Decoupled Modeling and Control of the Modular Multilevel Converter

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***Abstract*—The modular multilevel converter (MMC) has become a very popular topology in the field of HVDCs. However, the MMC control strategies still inherit from traditional two-level voltage source converter, in which the DC voltage regulation relies on an AC current control loop. In this paper, according to the specific energy storage characteristic of the MMC sub-module capacitors, a decoupled control strategy is proposed which can independently control the AC and DC loops. This strategy not only has a faster response of DC voltage regulation, but also has DC current control capability which avoids overcurrent/oscillation. In addition, a new average-value model is further designed to reflect the energy storage and control decoupling features of MMC. Effectiveness of the proposed control strategy and accuracy of the proposed model are both verified by simulation results.**

Keywords–HVDC; MMC; Simulation Model; Control Strategy; Decoupled Modeling

I. INTRODUCTION

The modular multilevel converter, due to its distinctive features such as modularity, scalability and high-quality voltage waveform, has attracted widespread attention in the fields of renewable power generation, high-voltage direct current (HVDC) power transmission, and industrial motor drives [1]-[2], etc.

Different control strategies affect MMC in both steady and dynamic characteristics. So far, most of the DC voltage control strategies used in MMC is similar to traditional two-level voltage source converter (VSC), in which the converter DC voltage has to be regulated by the absorbed active power from the AC side [3]-[5]. In order to control the DC voltage, the absorbed power from AC side should be adjusted firstly, charging or discharging the SM capacitor, and finally affecting the DC voltage, presenting a slow dynamic response [6]-[9].

However, the MMC topology is essentially different from the two-level VSC. The power transfer between the AC and DC sides is actually buffered by the sub-module (SM) capacitors in MMC, as shown in Fig. 1. Thus, it is not necessary to wait for the active power transferring from AC side to DC side. MMC could regulate the DC voltage or AC voltage directly by extracting the energy from the SM capacitor, which can be referred to as the AC-DC energy decoupling feature.

The traditional control method does not take into account this special decoupling feature of MMC, wasting the dynamic performance advantages caused by MMC's energy storage

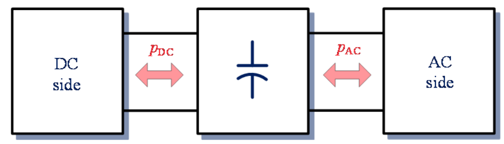

Fig. 1. Power flow between AC side and DC side of MMC

capability. Thus, by utilizing this power storage characteristic, a decoupled control strategy is proposed in this paper, which can independently control DC voltage with a much faster response.

In addition, in order to fit on the proposed energy decoupling control strategy, the corresponding simulation model is required. At present, the simulation model of MMC can be divided into four types: detailed model (DM), sub-module equivalent model (Also known as traditional detailed model, TDM), arm average model, and converter average model. Detailed model uses a lot of semiconductor switch models (e.g. IGBT) to establish a MMC simulation model. Although it has accurate simulation results, but it is extremely slow and not suitable for large-scale HVDC research [10]. The sub-module equivalent model has been proposed in reference [11]-[12], where the semiconductor switching device is equivalent to a variable resistor. This model cannot reflect the characteristics into the sub-module, but it is faster than detailed model. In order to further speed up the simulation, reference [13] proposed arm average model, which assume that all sub-modules on the same arm are exactly the same, so that an arm can be simplified as a voltage source. For the study of HVDC, it only concerned about the external electrical characteristics of MMC. Therefore, literature [14]-[15] proposes the converter average model, ignoring internal features of MMC.

Nevertheless, even though many average-value models have been proposed for MMC to accelerate the simulation speed, but they cannot reflect the decoupling feature of MMC at all. Therefore, a new average-value model is further proposed in this paper, which not only applicable to the normal operation of the MMC, but also to the case of short-circuit faults on the DC side.

The rest of the paper is organized as follows. The mathematic model of MMC is presented in Section II. The energy decoupling control strategy is discussed in Section III. And a new simulation model based on energy decoupling is carried out in Section IV. Finally, the effectiveness of proposed strategy and model is validated by simulation

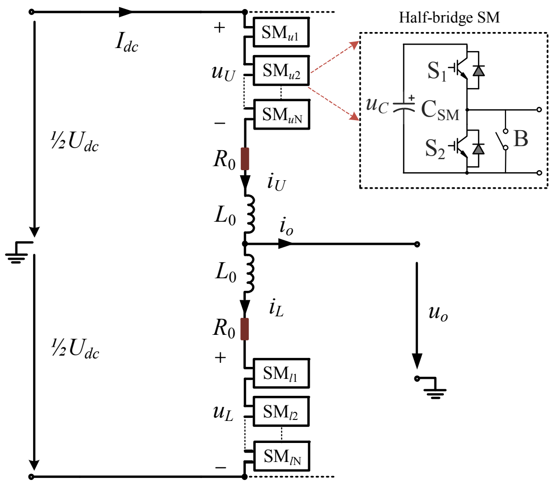

Fig. 2. The circuit structure of one phase in MMC

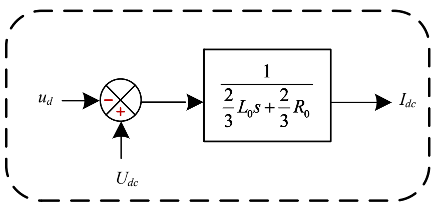

Fig. 3. Block diagram of DC side model

results in Section V. Conclusions are summarized in Section VI.

II. Topology and Mathematic Model of MMC

The circuit structure of one phase in MMC is shown as Fig. 2. Each phase contains two arms, and each arm includes N SMs with an arm inductance L_0 and a resistance R_0. U_{dc} and I_{dc} are the voltage and current of the DC lines, and u_o, i_o are AC output voltage and current of this phase, respectively. u_U, i_U and u_L, i_L represent the voltages and currents of the upper and the lower arm, respectively. According to Kirchhoff's voltage law, the mathematic model of MMC can be obtained as

$$u_L + u_U = u_d = U_{dc} - 2R_0 i_c - 2L_0 \frac{di_c}{dt} \tag{1}$$

$$u_L - u_U = 2u_e = 2u_o + R_0 i_o + L_0 \frac{di_o}{dt} \tag{2}$$

where, u_d is the sum of voltages of upper and lower arm, i_c is circulating current and u_e is defined as internal electromotive force of MMC, which can be presented as follow equations

$$i_c = \frac{1}{2}(i_L + i_U) \tag{3}$$

$$u_e = U_e \cos(\omega t) \tag{4}$$

where U_e is amplitude of the voltage.

Eq. (1)-(2) show that U_{dc} and u_o can be controlled independently by u_d and u_e, respectively, which reflects the decoupling feature of DC voltage and AC voltage in MMC.

Assume that the ripple of circulating current has been completely suppressed by control, that is

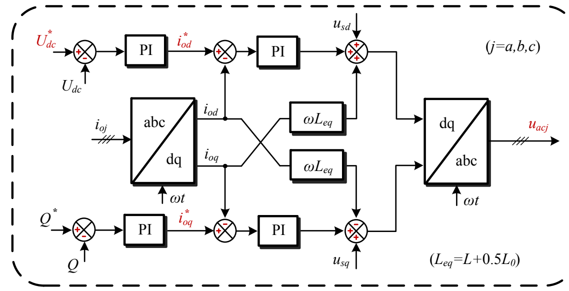

Fig. 4. Traditional control strategy of MMC

$$i_c = \frac{I_{dc}}{3}. \tag{5}$$

By observing MMC from the DC circuit loop, combing Eq. (5) and Eq. (1), and then transforming into the complex frequency domain, the DC side model of MMC can be expressed as

$$u_d(s) + \left(\frac{2}{3}R_0 + \frac{2}{3}sL_0\right) I_{dc}(s) = U_{dc}(s). \tag{6}$$

This model can be plotted in block diagram as shown in Fig. 3.

III. Decoupled Control Strategy of MMC

A. Traditional Control Strategy

Fig. 4 shows the traditional control strategy for MMC rectifier. In this method, the sum of the output voltage in the upper and lower arm is fixed. And U_{DC} is controlled by active current (i_{od}) control loop to adjust the absorbed power from AC side. On the other hand, there is no inner control capability of the DC current, which may result in temporary overcurrent or oscillations.

B. DC Side Control of proposed Strategy

As mentioned in section I, MMC is different from the two-level VSC. The MMC sub-module capacitors can be fully utilized to behave as power buffer, to decouple the DC and AC sides. Therefore the DC voltage can be independently controlled by Eq. (6).

According to Eq. (6) and Fig. 3, it can be found that DC current is affected by DC voltage and u_d, where u_d is a controllable variable. Therefore, an inner PI controller is incorporated to regulate the DC current, to limit overcurrent and to suppress the current oscillation, as shown in Fig. 5. I_{dc} is adjusted by PI controller to generate u_d. The controller is described as follow equation

$$u_d = U_{dc} - K_p\left(I_{dc}^* - I_{dc}\right) - K_i \int \left(I_{dc}^* - I_{dc}\right) dt \tag{7}$$

where K_p and K_i are parameters of PI controller, I^*_{dc} is DC current reference. U_{dc} is added here as a feed-forward to speed up response. From Eq. (6)-(7), the open-loop transfer function of DC current loop is derived as

$$G(s) = \left(K_p + \frac{K_i}{s}\right)\left(\frac{3}{2}\frac{1}{L_0 s + R_0}\right) = \frac{3}{2}\frac{K_p s + K_i}{L_0 s^2 + R_0 s}. \tag{8}$$

The appropriate K_p and K_i can be selected according to the DC current dynamic response requirements.

If there are any control requires for the DC voltage or active power, DC current control loop can be deal with an

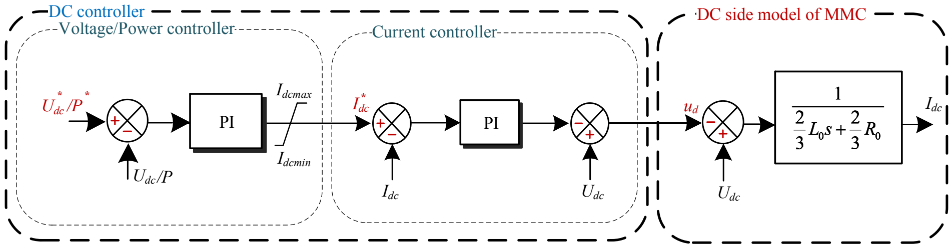

Fig. 5. DC control strategy

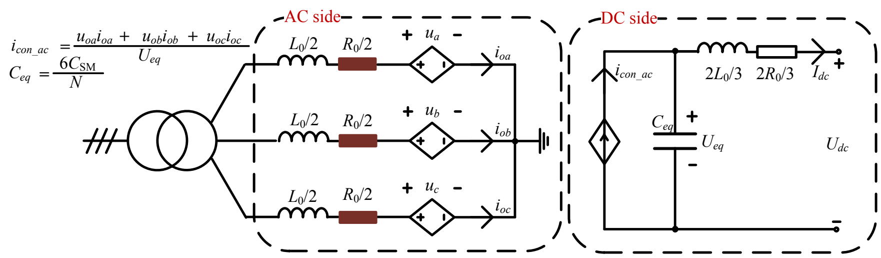

Fig.6. The traditional MMC simulation model

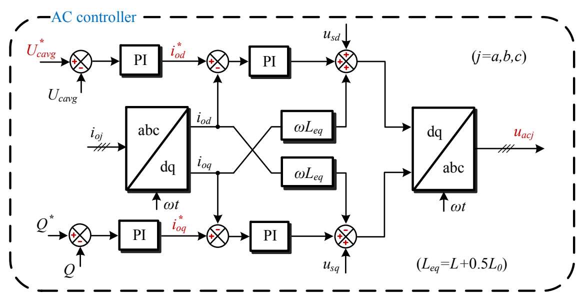

Fig. 7. Modified AC control strategy

inner loop. And DC voltage or active power can be controlled by outer loop with an additional PI controller. The overall control block diagram of DC side is shown in Fig. 5.

C. AC Side Control of proposed Strategy

The DC control strategy directly extracts the energy from the SM capacitor to output to the DC side, resulting in a decrease of capacitor voltage. Therefore it is necessary to stabilize the SM capacitor voltage by AC control strategy.

As shown in Fig. 7, the power balance of MMC between AC and DC sides now are achieved by keeping stable energy storage in the sub-module capacitors. This is realized by the AC control loop by setting the capacitor voltage as control variable instead of U_{dc}, ensuring that the capacitor voltage is stabilized at the rated value. This control approach fully decouples the DC and AC control variables, thus it can speed up the response of the DC voltage control.

IV. The Simulation Model based on Energy Decoupling

The traditional MMC simulation model is shown in Fig. 6 [15], in which the MMC sub-module capacitors are equivalent into the DC link. Increasing/decreasing the DC voltage has to charge/discharge this capacitance at first, resulting in a very slow control response. The dynamic characteristics of proposed DC control strategy cannot be reflected in this model. Thus it have to build a new simulation model to fit on the proposed decoupling strategy.

A. Basic Simulation Model

For shortcomings of the traditional simulation model, the proposed model is improved by adding the storage link of MMC, as shown in Fig. 8. The capacitor voltage U_{eq} reflects the energy stored in the MMC. The two controlled current sources reflect the part of MMC energy that injecting into DC side and drawing from AC side.

Since the model structure has been changed, the working principle compared to the traditional counterpart is also different. AC control signal of three controlled voltage sources u_a, u_b and u_c is calculated by follow equations

$$u_a = u_{aca}\frac{U_{eq}}{2} \tag{9}$$

$$u_b = u_{acb}\frac{U_{eq}}{2} \tag{10}$$

$$u_c = u_{acc}\frac{U_{eq}}{2} \tag{11}$$

where u_{aca}, u_{acb}, u_{acc} is the three-phase AC modulation signal, U_{eq} is the voltage of equivalent capacitor C_{eq}. And the current of the controlled current source, i_{con_ac} and i_{con_dc}, are given by the Eq. (12) and Eq. (13) respectively.

$$i_{con\_ac} = \frac{P_{AC}}{U_{eq}} = \frac{\sum_{j=a,b,c} u_j i_{oj}}{U_{eq}} \tag{12}$$

$$i_{con\_dc} = \frac{P_{DC}}{U_{eq}} = \frac{u_d I_{dc}}{U_{eq}}. \tag{13}$$

According to the energy conservation law, the energy stored in 6N SMs of the MMC should be equal to the energy stored in the equivalent capacitor which can be presented by

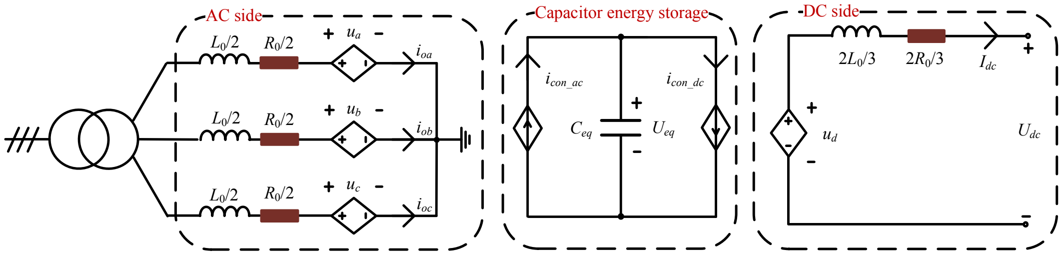

Fig.8. Basic simulation model based on energy decoupling

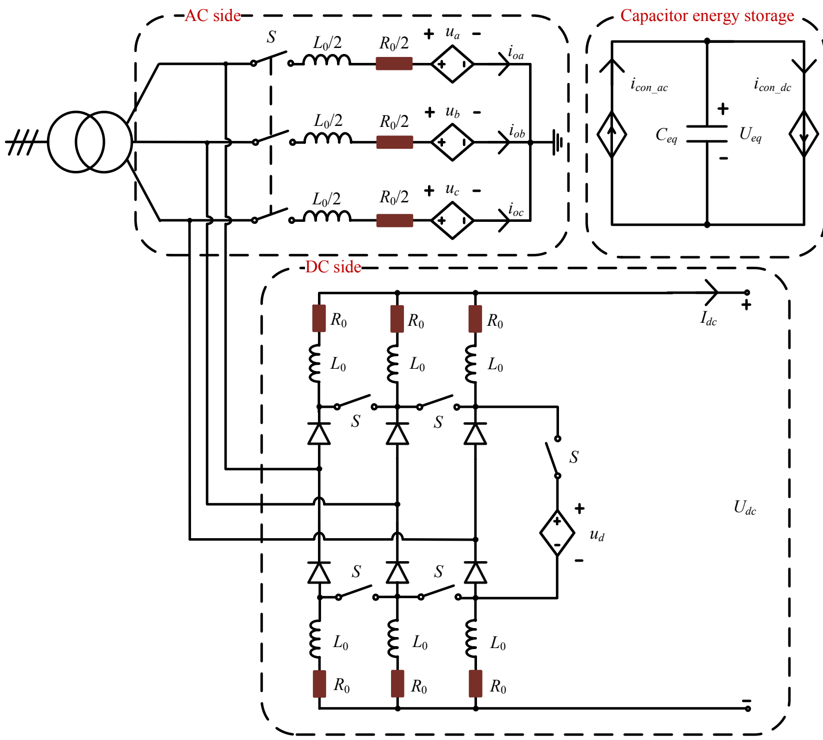

Fig.9. Improved model considering SM blocking

$$6N\frac{1}{2}C_{SM}u_c^2=\frac{1}{2}C_{eq}U_{eq}^2 \tag{14}$$

where u_c is the voltage of SM capacitor. Due to the average value of u_c is U_{dc}/N and U_{eq} is approximately equal to U_{dc} when the MMC operates at steady state. Eq. (14) can be rewritten and the equivalent capacitor is

$$C_{eq}=\frac{6C_{SM}}{N}. \tag{15}$$

The proposed model reflects the energy decoupling feature between AC and DC side power. The voltage of the AC/DC side can be controlled independently by the AC modulation signals u_{aca}, u_{acb}, u_{acc} and the DC modulation signal u_d, respectively.

B. An Improved Model Considering SM Blocking

The basic model considers the energy decoupling features of MMC, thus it is possible to control the DC voltage directly. However, it only can simulate normal operation state of MMC. When DC faults occur, the basic model is no longer applicable. To deal with this problem, this part proposes an improved model considering SM blocking situation.

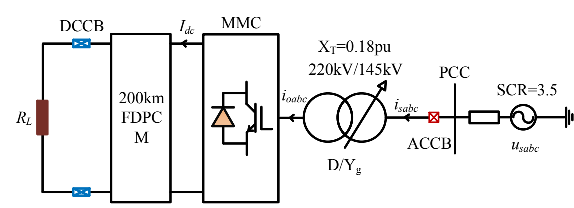

Fig. 10. Simulation model in PSCAD

TABLE I Simulation parameters I

Parameter	Value
The number of SMs in one arm	N=200
DC side voltage	U_{dc}=1000kV
AC side voltage (RMS)	U_{sabc}=220kV
Transformer ratio (D/Yg)	220kV/145kV
Rated voltage of SM capacitor	U_C(rated)=5kV
capacitance of SM capacitor	C_{SM}=5000μF
AC voltage frequency	f=50Hz
Arm inductance	L_0=29mH
Modulation method	NLM
Capacitor voltage balance method	Sorting algorithm

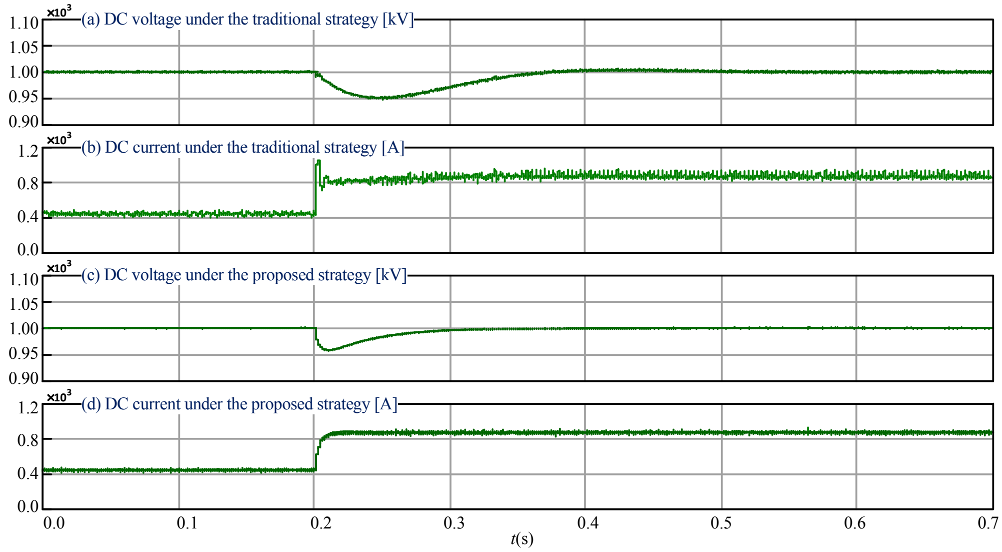

Fig. 11. DC voltage and current waveforms under traditional and proposed control strategy

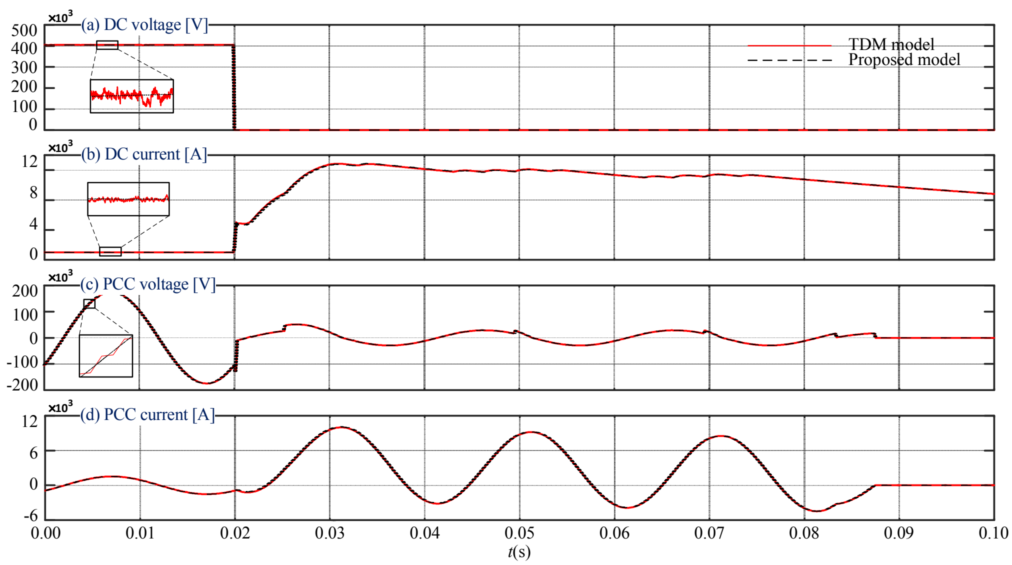

Fig. 12. Voltage and current on DC side and PCC under TDM model and the proposed improved model

As shown in Fig. 9, when the MMC at normal operation state, all switches S are closed, so that all diodes are cut off due to withstand the negative voltage, and the model structure is the same as basic model in Fig. 8. When short circuit faults occur on the MMC DC side, all switches S are opened and the entire circuit becomes a diode rectifier, which is consistent with the actual situation when the SM is blocked.

TABLE II Simulation parameters II

Parameter	Value
DC side voltage	U_{dc}=400kV
Rated voltage of SM capacitor	U_C(rated)=2kV
capacitance of SM capacitor	C_{SM}=10000μF

V. Simulation Results

A. Simulation Verification for Proposed Control Strategy

The proposed decoupled control strategy is verified by simulation in PSCAD. The simulation model is shown in Fig. 10 and the simulation parameters are given in TABLE I.

At 0.0s, MMC worked as a rectifier, and the load resistance on DC side (R_L) is 2500Ω with the active power 400MW. At 0.2s, R_L is reduced to 1250Ω, with load power increasing to 800MW. DC voltage and current waveforms under traditional and proposed control strategy are plotted in Fig. 11.

As can be seen from Fig. 11, DC voltage adjustment speed is slow under the traditional control strategy with an obvious oscillation in the DC current. Compared to traditional strategy, the proposed energy decoupling control method not only has the faster control speed for DC voltage, but also can suppress the oscillation of DC current. This simulation results illustrate that the energy decoupling control method has better dynamic performance compared to the traditional one.

B. Simulation Verification for Proposed Simulation model

The traditional detailed model (TDM) takes into account the characteristics of each sub-module and has high accuracy which has been verified in reference [12]. Therefore, the correctness of the simulation model proposed in this paper can be proved by comparison with the standard TDM in PSCAD. Some simulation parameter changings are shown in TABLE II, and other parameters are same as TABLE I. The simulation results of comparison are plotted in Fig. 12.

Before 0.02s, MMC operated normally, and it can be seen that the voltage and current waveforms of the proposed model coincide with TDM very well. But note that the proposed model is essentially an average model, thus it cannot reflect the high frequency harmonics caused by the switching action in the MMC. This feature has illustrated in zooming zone, Fig. 12.

At 0.02s, bipolar short circuit faults occur on DC side with the DC voltage dropping rapidly from 400kV to zero. Meanwhile both DC and AC current increased quickly, causing SMs blocking, so that MMC operating as an uncontrolled diode rectifier. The voltage on the AC side is reduced but does not become zero. It because that the short-circuit current generates a voltage across the transformer leakage inductance as well as the MMC arm inductance. It is also due to the presence of inductance, there is an overlap angle of commutation in PCC voltage waveform.

At 0.08s, the disconnecting command was triggered, and the AC circuit breaker (ACCB) cuts off the circuit at the next current zero crossing point. After cutting off the AC-side circuit, the DC current is gradually decreased.

From Fig. 12, the proposed average model accurately follows the standard TDM model throughout the whole process.

VI. CONCLUSIONS

Control strategy has significant impacts to the MMC dynamic performance. This paper firstly points out the difference between MMC and traditional two-level converter in structure, and then proposes a new control strategy based on energy decoupling features of MMC. The proposed strategy not only has a faster response of DC voltage regulation, but also has DC current control capability. In order to fit on the proposed energy decoupling control strategy, a new average-value model is also proposed in this paper, which has taken into both the steady states and fault-blocking states of MMC. The effectiveness of proposed strategy and the accuracy of proposed model are both validated by simulation results in PSCAD, presenting good prospects in HVDC applications.

ACKNOWLEDGMENT

This research was supported by Young Elite Scientists Sponsorship (YESS) Program by CAST and National Natural Science Foundation of China (51477034).

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