DC Current Suppression Circuit in HVDC Power Transmission System

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Abstract

To increase the popularity of HVDC power transmission system, the Multi-Terminal Direct Current (MTDC) power transmission system is expected to be installed. Since the Voltage Source Converter HVDC (VSC-HVDC) is available, the MTDC systems are much more likely to be installed soon. However, an efficient Direct Current blocking measure such as DC circuit breaker remains as the most critical hurdle to implement MTDC system. In this paper, a new DC current suppression circuit is proposed. This circuit is a kind of the semiconductor DC circuit breaker, and can be used for very quickly interrupting the DC current against the short circuit fault condition at the cost of minimum conduction loss at the normal operation. Because of the modular configuration, the proposed circuit has inherent redundancy and no need of the series-connection of the semiconductor switches and bulky surge voltage arrestor bank.

I. Introduction

Globally, the electric power demand is continuously increasing at a fast-growing rate, and rapid urbanization has caused the power demand centralization. Moreover, the recent oil shortage has brought the need of development of the renewable energy sources: wind energy, solar energy, and so on. These renewable energy resources have penetrated into a conventional Alternating Current (AC) power grid and the AC electric power transmission systems are getting complicated. To supply the electric power into the centralized demands, High Voltage Direct Current (HVDC) power transmission system has been considered an alternative [1].

Actually, many HVDC power transmission systems had already been installed as point-to-point power transfer for last several decades. These traditional HVDC systems have used Line Commutated Converter (LCC). The LCC-HVDC has lower conduction losses, higher reliability and DC short fault current suppression ability. However, it has some demerits. As a strong AC grid and large interface filter are mandatory, the reactive power of interfaced AC gird is not able to be controlled, and the polarity of DC voltage should be changed according to the direction of power flow. Recently, the Voltage Source Converter (VSC) based HVDC system has been proposed and was already implemented in the real grid [2]. Compared with LCC-HVDC system, VSC-HVDC can control the reactive power of interfaced AC grid, and have the black start capability, and the DC output voltage polarity does not change according to the direction of power flow. Especially, Modular Multilevel Converter (MMC), which is a kind of VSC-HVDC, does not need AC side filter. These advances of VSC-HVDC power transmission system can make it possible to install the Multi-Terminal DC (MTDC) power transmission system.

However, the MTDC system requires that every terminal converter has the DC short fault current suppression capability by the DC circuit breaker, which is not commercialized yet. Because VSC-HVDC does not have the inherent DC short fault current protection capability, additional DC current suppression measures have been researched in various ways. In the MMC's case, some different types of module such as a full-bridge module have been proposed to deal with the DC short-fault current instantly [3]. Basically, this full-bridge type module increases the conduction losses in MMC compared with the conventional half-bridge module type MMC. Moreover, the MMC based on the full-bridge modules controls the DC short fault current by varying the output DC voltage instantaneously. That would not be acceptable to MTDC power system.

In a different way, DC circuit breaker is considered to solve the DC short circuit current problem in VSC-HVDC. Since the DC circuit breaker can be placed between the VSC-HVDC and the DC lines, it is suitable to apply to the MTDC systems. Even though the power of DC link in the VSC-HVDC is unavailable during the DC fault condition, the VSC-HVDC can work as the STAtic synchronous COMpensator (STATCOM) for AC grid. And, if available, DC circuit breaker would be an important asset in MTDC. Ideally, it has been known that the DC circuit breaker consisted of the semiconductor switching devices, so-called a solid-state DC circuit breaker, can be implemented based on the current technologies. Nevertheless, the cost and the conduction losses associated with the breaker are the huddle in the wide spread application of the solid-state DC circuit breaker.

In this paper, a new DC Current Suppression Circuit (DC-CSC) is proposed. This DC-CSC is a kind of a solid-state DC circuit breaker. Since this proposed suppression circuit works with VSC-HVDC, the conduction loss is about a half of the conventional solid-state DC circuit breaker. This circuit can interrupt the bidirectional DC current in the normal operation, and quickly disconnect the VSC-HVDC against the DC short circuit fault in the DC grid as a solid-state DC circuit breaker.

II. DC Short Fault Strategies of VSC-HVDC

The protection strategy for the DC short fault is one of the most critical issues in the VSC-HVDC. When the DC short fault happens, the DC current in the steady state is limited only by the resistance of the DC grid. Because of very low resistance, the DC fault current should be interrupted before the increased DC current destroys the VSC-HVDC and other equipment. The DC circuit breaker can be the best measure for interrupting the DC fault current. However, the DC circuit breaker is not yet available in the HVDC power transmission system.

A. Two- or three-level VSC with DC link capacitor

In the initial stage, the VSC-HVDCs were traditional two- or three-level VSCs. It has a bulky DC link capacitor of which voltage is the DC voltage of HVDC system. Soon after detecting the DC short fault, the semiconductor switching devices are turned off and the VSC acts as diode-rectifier. Then, the short circuit current of the VSC is limited by the AC line impedance. The conventional AC circuit breaker interrupts the AC short circuit current after several cycles of AC grid voltage. And, the DC capacitor of VSC discharges and is de-energized. After then, the mechanical DC disconnecting switch decouples the AC grid from the DC grid. The DC inductor of the DC grid and the DC capacitor of VSC should be designed to limit the DC fault current. Because the DC voltage of the VSC goes to zero for the DC short fault condition, this protection strategy can be only applied into the point-to-point power transmission system. Moreover, the VSC-HVDC loses its controllability and the ability of the STATCOM for AC grid.

B. MMC with half-bridge module

The MMC is getting popularity in the VSC-HVDC transmission system. The MMC consists of many modules which gives the MMC scalability with respect to the number of levels of the AC voltage. This module can determine the additional function for DC short fault and etc.

The most general module is the half-bridge module which composed of two IGBT switches with free-wheeling diodes and a DC link capacitor. The output voltage of the module can be zero or a DC voltage of the capacitor in the module. With this module, the MMC can fulfill all normal function of the VSC-HVDC.

In the case of the DC short fault, all IGBT switches are switched off and the AC current flows from the three phase AC system through the free-wheeling diodes [4]. Because all IGBT switches are off, the output DC voltage is zero and the DC fault current goes to zero according to R-L impedance of DC grid. Then, the AC circuit breaker opens and the AC short circuit current stops after several AC cycles. Actually, the free-wheeling diodes do not have capability to withstand a high surge current by the DC short fault. In actual system, a thyristor which is connected in parallel to the output terminal of a module is fired for the DC short fault condition. Then, the mechanical DC disconnecting switch can be used to decouple the AC grid from the DC grid.

Compared with the case of the VSC with DC link capacitor, there can be no discharging current in the DC grid even under DC short fault condition. Because the capacitors of all modules do not discharge under the DC short fault condition, the VSC can restart immediately after clearing of the DC short fault or disconnecting the DC fault grid. As the output DC voltage becomes zero for the DC short fault, however, this strategy is unsuitable for the MTDC system.

C. MMC with a DC fault handling module

To handle the DC short fault current, two different types of the module have been noticed: full-bridge module and double-clamp module. The MMC consisted of full-bridge module has the capability to suppress the DC current by control its output voltage instantaneously from the negative DC voltage to the positive DC voltage. Compared with the MMC with half-bridge module, the MMC with full-bridge module can work as STATCOM for AC grid in the case of DC short fault condition. Because the output DC voltage is controlled as almost zero voltage to suppress the DC fault current, however, this strategy is not proper to the MTDC system. The most critical problem of the MMC with full-bridge module is losses in the normal operation mode, which is the twice of the case of MMC with half bridge.

The double-clamp module connects two half-bridge modules in series with one IGBT and two diodes [5]. When the additional bypass IGBT is turned on, two half-bridge modules are series-connected. In the DC short fault condition, the bypass IGBT is turned off and the DC fault current is limited. Because the current is limited, the AC circuit breaker does not need to disconnect the AC grid from the VSC. And, the voltage of capacitors does not discharge. Therefore, the converter can restart immediately after clearing the DC short fault condition. Compared with the MMC with full-bridge, the additional conduction loss due to the additional IGBT can be reduced to a half. However, the STATCOM operation is either not provided for the DC short fault condition and this strategy is not suitable for the MTDC system.

D. VSC with DC circuit breaker

Intuitionally, the DC circuit breaker is the best solution to protect the VSC-HVDC and the AC grid against the DC short fault condition [6]. Since conventional protection strategies would lose the DC voltage in the DC short fault condition, the DC circuit breaker is a good alternative for the MTDC power transmission system. The DC circuit breakers in the HVDC systems can be divided into three groups: mechanical circuit breaker, solid-state circuit breaker, and hybrid circuit breaker. Since DC circuit breaker does not have zero current point in DC system, the DC circuit breaker has to create a zero current point to interrupt the current by additional commutation path. The mechanical circuit breaker has very low conduction losses. However, the mechanical circuit breaker is not able to be applied to the HVDC transmission system because the DC current interruption time is quite long up to several tens of milliseconds.

The solid-state DC circuit breaker consists of series-connected semiconductor switches. Initially, it has been researched for low and medium AC and DC systems. Because the switching time of semiconductor switches is less than a few microseconds, it has high probability to be applied to the

HVDC system. However, it has three major weaknesses: cost, conduction loss and switching technique of series connected power semiconductors. To interrupt the DC current, the semiconductor should be connected in series for blocking the high DC voltage. At the same time, the huge fault current asks the higher current handling capability of semiconductor switching device by parallel connection. This requires many series-parallel connected costly semiconductor switching devices. And, the conduction loss of semiconductor switching devices would be about 0.1-0.5% of the transferred power. Compared with the mechanical DC circuit breaker, this high conduction loss could be the largest huddle in the application of this type of DC circuit breaker.

Some hybrid DC circuit breakers are announced by company and university. This hybrid concept is simple: in the normal operation, the current flows through the mechanical switch, and in the opening operation, the power electronics circuit such as semiconductor switching devices interrupts the DC current. The interruption time of the hybrid DC circuit breaker was known less than 5ms and the test DC voltage was over 80kV. However, while the mechanical switch is in the open behavior, the VSC should be connected to the short faulted DC circuit. Even though this connection time is very short such as less than 5ms, the DC current increases rapidly and is only limited by the DC inductor. This surge current which is named as the maximum interruption current in this paper has to flow through the VSC-HVDC. And the DC current capability of VSC-HVDC should be designed to endure this maximum interruption current. The shorter the current interruption time of the DC circuit breaker is, the smaller the maximum interruption current is. However, the absolute maximum interruption current is related to the DC inductance. Therefore, DC breaker should consider not only the current interruption time but also the maximum interruption current.

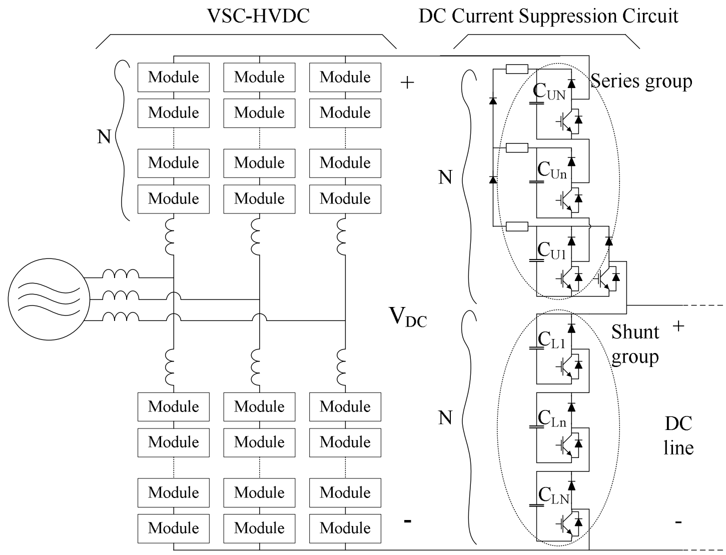
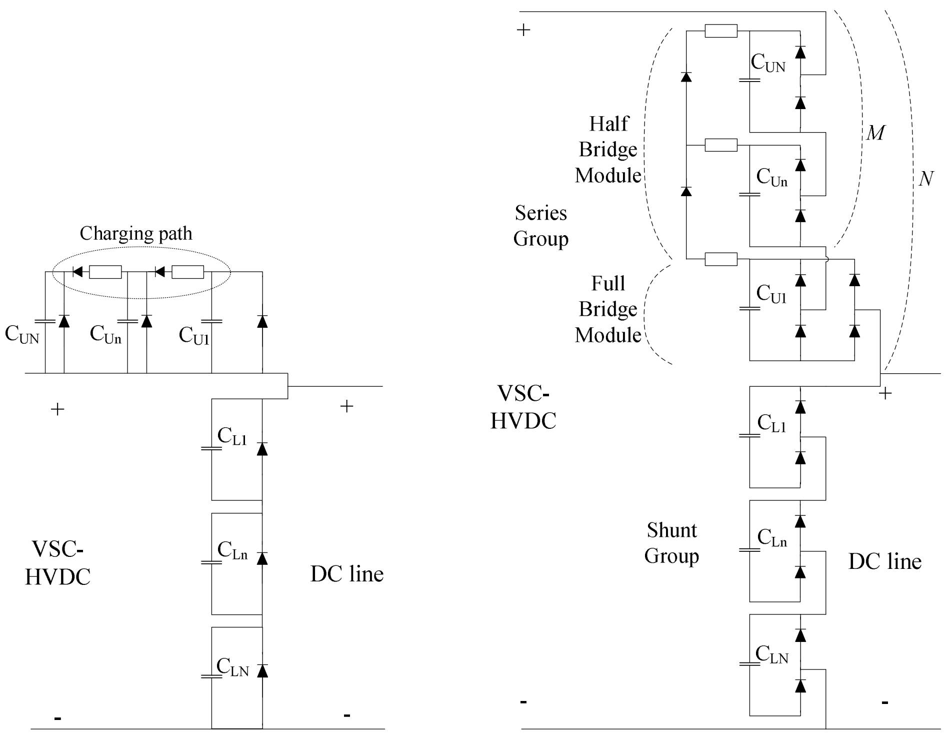


Fig. 1: DC Current Suppression Circuit with VSC-HVDC

III. Proposed DC Current Suppression Circuit

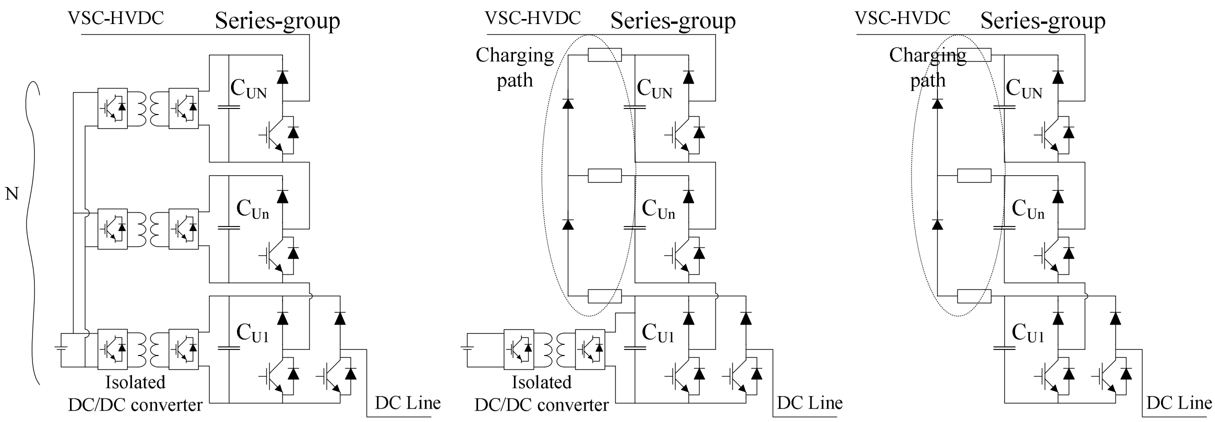
Fig. 1 shows the proposed DC Current Suppression Circuit (DC-CSC). Since the proposed DC-CSC is a modular structure, the rated voltage is scalable and the series connection of power semiconductor is not required. The module mostly consists of a DC capacitor, and a bridge having one diode and one semiconductor switching device with a freewheeling diode. The proposed DC current suppression circuit has two groups, the series-group and the shunt-group as shown in Fig. 1. The module number of each group, *N*, is determined by the rated DC link voltage and the rated voltage of each module. Especially, some modules of the series-group have full bridges as shown in Fig. 1. These full bridges in the series-group are used for disconnecting the VSC-HVDC from the DC link line in the normal condition. The number of the modules having full bridge is could be about 5% of the total module number.



(a) Conducting operation (SW on) (b) Disconnecting operation (SW off)

Fig. 2: Circuit configuration of DC-CSC.

When all switching devices are turn-on, the circuit configuration can be depicted as shown in Fig. 2(a). This is a normal operation mode. In the normal operation mode, the capacitors in the shunt-group are simply series-connected, and the capacitors in the series-group are bypassed in the DC current flowing path. Therefore, the proposed circuit works as a conventional shunt DC capacitor bank. The DC current flows through about *N* semiconductor switching devices of series group, and the number of the conducting power semiconductor of the proposed circuit is a half of that of the conventional solid-state DC circuit breaker circuit. When all switching devices are turned-off, the configuration of the proposed circuit is set as shown in Fig. 2(b). The capacitors in series-group and shunt-group are connected by the diode bridge. In this configuration, the VSC-HVDC is disconnected from the DC line by the series-connected diode bridges. The series-connected capacitor modules having the diode bridge in series group work as a voltage barrier between the VSC-HVDC and the DC link line.

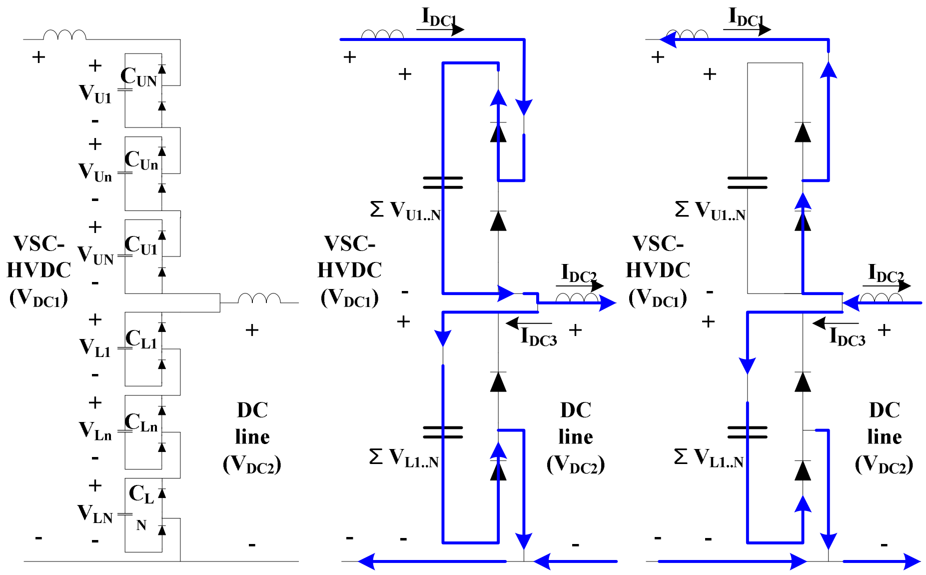


(a) With each DC/DC converter (b) With one DC/DC converter (c) Without DC/DC converter

Fig. 3: DC capacitor charging strategies of the series-group.

A. Conducting operation in the normal condition

In the normal condition, the proposed DC-CSC works as a shunt DC capacitor bank. Therefore, the current flowing into the shunt-group is negligible, and the DC current flows through the only switching devices in the series-group. The conduction loss associated with these conducting devices is a drawback of the proposed DC-CSC. Compared with the conventional solid-state DC circuit breaker, the conduction loss is about a half. And, compared with the modified MMC having the DC current suppression capability, the additional conduction losses are less than one third. Since the capacitor of the series-group should work as a voltage barrier between the VSC-HVDC and the DC link, the capacitors of the series-group need to be charged in the normal operation. Because the DC current detours the DC capacitor of the series-group, modules in series-group should have their DC/DC converter as shown in Fig. 3(a). These isolated DC/DC converters support only the DC capacitor voltage of each module. Therefore, the rated power of these DC/DC converters would be quite small. However, the isolation voltage is a rated DC link voltage of the HVDC system, and it is very expensive and the entire volume and the cost of the circuit would be prohibitive. In Fig. 3(b), the charging path consisting of one diode and one resistor is employed. Every module has its own charging path. By the charging path, the power for compensating the module's losses is transferred from the lower module to upper module successively. Therefore, only one isolated DC/DC converter is used in the bottom module. In the normal operation, all switching devices are turn-on. Then, all capacitors in the series-group are parallel-connected through the charging path as shown in Fig. 2(a). On the other hand, the module capacitor in the series-group can be charged by the DC current flowing between VSC-HVDC and DC grid. By employing proper gating pulses in the full-bridge module, the capacitor of the full bridge module can be charged instantaneously. The charged energy in the full-bridge module can be transferred through the charging path, and the capacitor voltage of all modules in series-group would be maintained above the designed value. In this case, the DC/DC converter for charging the module capacitor in the series-group is not necessary any more.



(a) Configuration (b) Current path ($I_{DC1} > 0$) (c) Current path ($I_{DC1} < 0$)
Fig. 4: Current path with a series-group consisted of only half bridge module.

B. Disconnecting operation in the normal condition

The DC circuit breaker should have the capability to disconnect the VSC-HVDC from the DC grid not only in the DC short circuit condition, but also in the normal operation. For the disconnecting operation, the all switching devices in the proposed DC-CSC are turn-off. If all modules have half bridge as shown in Fig. 4(a), the DC current suppression circuit can be modelled as series-connected two half bridge as shown in Fig. 4(b). The DC current from the VSC-HVDC through DC inductor, I_{DC1}, can be written as (1).

$$
\begin{aligned}
&L_{DC1}\frac{dI_{DC1}}{dt} = V_{DC1} - \left(\sum_{i=1}^{N} V_{Ui} + \sum_{i=1}^{N} V_{Li}\right) && (I_{DC1} \geq 0, I_{DC3} \geq 0) \\
&(L_{DC1} + L_{DC2})\frac{dI_{DC1}}{dt} = V_{DC1} - \left(\sum_{i=1}^{N} V_{Ui} + V_{DC2}\right) && (I_{DC1} \geq 0, I_{DC3} = 0)
\end{aligned} \quad (1)
$$

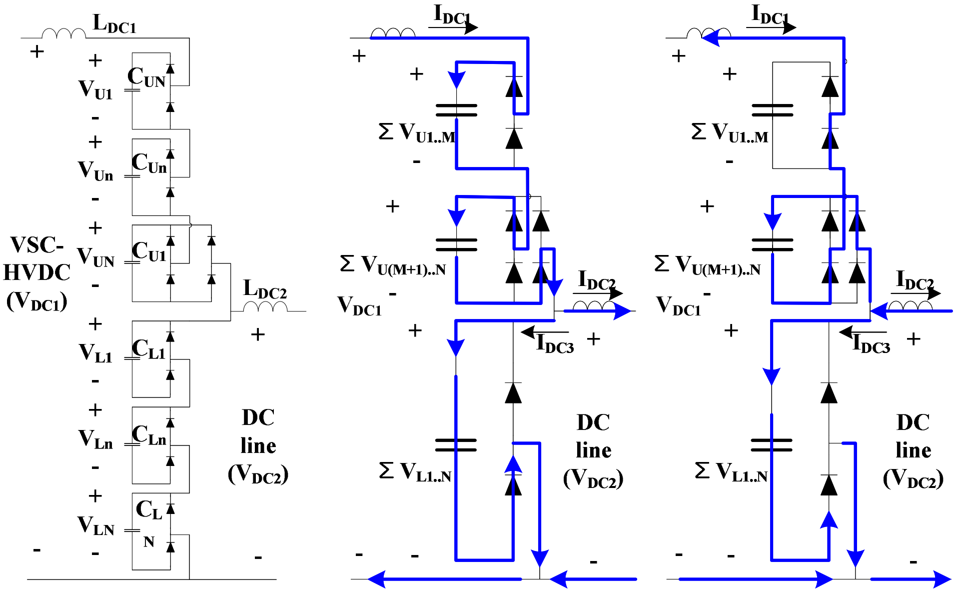
$$L_{DC1}\frac{dI_{DC1}}{dt} = V_{DC1} - \sum_{i=1}^{N} V_{Li} \qquad (I_{DC1} < 0, I_{DC3} \geq 0)$$

$$(L_{DC1} + L_{DC2})\frac{dI_{DC1}}{dt} = V_{DC1} - V_{DC2} \qquad (I_{DC1} < 0, I_{DC3} = 0)$$

When the DC current from the VSC-HVDC is positive, the capacitor voltage of the proposed DC-CSC can reduce the DC current, because the sum of the capacitor voltage of series-group modules is positive. If the DC link voltage, V_{DC2} is higher than the DC voltage of the VSC-HVDC, V_{DC1} then the DC current from the VSC-HVDC, I_{DC1} increases reversely. Therefore, the DC current flowing from the VSC-HVDC is not suppressed when the DC link voltage is higher than the DC voltage of the VSC-HVDC. The current flowing into the shunt-group, I_{DC3}, is written as (2). When the DC current into the shunt-group is positive, the DC current decreases by the voltage difference between the sum of the capacitor voltage in the shunt-group and the DC link voltage. The positive DC current charges the capacitors, and the DC current decreases naturally. And, the negative DC current is suppressed by the DC link voltage inherently. Therefore, the DC current flowing into the shunt-group decreases till null.

$$L_{DC2}\frac{dI_{DC3}}{dt} = V_{DC2} - \sum_{i=1}^{N} V_{Li} \qquad (I_{DC3} \geq 0)$$

$$L_{DC2}\frac{dI_{DC3}}{dt} = V_{DC2} \qquad (I_{DC3} < 0) \tag{2}$$



(a) Configuration (b) Current path ($I_{DC1} > 0$) (c) Current path ($I_{DC1} < 0$)

Fig. 5: Current path with a series-group consisted of half bridge modules and full bridge modules.

To suppress the DC current from the VSC-HVDC, I_{DC1}, by the proposed DC-CSC in the normal operating condition, about 5% of the number of modules in the series-group are replaced with the full bridge type module as shown in Fig. 5. Then, the DC current from the VSC-HVDC, I_{DC1}, is rewritten as (3).

$$L_{DC1}\frac{dI_{DC1}}{dt} = V_{DC1} - \left(\sum_{i=1}^{N} V_{Ui} + \sum_{i=1}^{N} V_{Li}\right) \qquad (I_{DC1} \geq 0, I_{DC3} \geq 0)$$

$$(L_{DC1} + L_{DC2})\frac{dI_{DC1}}{dt} = V_{DC1} - \left(\sum_{i=1}^{N} V_{Ui} + V_{DC2}\right) \qquad (I_{DC1} \geq 0, I_{DC3} = 0) \tag{3}$$

$$L_{DC1}\frac{dI_{DC1}}{dt} = \left(V_{DC1} - \sum_{i=1}^{N} V_{Li}\right) + \sum_{i=M+1}^{N} V_{Ui} \qquad (I_{DC1} < 0, I_{DC3} \geq 0)$$

$$(L_{DC1}+L_{DC2})\frac{dI_{DC1}}{dt}=(V_{DC1}-V_{DC2})+\sum_{i=M+1}^{N}V_{Ui} \qquad (I_{DC1}<0, I_{DC3}=0)$$

In the normal condition, the voltage difference between the VSC-HVDC voltage and the DC line voltage is assumed to be less than 5% of the rated DC link voltage. By replacing 5% of the number of modules (*N-M* in (3)) in the series-group with the modules having the full bridge, the DC current from the VSC-HVDC can be suppressed in the normal condition. Since the module having the full bridge has more switching devices, the conduction loss increases by a little.

C. Disconnecting operation in the DC short circuit condition

When the DC short circuit fault happens, the DC line voltage, V_{DC2} is considered as almost zero. Then, the DC current from the VSC-HVDC, I_{DC1}, and the DC current flowing into the DC line, I_{DC2}, rapidly increases and the DC short circuit fault can be detected. To interrupt the DC short circuit current, all switching devices are turned-off as the disconnecting operation in the normal condition. Then, the DC current from the VSC-HVDC, I_{DC1}, can be derived as (4). And, the DC short circuit current flowing into the DC line is calculated as (5).

$$(L_{DC1}+L_{DC2})\frac{dI_{DC1}}{dt}=V_{DC1}-\sum_{i=1}^{N}V_{Ui} \tag{4}$$

$$L_{DC2}\frac{dI_{DC2}}{dt}=-V_{DC2}\cong 0 \tag{5}$$

Since the sum of the capacitor voltages of the shunt-group is higher than zero, the DC current of the shunt-group, I_{DC3} flows through not the capacitor, but the diodes. The DC current of the shunt-group is calculated as (6) from (4) and (5).

$$I_{DC3}=I_{DC1}-I_{DC2} \tag{6}$$

Because the series-connected capacitor voltages of the series-group prevent the short circuit current from increasing, the DC current from the VSC-HVDC, I_{DC1}, is quickly suppressed. Since the short circuit current in the DC line does not have a voltage source anymore, the DC line current, I_{DC2}, is naturally reduced by the line impedance. If the DC short circuit fault happens temporarily and is cleared soon, then the VSC-HVDC immediately restarts after the switching devices of the DC current suppression circuit are turn-on.

IV. Simulation Results

To verify the feasibility of the proposed DC current suppression circuit, two-terminal HVDC power transmission system is simulated by Matlab/Simulink and PLECS as shown in Fig. 6. The specification of the MMC in the converter station #1 and the DC grid system are listed in Table. I. The converter is modelled as a MMC having half-bridge modules and the proposed DC-CSC is interfaced with the disconnecting switch. The number of the modules in the actual system whose rated DC voltage is 600kV should be higher than three hundreds under the assumption of nominal 2kV DC link voltage of each module. In this simulation, however, the module number is decided as three for reducing the simulation time. The capacitor of the module is determined from the value of the real system. Even though the simulation model has been simplified, the fundamental principle of the proposed DC-CSC can be verified.

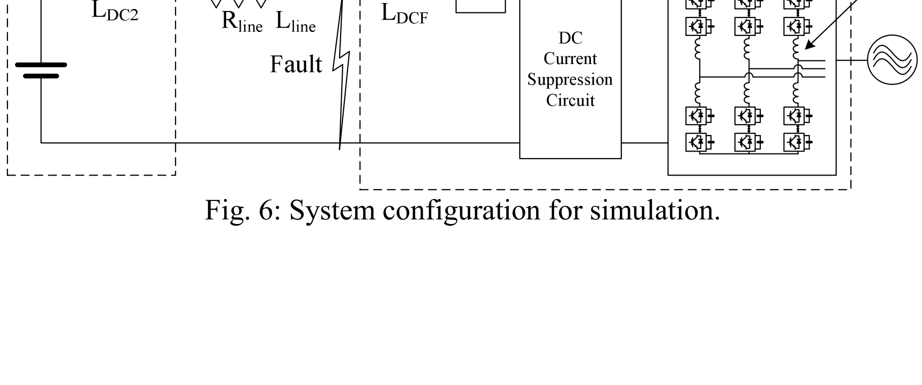


Fig. 6: System configuration for simulation.

Table I: Specification of the simulation system

Specification of MMC			
Rated DC Voltage	600kV	AC Voltage	276kV
# of module per arm, *N*	3	Modulation Index	0.75
Module capacitance	175uF	Arm inductance	22.5mH
Specification of DC Grid			
DC line resistance	6Ω	DC line inductance	200mH
DC filter inductance	35mH	Short circuit resistance	0.05 Ω
Specification of the DC current suppression circuit			
# of module in each group	3	Full bridge module	1
Module capacitance	175uF	Module Cap. voltage	200kV

In the normal operation, the converter #1 transferred the rated power into the converter #2 which is modelled as a constant voltage source whose voltage is the rated DC voltage. At 0.8s, the proposed DC-CSC operates in the disconnecting mode. Then, the DC current in the DC line is rapidly reduced till null. Fig. 7(a) shows the DC current in the DC suppression circuit. In the normal operation, I_{DC3} is almost zero and I_{DC1} is almost identical with I_{DC2}. When the DC suppression circuit disconnects the DC line, I_{DC1} and I_{DC2} rapidly decrease. Because the energy stored in the arm inductor of the MMC is transferred into the capacitors in the series-group of the DC-CSC, the capacitor voltage of the series-group increases as shown in Fig. 7(b). Meanwhile, the capacitor voltages of the shunt-group are reduced by the internal losses of the modules. Fig. 7(d)-(f) shows the voltage level of the series group, DC line voltage, and the DC voltage of the VSC-HVDC in the DC-CSC during the disconnecting operation, respectively.

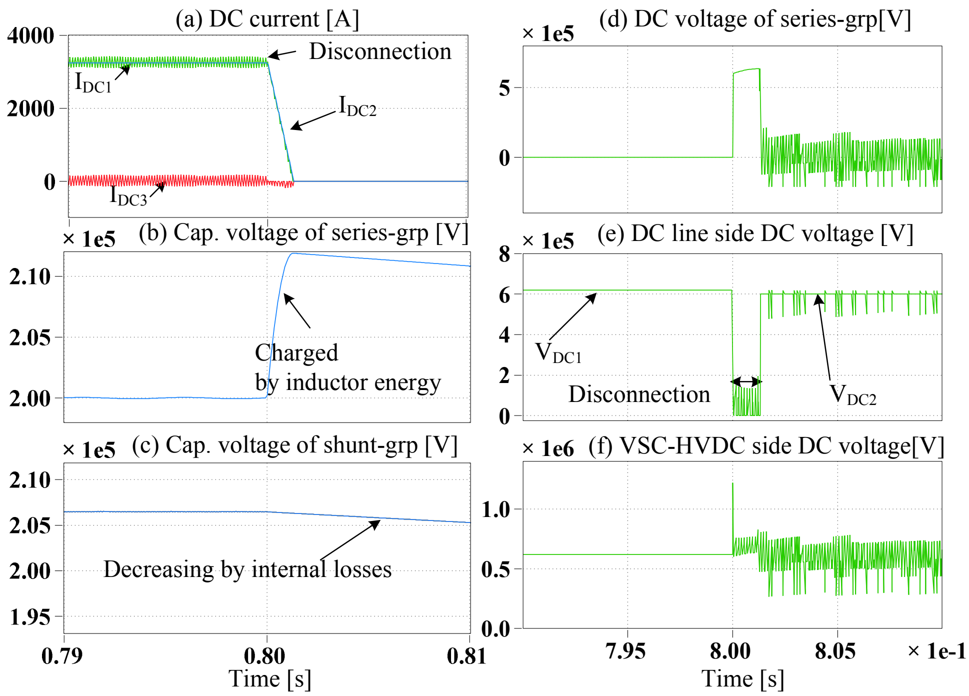


Fig. 7: Disconnection operation in normal condition.

In the DC short circuit fault condition, the proposed DC-CSC should disconnect the VSC-HVDC from the faulty DC line. In this simulation, the short circuit fault is detected according to the magnitude of the DC current. The time delay to operate the DC current suppression circuit is assumed as 100us. When the short circuit fault happens, I_{DC2} and I_{DC3} rapidly increase. The DC current from the VSC-HVDC increases slowly because the proposed DC-CSC works as a shunt capacitor bank in the normal operation. Along with the results in the normal operation, the capacitors of the series-group are charged by the energy stored in the inductor of the MMC. Because the magnitude of the DC current is larger than that in the normal operation, the capacitor voltage increases higher as shown in Fig. 8(b). Since this variation of the capacitor voltage should be limited to protect the switching devices, the parameters of the DC current suppression circuit need to be designed in consideration of the worst fault condition

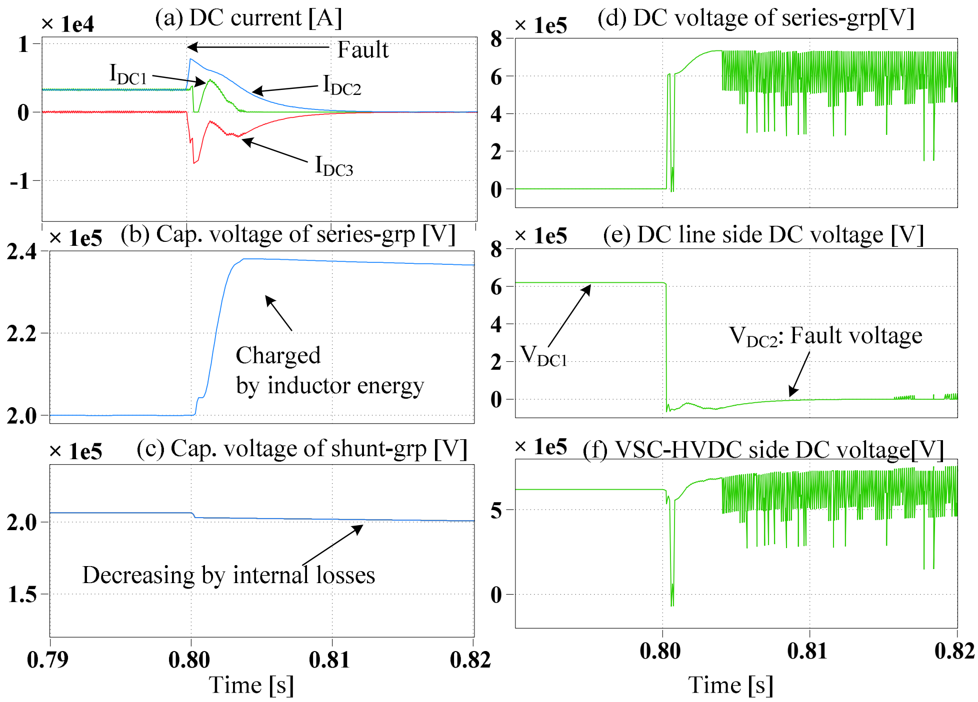


Fig. 8: Disconnection operation in DC short circuit fault.

V. Conclusion

This paper has proposed a new DC Current Suppression Circuit with a disconnecting switch as a DC circuit breaker. Even though this DC-CSC has higher conduction losses compared with the hybrid DC circuit breaker, it has about a half loss of the conventional solid-state DC circuit breaker. And, it is more economical and efficient than the modified MMC having the DC current suppression ability. Because this DC-CSC is a modular configuration, it is scalable and reliable. The DC-CSC can interrupt the DC current not only in the normal operation, but also at the DC short circuit fault condition. And, it can be applied in the MTDC system as a DC circuit breaker.

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