

DC fault ride-through method for full-bridge MMC-based MTDC systems

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Abstract: The DC fault protection is one of the main issues in multi-terminal voltage source converter based high-voltage direct current (VSC–MTDC) transmission systems. In this study, a DC short-circuit fault ride-through method for full-bridge modular multi-level converter (FB-MMC) based MTDC systems is proposed. First, the model of the FB-MMC topology is analysed. Then, the principle of fault current clearing in full-bridge sub-module (FB-SM) is introduced. The converter protection control strategy and the system protection scheme are proposed, benefitting from the capability of quick fault current elimination with the valves blocked using the FB-MMC topology. With this method, the MTDC system could restart quickly after clearance of DC fault without cutting off the AC grid. The proposed protection strategy is demonstrated using the simulation model in PSCAD/EMTDC. Simulation results verify the feasibility and effectiveness of the strategy.

1 Introduction

Compared with the conventional line-commutated converter-based high-voltage direct current (LCC-HVDC) transmission technology, voltage source converter based HVDC (VSC-HVDC) possesses many advantages such as no commutation failure and independent active and reactive power control. Thus, it is suitable for building a multi-terminal HVDC (MTDC) system [1–4]. The MTDC system has multiple power sending and receiving ends and is capable of delivering distributed energy to multiple load centres, which makes it to have low transmission loss, flexible power flow control, capability of connecting asynchronous power grids and good extendibility.

The DC short-circuit fault is one of the most serious faults in VSC–MTDC transmission systems. The conventional two-level or three-level VSC topologies and the half-bridge modular multi-level converter (HB-MMC) topology, which is commonly used in the current practical projects, cannot deal with the DC short-circuit fault rapidly. On the other hand, the DC circuit breakers [5, 6] for high-voltage bulk-power applications are much expensive. Thus, the common approach to interrupt the fault current and protect the converter valve is to cut off the connection between the AC and DC systems with AC breakers. However, AC circuit breakers are slow-acting mechanical switches. During DC pole-to-pole short-circuit, the AC grid is equivalent to a three-phase short-circuit before the interruption of the AC circuit breakers. The sharply increasing fault current has a serious impact on the stability of the power grid and the safety of the converter valves [7]. Besides, complex operations are required in this protection strategy to restart the transmission system after DC fault elimination. Due to those problems, cables are commonly used in VSC–MTDC systems to reduce the failure rate, which however significantly increases the economic cost of VSC–MTDC projects.

Marquardt proposed several sub-module topologies of MMC: HB-SM, which has fewer power electronic devices and low loss but is with no DC fault ride-through capability; full-bridge sub-module (FB-SM) and CD-SM (clamp-double sub-module) need more power electronic devices and the operating losses are higher, but those topologies have the capability of DC fault ride-through. The DC fault ride-through mechanism of CD-MMC is studied in [8]: the back-electromotive force provided by the DC capacitors in the fault circuit could cut off the arc and clear the fault current with the unidirectional conduction characteristics of the anti-parallelled

diodes in insulated gate bipolar transistors (IGBTs). The parameters and the performance of various MMC sub-module topologies are compared in [9] and an optimised design method of hybrid MMCs is proposed to reduce the number of switching devices and the switching losses. In [10], a protection strategy is presented to achieve the single-pole-to-earth and bipolar short-circuit fault ride-through capability, by reducing the DC bus voltage to inhibit fast raising of the fault current.

To solve the existing problems in DC short-circuit fault protection of MMC-MTDC systems, this paper developed an improved converter protection strategy: (i) The FB-MMC valves are blocked immediately, while DC fault occurs to ensure the rapid elimination of the short-circuit fault current. (ii) Then, the converter restarts in several microseconds and operate as two cascaded H-bridge STATCOMs in parallel, providing reactive power for the AC grid until the system certainly cuts the trouble area. (iii) At last, the MMCs return to normal operating model to transfer active power and the MTDC system resumes quickly without tripping any AC circuit breakers. The validity of the proposed fault protection strategy is verified in PSCAD/EMTDC.

2 Operating principle of MMC-MTDC

2.1 MMC–MTDC system

A typical MMC–MTDC system is shown in Fig. 1, which consists of several MMC converter stations, AC grids and DC network. The active power of different generation units, such as off-shore wind farms, is collected by the wind farm converters (WFCs) and injected into the common DC lines. Then, the power is allocated to each AC grid through the grid-side converters (GSCs).

Generally, one or several GSCs connected with main AC grids are set up for controlling the DC-link voltage of the MTDC system, which are commonly named as the master station and adapt with a constant DC voltage control method in master–slave control or voltage margin control strategies. However, in the droop control strategy [11, 12, 13], some or all of GSCs operate according to a P – V or I – V characteristic function to distribute active power and control DC voltage in a coordinated manner, where high-speed communication is not required; thus, the reliability is improved. On the other hand, WFCs connected with weak AC systems like renewable generation units or passive networks like offshore boring island are in charge of power injection or distribution and

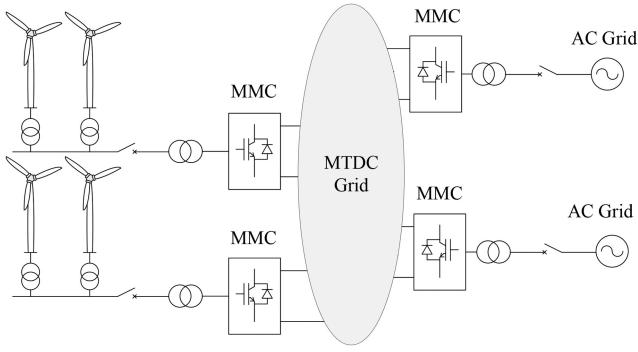


Fig. 1 Structure of MTDC systems

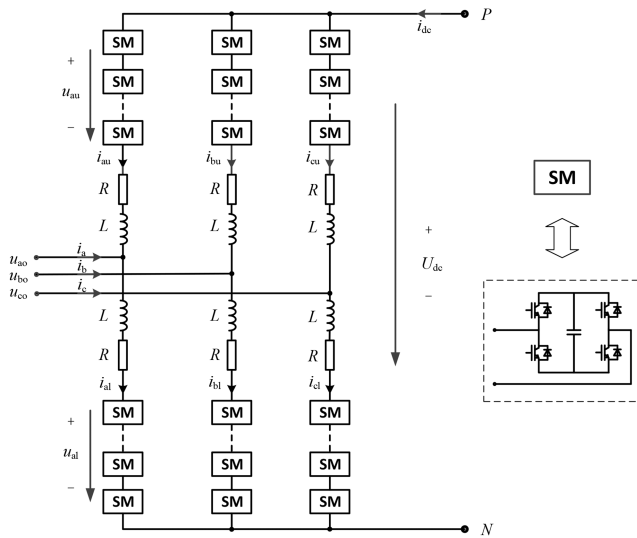


Fig. 2 Circuit topology of MMC

AC voltage–frequency support. A constant AC voltage control and a constant active power control are commonly adopted with those converters.

Fig. 2 shows a three-phase MMC topology. The MMC consists of six arms; each arm includes N identical SMs and one arm inductor L . Each SM in FB-MMC has four full-controlled switch devices and one DC storage capacitor. According to the states of the switches, four operation modes exist: PLUS, MINUS, ZERO and BLOCK. Under normal operation, FB-SM works in the same way with HB-SM and the output voltage is $+U_c$ (PLUS) or 0 (ZERO).

As is shown in Fig. 2, u_{io} is the AC output voltage, while ‘o’ is the virtual neutral point, i_i is the AC output current, $i = a, b, c$. U_{dc} is the DC bus voltage of MMC. According to Kirchhoff's voltage law, the upper arm voltage and lower arm voltage can be expressed, respectively, as

$$\begin{cases} u_{ao} = \frac{1}{2}U_{dc} - u_{au} - L\frac{di_{au}}{dt} - Ri_{au} \\ u_{ao} = -\frac{1}{2}U_{dc} + u_{al} + L\frac{di_{al}}{dt} + Ri_{al} \end{cases} \quad (1)$$

where u_{au} and u_{al} are the upper and lower arm output voltages, respectively; i_{au} and i_{al} are the upper and lower arm currents, respectively.

According to Kirchhoff's current law, the arm currents of phase A can be written as

$$\begin{cases} i_{au} = -\frac{1}{2}i_a + \frac{1}{3}i_{dc} + i_{diff} \\ i_{al} = \frac{1}{2}i_a + \frac{1}{3}i_{dc} + i_{diff} \end{cases} \quad (2)$$

where i_{dc} is the DC current; i_{diff} is the AC component of the circulating current.

Adding the upper and lower in (1), the ac-side voltage is obtained as

$$u_{ao} = \frac{(u_{al} - u_{au})}{2} - L\frac{d(i_{al} - i_{au})}{2dt} - R\frac{i_{al} - i_{au}}{2} \quad (3)$$

According to (1) and (3), the DC-link voltage and current can be expressed, respectively, as follows. Equations (1)–(5) describe the model of MMC.

$$U_{dc} = u_{au} + u_{al} + 2L\frac{di_{diffj}}{dt} + 2Ri_{diffj} \quad (4)$$

$$I_{dc} = \sum_{i=a,b,c} i_{iu} = \sum_{i=a,b,c} i_{il} \quad (5)$$

3 Proposed protection strategy

According to Kirchhoff's current law, the arm currents of phase A can be written as benefit from the full-bridge topology; the FB-SM has higher control degrees of freedom and capability of DC fault current clearance. The arm current charges DC capacitor after valve blocking, no matter the initial current direction is plus or minus, that all the capacitors in the arm are connected in series with the fault circuit, providing back-electromotive force to cut off the short-circuit arc. As the total capacitor voltage of the MMC arm is higher than the peak value of the AC-output voltage, the fault current will be rapidly cleared.

However, in practical MMC applications, especially MMC-based HVDC systems, sustained blocking of converter valves without cutting off the connection between the AC grid and converter can bring some serious problems. Owing to the parameter differences in SMs, capacitor voltages diverge gradually and may exceed high-/low-voltage protection value. In that case, the converter station has to exit operation, which can terminate the power transfer of the HVDC system and even cause system instability. Aiming at solving this problem, a novel DC short-circuit ride-through strategy is proposed in this paper, based on the high control flexibility of FB-MMC.

3.1 Converter-level protection

The fault current of MMC under pole-to-pole short-circuit situation can sharply rise even ten times above the normal safety limit in just several microseconds, which poses a serious threat to the safety of the converter valve and other equipment. Therefore, the key issue of converter-level DC fault protection is to inhibit the fault current raising to protect the expensive semiconductor devices and capacitors in the converter.

As introduced in existing literatures, the short-circuit current consists of the DC component of the series capacitors discharging current and the AC component fed from AC grids. After DC fault occurrence, all of the SMs still remain operating that the capacitors are kept being charged or discharged alternately due to the voltage balancing algorithm. The fault current is mainly limited by the arm inductor before converter valve blocking. However, for reducing the volume and building cost of the MMC station, the arm inductor is usually designed relatively small, which results in a rapid increase of the fault current. The capacitor discharging current can be significantly and quickly suppressed by blocking converter valve rapidly. However, as the AC grid is equivalent to that operating under three-phase short-circuit fault under the pole-to-pole DC short-circuit situation, the AC component of the fault current remains injecting into the fault point continuously even after converter blocking.

Based on the advantage of FB-SM that it can output three levels of voltages: $+U_c$, $-U_c$ and 0, the proposed converter-level protection method is implemented as follows. As shown in Fig. 3, due to the symmetry of the upper and lower arms, the mathematical models of upper and lower three-phase arms are established, respectively

$$\begin{cases} -L \frac{di_{au,l}}{dt} - R \cdot i_{au,l} - u_{au,l} = u_{ao} + u_{oP,N} \\ -L \frac{di_{bu,l}}{dt} - R \cdot i_{bu,l} - u_{bu,l} = u_{bo} + u_{oP,N} \\ -L \frac{di_{cu,l}}{dt} - R \cdot i_{cu,l} - u_{cu,l} = u_{co} + u_{oP,N} \end{cases} \quad (6)$$

In a three-phase balanced system, $u_{ao} + u_{bo} + u_{co} = 0$ is satisfied. By summing (1), the voltage of the AC-side neutral point to the positive and negative poles, $u_{oP,N}$, can be expressed as

$$u_{oP,N} = -\frac{1}{3} \left(\sum_{i=a,b,c} u_{iu,l} + L \cdot \frac{d}{dt} \sum_{i=a,b,c} i_{iu,l} + R \cdot \sum_{i=a,b,c} i_{iu,l} \right) \quad (7)$$

According to (8) and (9), only with the fundamental component considered under three-phase balance condition, u_{oP} and u_{oN} can be rewritten as

$$u_{oP} = -\frac{1}{3} (u_{au,dc} + u_{bu,dc} + u_{cu,dc}) \quad (8)$$

$$u_{oN} = -\frac{1}{3} (u_{al,dc} + u_{bl,dc} + u_{cl,dc}) \quad (9)$$

where $u_{iu,dc}$ and $u_{il,dc}$ ($i = a, b, c$) are the direct current bias voltages of the upper and lower arms, respectively.

Benefitting from the capability of FB-SM to output negative voltage, the dc bias voltage of the FB-MMC arm can be regulated from $+U_{dc}$ to $-U_{dc}$. Therefore, u_{oP} and u_{oN} can be controlled to zero. Based on the above analysis, the mathematical models of the upper FB-MMC arms in (6) can be rewritten through the dq transformation, as follows:

$$\begin{cases} L \frac{di_{ud}}{dt} + R i_{ud} - \omega L i_{uq} = e_{ud} - u_{ud} \\ L \frac{di_{uq}}{dt} + R i_{uq} + \omega L i_{ud} = e_{uq} - u_{uq} \end{cases} \quad (10)$$

where $i_{ud,q}$, $u_{ud,q}$ and $e_{ud,q}$ are the dq components of the upper arm. The dq model of the lower arms can be obtained in the same way.

Based on the model mentioned above, the voltage of the DC positive pole and the grid voltage neutral point can be regulated to zero by controlling the upper arm voltages individually. Similarly, the lower arms can be controlled with the same method to keep the negative pole and the grid voltage neutral point potential, which make it possible to isolate fault points reliably by using existing isolating switches. The control scheme of converter protection strategy is shown in Fig. 3.

The converter protection strategy is divided into two stages: (i) block the converter immediately while the fault occurs to clear the fault current rapidly; (ii) restart the converter after the clearance of the fault current, and the upper and lower arms are under control independently with the strategy in Fig. 3 until fault isolation is completed. In the second stage, the FB-MMC operates as two star-cascaded H-bridge STATCOMs in parallel. During fault isolation and system recovery, the converter is under control, which avoids the capacitor voltage exceeding the safety threshold, which will damage the system security and even lead to power interruption.

3.2 System level protection

Based on the converter-level protection method, a MTDC system level protection strategy is presented in this paper. Due to the extremely high-cost bulk-power DC circuit breaker, the presented strategy focus on isolating fault point by existing isolation switches and quickly restoring of power transmission. A 'handshake principle' for FB-MMC-based MTDC system is introduced in [14]. However, this method can hardly deal with a permanent fault, because it requires a quick clearance of the fault current (about 10

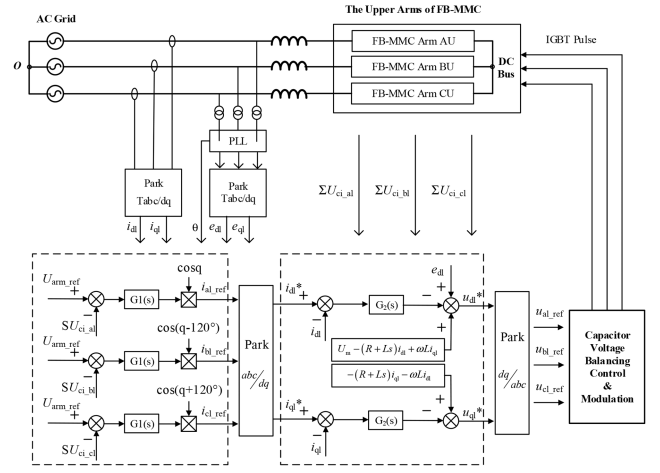


Fig. 3 Control scheme of the converter protection strategy

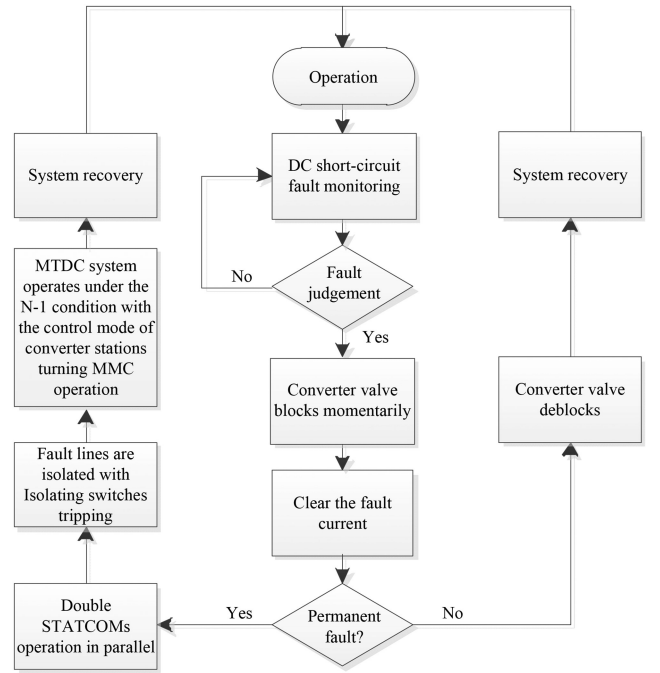


Fig. 4 Control scheme of the system protection strategy

ms) and a long-time converter blocking will result in AC circuit breakers tripping and system outage. To solve these problems, the system-level protection strategy is implemented as follows:

- Clearance of the fault current:** The converter valves are blocked immediately when DC short-circuit fault occurs to clear the fault current.
- Parallel operation of double star-cascaded STATCOMs:** After clearance of the fault current, the FB-MMC is unblocked in a short time and the control mode turns to parallel operation of double STATCOMs shown in Fig. 3.
- Fault isolation:** DC lines isolation switches cut-off the fault area.
- System recovery:** The rest converters of MTDC system that are maintained under normal condition turn to power transmission mode from STATCOM operation. The system resumes normal running within short time.

The control scheme of the system-level protection strategy is shown in Fig. 4. After clearance of fault, the rest MTDC system operates under N-1 condition, where a voltage droop control strategy should be adopted. Thus, the high-speed communication between converter stations is unnecessary, which ensures the system's reliability.

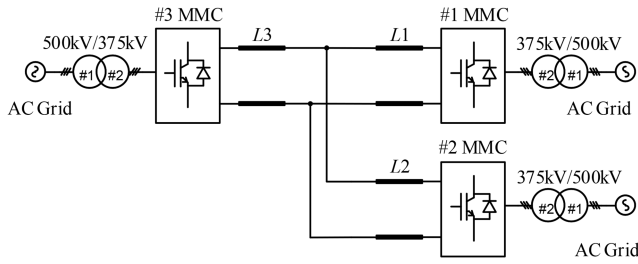


Fig. 5 Simulated three-terminal FB-MMC-based MTDC system

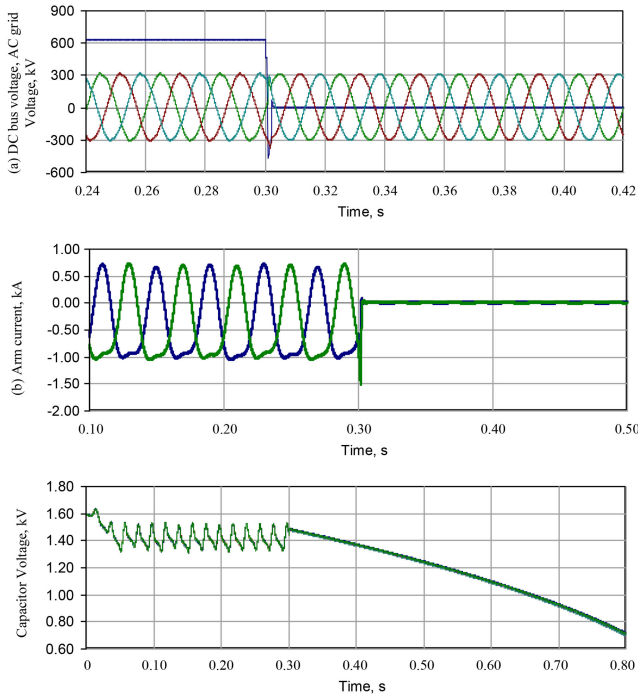


Fig. 6 Simulation results with the blocking method

4 Simulation

4.1 Simulation system

In order to verify the validity of the proposed strategy, compared simulations with the proposed strategy and the traditional blocking method in a three-terminal FB-MMC-based MTDC system, as shown in Fig. 5, are performed in PSCAD/EMTDC. The detailed simulation parameters are listed in Table 1.

4.2 Simulation results

To verify the proposed strategy, a permanent bipolar DC short-circuit fault is simulated. Under normal condition, MMC2 and MMC3 are adopted with a conventional dq closed-loop control method and inject active power generated by wind farms to the MTDC system. MMC1 is with a constant DC voltage control and delivers active power to the AC grid. Meanwhile, a voltage droop control in [15] is adopted with this system to maintain the voltage and power balance.

As shown in Fig. 6, a bipolar DC short-circuit fault occurs 30 km from the DC terminal of MMC3 at $t=0.3$ s in L3, with the traditional valve blocking protection strategy. MMC1 and MMC2 absorbed 800 MW and delivered 200 MW active power to the connected AC grids before the fault. After the fault occurred, all of the three MMCs in the MTDC system were blocked immediately to stop the short-circuit current. Meanwhile, L3 was cut off to isolate the fault area. It can be seen in Fig. 6a that the DC bus voltage reduced from about 700 kV to zero in no more than 2 ms, leading to a large spike of the arm current of MMC, as shown in Fig. 6b, which exceeded the safety value of 1500 A. With the conventional valve blocking method, the fault current can be cleared quickly after the fault is detected. However, the main

Table 1 Simulation parameters

Parameters	Value
rated power	1000 MW
AC grid voltage	375 kV
DC bus voltage	± 350 kV
total SM number per arm	480
redundant number per arm	40
arm inductor (L)	115 mH
SM capacitor (C)	12 mF
sampling frequency	10 kHz

advantage of this method is that floating capacitors in MMC discharge though voltage balancing resistance in SM after valve blocking, in Fig. 6c. As a result, the MMC station has to recharge all the capacitors after fault clearance, which cost a long time, and then restore DC bus voltage.

The simulation results of the proposed method in this paper are shown in Fig. 7. It can be seen that the DC bus voltage drops quickly after the fault, while the DC current increases sharply to >3000 A, which doubles to the normal value, in about 600 μ s. As a result, the converter stations are blocked immediately after the arm currents exceed the upper limit protection value, which is 2 kA, to protect the expensive IGBTs and capacitors, while L3 was cut off to isolate the fault area. With the converter blocked, the fault current reduced to zero rapidly, as shown in Fig. 7b, and the module capacitor voltage gradually decreases and begins to diverge due to the parameter difference and load loss.

Aiming at balancing the capacitor voltages and avoiding cutting off the connection of AC grid, the converter restarts with a certain delay, confirming the clearance of the fault current, as introduced in Section 3. Within this period, MMC1 and MMC2 operate as STATCOMs; thus, the converters are controllable and the module capacitor voltages are rebalanced at the rated value stably, which is 1600 V, as shown in Fig. 7d. It should be noted that an inrush DC current exists at the de-blocking moment, due to the voltage differences among the sub-modules in six arms. However, the peak value of inrush current was lower than the safety threshold of the switching devices, without damage to the system safety. During this period, the DC bus voltage and current were controlled to zero so that the fault area could be isolated without high-voltage DC breakers. In the simulation, the fault isolation was completed at $t=0.55$ s, and the system resumed with an 80 ms delay at $t=0.63$ s.

What is more, it can be seen that the transferred power of MMC1 reduces from about 800 to 400 MW and the capacitor voltages increase from 1450 to about 1550 V, because of the DC bus voltage variation under a DC voltage droop control.

5 Conclusion

A DC fault ride-through method including converter-level and system-level protection strategies for full-bridge MMC-based MTDC systems is proposed in this paper. With this method, the converter is blocked as soon as short circuit occurs to clear the fault current. After the clearance of the fault current, the converter re-runs as two parallel star-cascaded STATCOMs and the DC bus voltage is controlled to be zero; thus, the fault area could be cut off without expensive high-voltage DC breakers, significantly reducing the cost of converter stations. Moreover, the system could restore quickly after fault isolation, because there is no need to trip AC breakers and all converters are controllable during the fault period. All capacitor voltages are controlled to a rated value; thus, the problem of voltage divergence after valve blocking in practical MMC applications can also be avoided. Simulations in PSCAD demonstrate the effectiveness of the proposed strategy.

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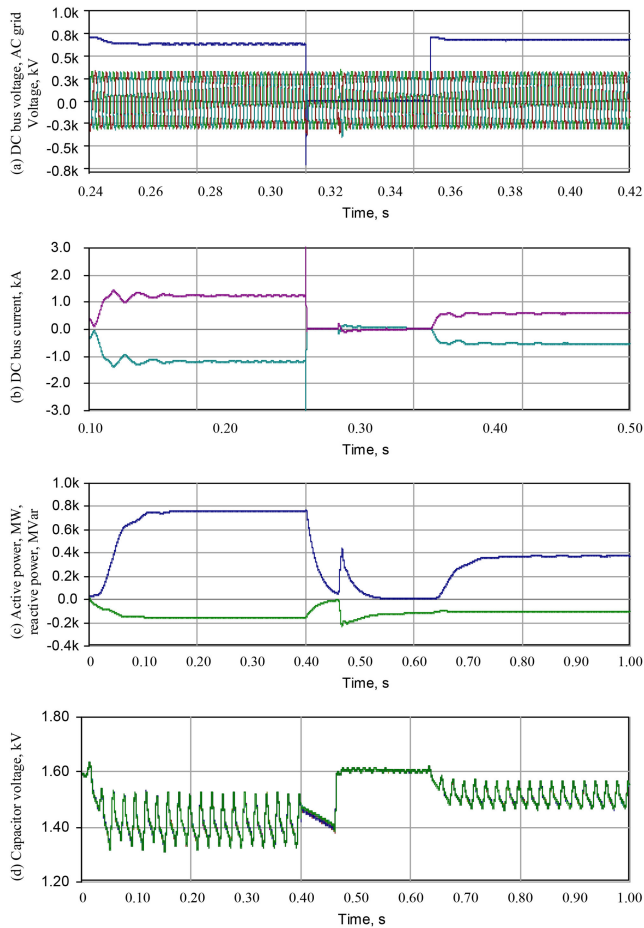


Fig. 7 Simulation results with the proposed method

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