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Fast Isolation Scheme for DC side faults of Flexible DC Grid Based on Voltage Characteristic Signal Extraction

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ABSTRACT

In order to realize the rapid detection and isolation of faults on the transmission lines of high voltage DC transmission system based on modular multilevel converters, a protection scheme based on the overvoltage transient characteristic signal of the faulted line is proposed. The dynamic fluctuation amplitude of the line voltage is detected to realize the rapid capture of the fault signal. The characteristic signal injection principle is adopted to suppress the fault current and line overvoltage, and create a reliable environment for the protection of the equipment against short-circuit faults. PSCAD/EMTDC simulation results show that the protection scheme can quickly and reliably transmit fault occurrence signals without complex communication systems and data processing units, reduce the impact of sudden changes in electrical quantities on the equipment, and meet the requirements of system protection reliability and rapid mobility.

Keywords: modular multilevel converter, DC fault, fault current-limiting, power system protection scheme, flexible DC grid

NONMENCLATURE

Abbreviations	
CDSM	Clamp Dual Sub-Modules
DCCB	DC Circuit Breakers
FBSM	Full-Bridge Sub-Modular
HBSM	Half-Bridge Sub-Modular
IGBT	Insulated Gate Bipolar Translator
MMC-HVDC	Modular Multilevel Converter Based High Voltage DC
Symbols	
ω_0	Phase angle of injected sine signal
Δu_{dcf}	Voltage fluctuation of u_{dcf}
C_0	Sub-module capacitance
C_{ij} (i=a,b,c; j=u,n)	Equivalent capacitance of HBSMs
C_{s}	Equivalent capacitance of three-phase bridge arm sub-module
$i_{\mathrm{dc}}(0)$	Instantaneous value of DC current before switching
k_{d}	Differential coefficient
K_{dcf}	Fault overvoltage transient characteristic value
K_{ref}	K_{dcf} threshold used to identify fault
L_0	Sub-module inductance
L_{dc}	Inductance of the fault lines
L_{ij} (i=a,b,c; j=u,n)	Bridge arm reactor
L_{s}	Equivalent inductance of three-phase bridge arm sub-module
N	Total number of HBSM
R_0	Sub-module resistance
R_{dc}	Resistance of the fault lines
Sig_1	Protection device trigger signal
Sig_2	Injected sinusoidal voltage signal
T_{i} (i=1,2)	Converter transformer
u_{dcf}	DC voltage at the outlet of the converter after the fault occurrence
u_{i} (i=a,b,c)	i-phase equivalent power of AC side
u_{i} *(i=d,q)*	Three-phase voltage reference value in dq coordinate

U_m	Amplitude of the injected sine signal
u_{ri} $(i=a,b,c)$	Three-phase voltage reference value in abc coordinate
U_{sc}	The equivalent potential of C_s energy storage before switching
U_{sL}	The equivalent potential of L_s energy storage before switching
VD_i	Diode
Z_i (i=a,b,c)	i-phase equivalent inductance of AC side

1. INTRODUCTION

Compared with traditional DC transmission technology, modular multilevel converter based high voltage DC (MMC-HVDC) has advantages on flexible transmission methods, lower power loss, and less harmonic content [1,2]. MMC-HVDC is the main technical direction to realize the rational allocation and efficient utilization of new energy resources on a global scale. It has huge development potential and broad application prospects in the process of building a transmission grid with clean energy.

However, based on the current technology development status, there are still many technical problems in the flexible DC grid. In order to better achieve long-distance, large-capacity power transmission, overhead transmission lines are gradually replacing cables as the main form of DC transmission. The MMC-HVDC with half-bridge sub-modular (HBSM) as its core structure does not have the ability to clear DC faults, while the Full-Bridge Sub-Modular (FBSM) and clamp dual sub-modules (CDSM) have fault clearance capabilities. However, the topologies of FBSM and CDSM are more complex [3-5]. In addition, the development of large-capacity high-voltage DC circuit breakers (DCCB) that can meet the breaking requirements still has problems, such as high technical difficulty and high cost.

The most practical solution in the current limiting is to install a current-limiting reactor at the exit of each converter station, so as to weaken the rising speed and peak value of the fault current [6-8]. But the value of the current-limiting inductor cannot be too large, otherwise it can affect the system control response speed and stability. In order to cut off the fault current, the most effective method is to block all insulated gate bipolar translator (IGBT) to prevent capacitor discharge [7]. However, one of the biggest shortcomings of this method is that when the blocking IGBT cuts off the fault current with extremely large amplitude, the bridge arm inductance and the transmission line produce serious overvoltage, which threaten the system insulation.

Based on the engineering application, this article first introduces the existing MMC-HVDC system topology and protection scheme configuration. On this basis, the transient characteristics of the overvoltage of the MMC-HVDC DC short-circuit fault line are analyzed, and the dynamic voltage fluctuation is used as the protection starting signal. By studying the characteristics of the output voltage reference signal of the converter station, a sinusoidal voltage signal is injected to suppress overvoltage and fault current. Finally, the PSCAD/EMTDC simulation model is used to verify the effectiveness of the proposed scheme.

2. ANALYSIS ON THE DC SIDE FAULT TRANSIENT PROCESS OF HALF-BRIDGE MMC-HVDC

2.1 MMC-HVDC system topology

When a fault occurs on the DC side of the line, HBSM does not have the ability to clear the fault. The tripping and restarting process of the traditional AC isolation switch takes a long time. With the continuous advancement of DCCB technology, it can already be applied to practical projects. Therefore, DCCB is installed at the outlet of the converter station to achieve DC side fault isolation. Refer to the Nanhui Flexible DC Transmission Demonstration Project, the double-ended MMC-HVDC system with traditional bipolar transmission lines is shown in Fig 1. In Fig 1, the DCCB topology scheme shown in [10] is adopted.

After a bipolar short-circuit fault occurs on the line, the decay process of the second-order underdamped oscillation of the system causes the line current and voltage to rise rapidly. In traditional protection schemes, the zero-crossing point of the line current is used as an important basis for fault clearance. However, during the period from the fault occurrence to the block of the converter station, severe voltage fluctuations pose a serious threat to the equipment insulation. Therefore, the fault clearing time of the DC grid is generally controlled within 5ms. Due to the huge control link of the DC power grid, the signal transmission link between devices becomes more complicated after the configuration of DCCB, which leads to delays in signal transmission between different devices and adversely affects the speed of the line protection scheme.

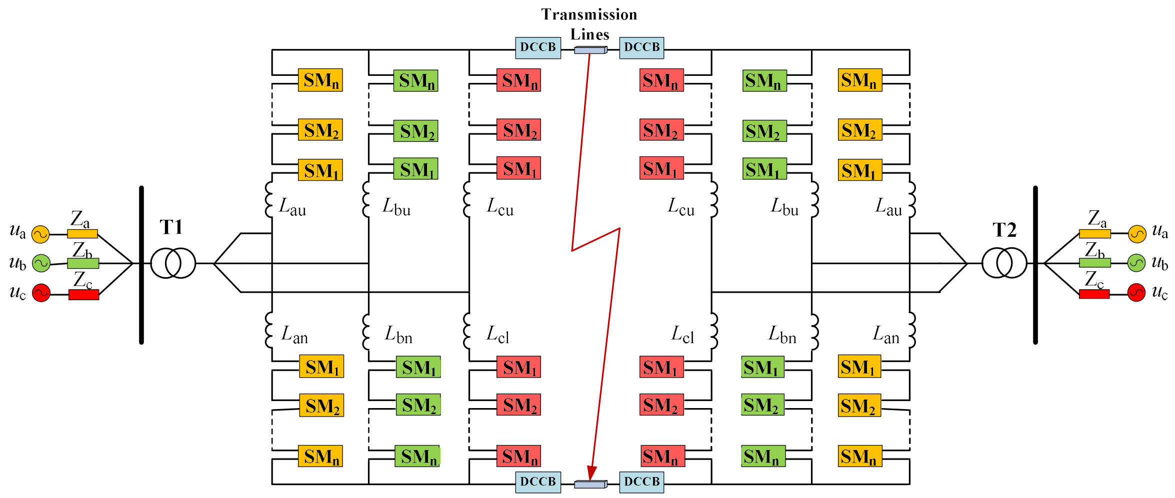


Fig 1 Double-ended MMC-HVDC system diagram

2.2 *Voltage transient characteristics of DC side*

Similar to the three-phase short circuit fault in the AC power grid, the bipolar short circuit still has symmetry. Under the premise of ignoring the influence of the AC grid, the fault circuit can be simplified to Fig 2.

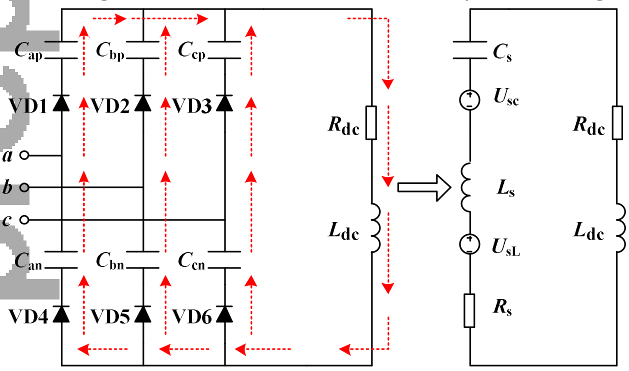


Fig 2 Simplified circuit diagram of fault circuit

Solving in the complex frequency domain can be obtained：

$$U_{\mathrm{dcf}}(s)=\frac{\mathrm{A}_1 s+6C_0R_{\mathrm{dc}}U_{\mathrm{dc}}-Ni_{\mathrm{dc}}(0)L_{\mathrm{dc}}}{(4C_0L_0+6C_0L_{\mathrm{dc}})s+(4C_0R_0+6C_0R_{\mathrm{dc}})s+N} \qquad (1)$$

Where:

$$\mathrm{A}_1=6C_0L_{\mathrm{dc}}U_{\mathrm{dc}}+4C_0L_0i_{\mathrm{dc}}(0)-4C_0L_{\mathrm{dc}}i_{\mathrm{dc}}(0)R_0 \qquad (2)$$

The inverse Laplace transform of equation (1) can be obtained:

$$u_{\mathrm{dcf}}(t)=2\mathrm{A}_1\,\mathrm{B}_2\,e^{-\frac{t}{\tau_{\mathrm{dc}}}}\cosh(\omega_{\mathrm{dc}}t)+2\mathrm{B}_3e^{-\frac{t}{\tau_{\mathrm{dc}}}}\sinh(\omega_{\mathrm{dc}}t) \qquad (3)$$

Where:

$$\mathrm{B}_2=\frac{\mathrm{A}_1}{4C_0L_0+6C_0L_{\mathrm{dc}}} \qquad (4)$$

$$\tau_{\mathrm{dc}}=\frac{4C_0L_0+6C_0L_{\mathrm{dc}}}{2C_0R_0+3C_0R_{\mathrm{dc}}} \qquad (5)$$

$$\omega_{\mathrm{dc}}=\sqrt{\frac{C_0(2R_0+3R_{\mathrm{dc}})^2-N(4L_0+6L_{\mathrm{dc}})}{C_0(2L_0+3L_{\mathrm{dc}})^2}} \qquad (6)$$

$$\mathrm{B}_3=\frac{\mathrm{B}_2(2C_0R_0+3C_0R_{\mathrm{dc}})-6C_0R_{\mathrm{dc}}U_{\mathrm{dc}}+Ni_{\mathrm{dc}}(0)L_{\mathrm{dc}}}{\sqrt{4{C_0}^2\left[(2R_0+3R_{\mathrm{dc}})^2-N(4L_0+6L_{\mathrm{dc}})\right]}} \qquad (7)$$

From equations (3)-(7), the voltage across the DC side exhibits oscillation attenuation characteristics after the fault. Since the overvoltage can reach its peak value in a relatively short period of time, the voltage fluctuation amplitude is the largest in this time period. At the same time, the characteristics of overvoltage changes are the most significant, which poses the greatest threat to system reliability.

3. OPTIMIZATION OF PROTECTION SCHEME

3.1 *Extraction of voltage transient characteristic signal*

According to the analysis in the Section 2, the DC voltage across the outlet of MMC changes in a large scale suddenly. Based on the above transient characteristics, the voltage dynamic deviation is used as the characteristic signal to capture the occurrence of a fault. In order to reduce the capture error, the original voltage signal is amplified, as shown in equation (8):

$$\Delta U_{\mathrm{dcf}}=k_{\mathrm{d}}\frac{\mathrm{d}u_{\mathrm{dcf}}(t)}{\mathrm{d}t} \qquad (8)$$

When the system sampling frequency is large enough, the voltage dynamic deviation value can be regarded as a continuous function：

$$K_{\mathrm{dcf}}(t)=\lim_{\Delta t\to 0}\left[u_{\mathrm{dcf}}(t+\Delta t)-u_{\mathrm{dcf}}(t)\right] \qquad (9)$$

This function reflects the oscillation amplitude of the line overvoltage in an infinitely small time interval. When the line voltage fluctuation range exceeds the threshold K_{ref}, it can be determined that the line has a bipolar short-circuit fault.

3.2 *Line overvoltage suppression measures before fault clearing*

In the system-level control link, the voltage PWM carrier signal input by the inner loop current controller is:

$$\begin{bmatrix} u_{\text{ra}} \\ u_{\text{rb}} \\ u_{\text{rc}} \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & 1 & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \end{bmatrix}\begin{bmatrix} u_{\text{d}} \\ u_{\text{q}} \end{bmatrix} + \begin{bmatrix} U_{\text{m}}\cos(3\omega_0 t) \\ U_{\text{m}}\cos(3\omega_0 t) \\ U_{\text{m}}\cos(3\omega_0 t) \end{bmatrix} \quad (10)$$

From equation (10), the voltage reference waveform output by the controller includes two cosine waveforms with different phase angles and amplitudes. When the line voltage fluctuates due to a fault, the output voltage waveform of the controller also changes, thereby affecting the switching strategy of the sub-module capacitor. Therefore, part of the oscillation attenuation amplitude can be offset by injecting a sine or cosine function signal of a certain frequency and amplitude.

3.3 *Timing optimization of multi-device coordination in fault removal scheme*

Assuming that the overhead transmission line has a bipolar short-circuit fault at t_0. At t_1, the voltage transient deviation $K_{\text{dcf}}(t_1) > K_{\text{ref}}$. At this time, a pulse signal Sig_1 is generated, which is used as a trigger signal for the action of DCCB and converter station.

When Sig_1 is transmitted to the controller, according to the principle shown in equation (10), the controller is prepared to inject a pre-set sinusoidal signal to reduce the line overvoltage and the converter station is blocked. This action is finished before the circuit breaker trips. According to the change characteristics of $u_{\text{dcf}}(t)$, the segmented injection method is adopted:

$$\begin{cases} Sig_2 = U_2\sin(\omega_2 + \theta_2), t_1 < t < t_2 \\ Sig_3 = U_3\sin(\omega_3 + \theta_3), t_2 < t < t_3 \end{cases} \quad (11)$$

After receiving Sig_1, the line fault is detected by the DCCB and the converter station, then the tripping and block subsequent is triggered respectively. Since $K_{\text{dcf}}(t)$ can be accurately captured in the fault development stage, it accurately reflects the characteristics of the line voltage change at each moment. By setting a reasonable threshold K_{ref}, the Sig_1 signal can be quickly generated, thereby improving the quick action of the system protection equipment.

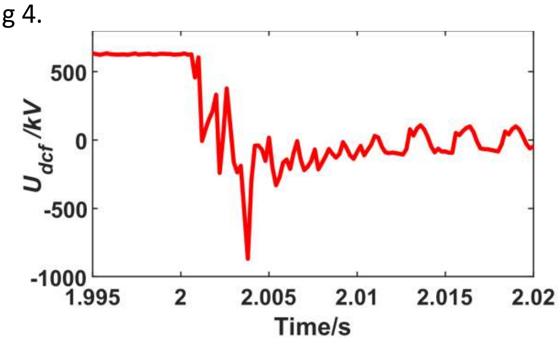
4. SIMULATION AND ANALYSIS

The bipolar double-ended MMC-HVDC system as shown in Fig 1 is built in PSCAD/EMTDC simulation software. Constant reactive power and constant DC voltage control are adopted in the rectifier side; constant reactive power and constant active power control are adopted in the inverter side. The parameters of the system and FIM are shown in Tab 1.

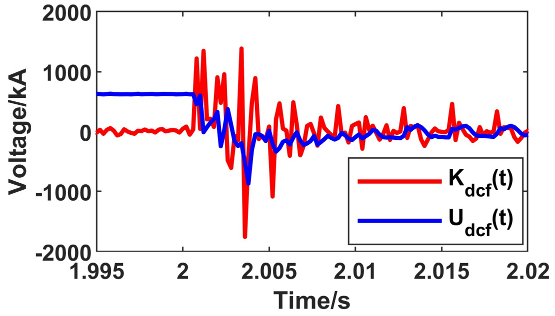
Tab 1 MMC-HVDC system simulation model parameters

Parameters	Value
DC voltage/kV	640
Length of transmission lines/km	400
Unit resistance of transmission lines / Ω / km	0.03182
AC source voltage/kV	240
Number of each bridge arm submodules	76
Bridge arm reactor /mH	10
Submodule capacitance/ μF	2800

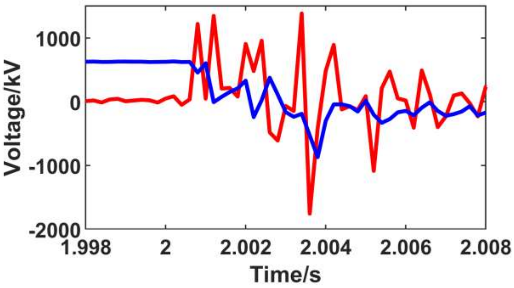
Suppose that a line-to-line short-circuit fault occurs at a distance of 200km from the outlet of the converter station at t_0 = 2s. The simulation results are shown in Fig 3-Fig 4.



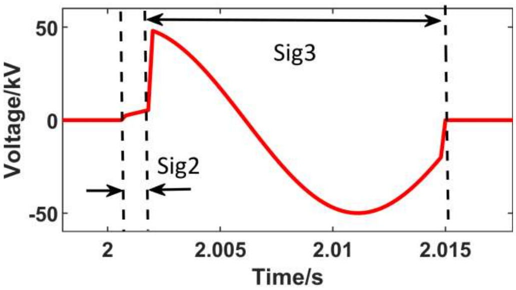
(a) Overvoltage across the outlet of MMC



(b) Simulation waveform of K_{dcf}(t) and U_{dcf}(t)



(c) Partial enlarged schematic diagram of Fig 3 (b)



(d) Injected specific sine signal waveform

Fig 3 simulation results of protection optimization

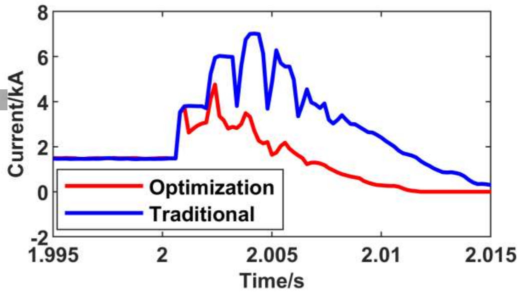


Fig 4 Current flowing through the lines

Figure 3(a) shows that when the control system injects a sinusoidal signal with a specific amplitude and phase angle, the line overvoltage can be effectively suppressed. Figure 3 (b) and Figure 3 (c) show that K_{dcf}(t) captures the oscillation amplitude of U_{dcf}(t) more accurately.

In 2.008-2.001 s, the voltage increased from 456.71 kV to 603.13 kV. At this time, the voltage change rate is low, and the characteristic signal reaches a minimum value of 48.37 kV. In contrast, taking 2.001-2.0012 s as an example, the line voltage dropped from 603.13 kV to -7.46 kV. The voltage change rate in this time interval is extremely large. Therefore, the characteristic signal also reaches the maximum value of 1346.84 kV at 2.0012 s, which accurately reflects the line voltage change.

According to the requirement of equipment operation safety margin, set K_{ref} to 1.5 times the rated voltage. The first amplitude peak of U_{dcf}(t) appears at 2.0008s. At this time, $K_{\mathrm{dcf}}(t_2)$ is greater than K_{ref}, indicating that Sig_1 has been generated before the fault fluctuates significantly, and the system protection scheme has been activated. This process greatly improves the fault identification speed and isolates the fault before the system is seriously threatened.

5. DISCUSSION

The scheme proposed in this study can quickly capture the MMC-HVDC system with HBSM. But the core of this scheme is the generation and capture of characteristic signals. Therefore, high accuracy and timeliness of each device are required in the signal capture, generation, transmission and reception processes.

In the next research, corresponding protection links should be adopted to maintain the strong stability of the characteristic signal. At the same time, the proposed scheme is optimized to make it suitable for flexible DC grids with different topologies.

6. CONCLUSION

Based on the analysis of MMC-HVDC DC short-circuit overvoltage transient characteristics, a rapid action scheme is proposed for protection equipment. The scheme has the following technical advantages:

(1) The single-ended unipolar voltage is used as the characteristic value calculation parameters. The signal tracking and detection speed is fast. It can capture the fault occurrence signal within 0.8ms after the fault occurs, so that the DCCB and the converter station can quickly take protective measures to meet the speed requirements of the DC grid protection scheme.

(2) By injecting a sinusoidal characteristic signal, the line impulse current is reduced to a certain extent and the rising speed of the buffer impulse current is reduced.

(3) This scheme does not require additional hardware facilities and complex data processing and analysis systems. The system complexity the hardware cost is reduced, which is conducive to the reliable and economic operation of the system.

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REFERENCE

[1] Jianzhong X, Chengyu L, Chengyong Z. The Enhanced DC fault current calculation method of MMC-HVDC grid with FCLs. IEEE J Emerg Sel Topics Power Electron 2019;3:1758-67.

[2] Pei L, Jing M, Xiaodong Z, Min Z, James ST. A protection scheme for DC-side fault based on a new MMC sub-module topology. Int J Elec Power 2020;114:1-9.

[3] Lanxi T, Xinzhou D. An approximate method for the calculation of transmission line fault current in MMC-HVDC grid. Proceedings of the CSEE 2019;2:490-8.

[4] Jian L, Nengling T, Chunju F, Wentao H. Comments on fault handling and protection technology for VSC-HVDC transmission lines. Automation of Electric Power Systems 2015;20:158-67.

[5] S. Wening, M. Goertz, C. Hirsching, M.Suriyah, T. Lerbfried. On full-bridge bipolar MMC-HVDC control and protection for transient fault and interaction studies. IEEE Trans. Power Del 2018;33:2864-73.

[6] Jianzhong Xu, Le W, Dongyi W, Hao J, Chengyong Z. Reliability modeling and redundancy design of hybrid MMC considering decoupled sub-module correlation. Int J Elec Power 2019;105:690-8.

[7] A. Pirhadi, M.T. Bina. Design of DC-side fault current limiter for MMC-HVDC systems: Safety of the MMC along with frequency stability, IET Gener. Transm. Dis 2020;14:2419-29.

[8] Y. Wang, J.Z Liu. An enhanced MMC-HVDC topology and system recovery strategy for DC fault protection, Power System Technology 2015;39:2312-19.

[9] Lanxi T, Xinzhou D, Shenxing Shi, Yufeng Q. A high-speed protection scheme for the DC transmission line of a MMC-HVDC grid. Electr Pow Syst Res 2019;168:81-91.

[10]Hafner J, Jacobson B. Proactive Hybrid HVDC Breakers - A key innovation for reliable HVDC grids. Integrating Supergrids and Microgrids International Symposium 2011;1-8.