting for several microseconds and could be explained by imperfection of mathematical calculations. Finally, the figure shows that the type III circuit breaker clears the fault current almost immediately after 'opening' the circuit breaker. After this operation, the pulse-generator capacitor Cpg is recharged within milliseconds. This fast recharging of the capacitor enables reclosing capabilities.

Fig. 13-right shows the recovery voltage stress on the breaker. This figure shows that the maximum voltage of the right breaker is reaching the protection voltage of the surge arrester in the PG branch. Next, the stored magnetic energy is dissipated in a relatively short time and the maximum voltage immediately drops to close to nominal voltage level.

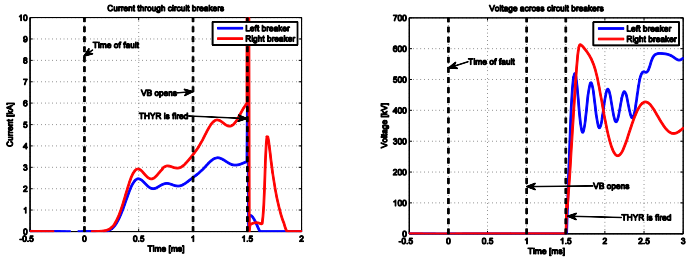

Fig. 13. Left: Current of the left (blue) and right (red) breaker;
Right: Voltage across left (blue) and right (red) breaker

Fig. 14 shows that the voltage drop at the converter stations is very low due to fast fault clearance. The voltage at the closest converter station shows a lot of oscillations/reflections, while the voltage at the converter station far away is affected much less.

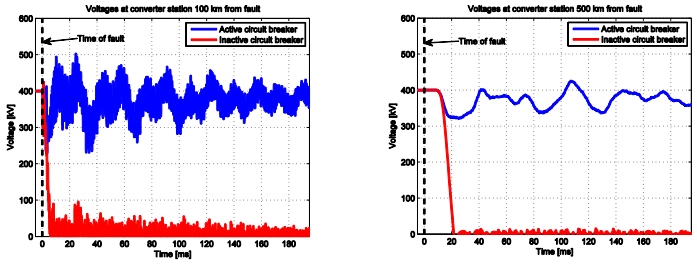

Fig. 14. Left: Voltage at Cb-B1, active (blue) and inactive (red) breaker;
Right: Voltage at Cb-D1, active (blue) and inactive (red) breaker

V. Hybrid Breakers Performance Comparison

The performance of the different types of hybrid HVDC circuit breakers is shown in Table I. In Table I the first column indicates the type of the circuit breaker. The second column indicates the average rate-of-rise of the current from the beginning of the fault to the maximum value. The third column indicates the average rate-of-rise of the recovery voltage when the circuit breaker has finished its final action. The maximum fault clearance time is indicated in the fourth column, and the maximum current through the breakers is shown in the fifth column. The minimum system voltage, which is measured at the nearest converter station, is shown in the sixth column. The seventh column indicates the maximum energy that is dissipated in the surge arresters.

TABLE I
Comparison of Performance of HVDC Hybrid Breakers

Type	di/dt [kA/ms]	dv/dt [MV/ms]	t_{clear} [ms]	I_{max} [kA]	$V_{sys,min}$ [pu]	$E_{sa,diss}$ [MJ]
I	3.35	27.0	7.17	11.1	0.41	8.70
II	4.63	10.9	5.44	7.69	0.68	5.07
III	4.27	3.39	1.92	6.00	0.82	1.31

VI. Conclusions

Results of the paper present system operation and stresses applied to the equipment during and after DC fault clearance. The models of different HVDC hybrid breaker concepts are presented and investigated. A simulation of Cigre HVDC test system with embedded models of hybrid circuit breakers are presented in this paper. The main focus is the analysis of the switching process and evaluation of the stresses on the hybrid circuit breaker and system performance under short circuit conditions.

Based on the results of performed simulations, performance comparison of hybrid HVDC breakers is presented allowing determination of system design and performance specification. Although curtain concept could provide fast fault clearing time and system voltage recovery, more detailed analysis of breakers performance and reliability is necessary prior being installed in a real system. Results of simulations could be used in development of future meshed HVDC grids and establishing requirements for hybrid HVDC breakers.

VII. References

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