Fault Characteristic Analysis and Simulation of Power Electronic Transformer Based on MMC in Distribution Network

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***Abstract*—The topology structures of input stage, isolation stage and output stage of power electronic transformer in distribution network were introduced. Using the type of half bridge modular multilevel converter sub module, the dual active bridge and three-phase inverter as the research object, the simulation model of 10kV distribution network power electronic transformer was built based on PSCAD simulation platform. The theoretical analysis and simulation verification of the possible fault types in power electronic transformer were carried out, including AC input side faults, MV DC side faults, LV DC side faults and power switch component faults, etc. The overvoltage and overcurrent levels of power electronic transformer under various faults were classified and tallied. The fault types which have greater impact on power electronic transformer in distribution network were pointed out.**

Keywords-power electronic transformer; fault characteristic; simulation analysis; overvoltage; overcurrent

I. INTRODUCTION

Power electronic transformer (PET), also known as solid state transformer (SST), which not only can replace the traditional transformer to improve the intelligent level of power grid, but also can be used as the energy router to realize power transmission and transformation between multi-source and multi-load. Since the concept of PET was proposed, widespread attention at home and abroad has been raised. However, the current research mainly focuses on the design of topology [1, 2], control strategy [2-4], new power devices [5], application scopes [6-8] and energy optimization [9, 10], but few studies on the fault characteristics and protection technology of PET. As the interface between the MV and LV distribution network, the fault of PET has a serious impact on the power grid and users, so it is significant to study the fault characteristics and protection technology of PET.

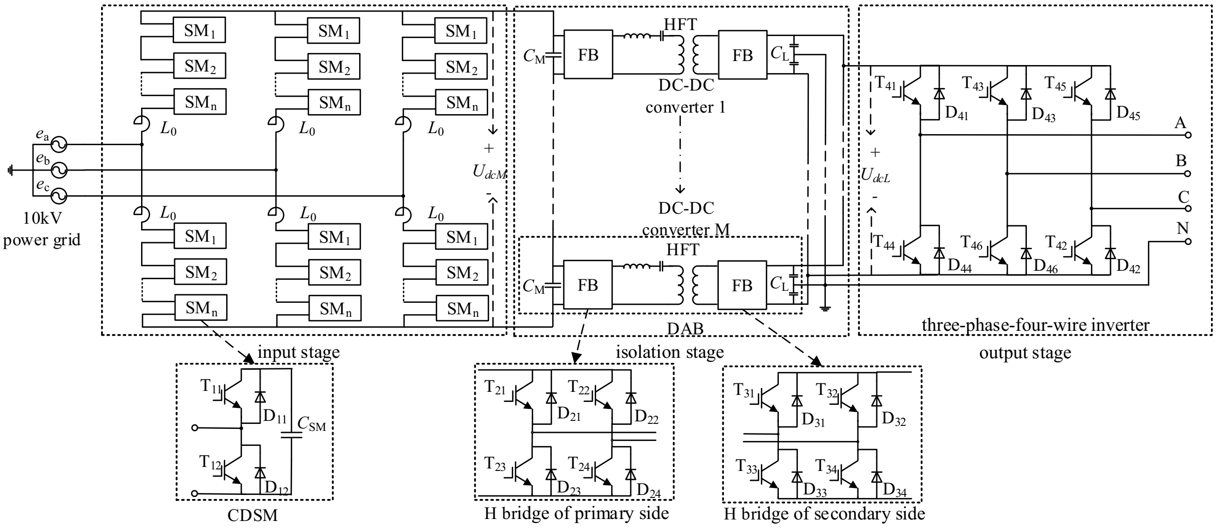

Figure 1. Topology of PET based on MMC

The MMC type of PET simulation model was built based on the PSCAD simulation platform in this paper. The different types of fault characteristics were analyzed in theory and simulation, including AC input side faults, MV DC side faults, LV DC side faults and the main power switch faults in different positions of PET, etc. The overvoltage and overcurrent levels of power electronic transformer under various faults were classified and tallied. The results of the fault analysis in this paper can provide the basis for the corresponding protection configuration and the selection of lightning arrester as well as insulation coordination.

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II. TOPOLOGY OF PET

Refer to [11], topology of PET based on MMC in this paper, which is divided into input stage, isolation stage and output stage, is shown in Fig 1. The input stage adopts the half bridge sub module MMC structure. The isolation stage adopts dual active bridge (DAB), including high frequency transformer (HFT) and primary and secondary H full bridge (FB). The output stage adopts three-phase-four-wire inverter, whose neutral line is grounded by the LV DC capacitors.

III. ANALYSIS OF FAULT CHARACTERISTICS

A. AC Input Side Faults

There are three-phase short circuit fault F_{11}, three-phase short circuit grounding fault F_{12}, single-phase grounding fault F_{13}, two-phase short circuit fault F_{14}, two-phase short circuit grounding fault F_{15} in AC input side. The grounding design of AC input side adopts the grounding transformer which is widely used in the MV AC distribution network [12]. The related contents of the grounding transformer can be referred to [13].

The single-phase grounding fault is taken as an example to be analyzed in depth since it's the most frequently occurring fault type in power system. The equivalent circuit diagram of MMC is shown in Fig 2. The ua, ub and uc in the figure indicate the instantaneous value of the input phase voltage on the AC side; uap, ubp and ucp indicate the three phase upper bridge arm voltage; uan, ubn and ucn indicate the three phase lower bridge arm voltage; iap, ibp and icp indicate the three phase upper bridge arm current; ian, ibn and icn indicate the three phase lower bridge arm current; Udc indicates the DC voltage of MMC.

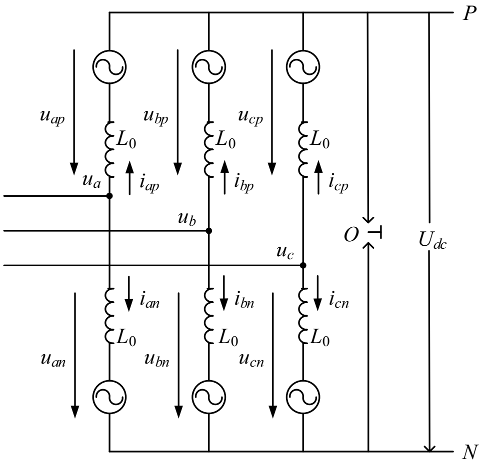

Figure 2. Equivalent circuit diagram of MMC

Taking phase A as an example, the mathematical model of MMC can be expressed as:

$$\begin{cases} u_a = \sqrt{2}U\sin(\omega t) \\ u_{ap} = \dfrac{U_{dc}}{2} - \sqrt{2}U\sin(\omega t) \\ u_{an} = \dfrac{U_{dc}}{2} + \sqrt{2}U\sin(\omega t) \end{cases} \tag{1}$$

Under normal operation, the voltage of the positive and negative poles of MV DC bus to the imaginary neutral point can be expressed as:

$$\begin{cases} U_{PO} = u_{ap} + u_a = \dfrac{U_{dc}}{2} \\ U_{NO} = -u_{an} + u_a = -\dfrac{U_{dc}}{2} \end{cases} \tag{2}$$

When the phase A is connected to the ground, the voltage of ua becomes zero. Therefore, the voltage of positive and negative poles to the imaginary neutral point after the fault can be expressed as:

$$\begin{cases} U'_{PO} = u_{ap} + u_a = \dfrac{U_{dc}}{2} - \sqrt{2}U\sin(\omega t) \\ U'_{NO} = -u_{an} + u_a = -\dfrac{U_{dc}}{2} - \sqrt{2}U\sin(\omega t) \end{cases} \tag{3}$$

According to (3), it is known that the voltages of MV DC positive and negative bus are sinusoidal, and the voltage between the positive and negative poles of MV DC bus is unchanged due to the synchronous fluctuation.

The single-phase grounding fault in AC input side was simulated under the simulation conditions: the rated power of PET was 2.5MW; the length of AC line was 6km; the line equivalent resistance and equivalent inductance were 0.263Ω/km and 1.108mH/km, respectively. In the simulation, the metal short circuit and grounding fault, whose short circuit contact resistance and grounding resistance were both 0.01Ω, were set at the middle of the AC line. The control strategy of MMC was constant DC voltage, and in the simulation the fault was triggered at 0.3 seconds. The simulation results are shown in Fig 3, and the fault characteristics are analyzed as follows: 1) after the single-phase grounding fault occurs, the fault phase voltage Ua is reduced to zero, and the voltages of healthy phase Ub and Uc rise to line voltage (about times of the phase voltage); the input line voltage does not change for PET, so the AC input current is constant; 2) the potential reference point of the DC system is changed due to the existence of the grounding transformer in AC side; the voltages of MV DC positive and negative bus are synchronous sinusoidal fluctuation; the voltage of MV DC bus is up to 1.81p.u. compared to the normal situation, which will test the insulation level of DC lines; however, the DC voltage between the positive and negative poles is kept unchanged, so it will not affect the isolation stage and output stage of the PET; 3) the zero sequence current loop is formed between the fault point and the grounding transformer, accompanied with the zero sequence current flowing through the grounding transformer increasing and the zero sequence voltage appearing.

Based on the above analysis, it is known that the system can work normally after the single-phase grounding fault occurs at the AC input side. The level of overvoltage and insulation coordination should be considered after the fault. In addition, for the grounding transformer, the current flowing through the neutral point is usually limited to a few seconds or usually 2 hours as the neutral point through the arc suppression coil grounding [12]. Therefore, the corresponding protection measures should be taken according to the current duration of neutral point of grounding transformer.

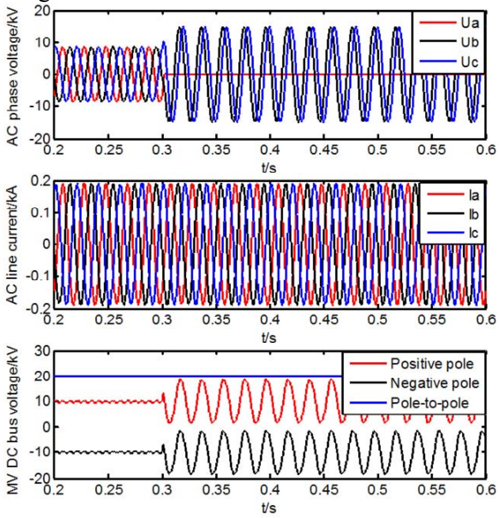

Figure 3. Waveforms for single-phase grounding fault in AC input side

The AC input line voltage G1, AC input peak line current G2, MV DC bus voltage G3, MV DC bus current G4, LV DC bus voltage G5, LV DC bus current G6 and MMC sub module capacitor voltage G7 were selected as the observations, whose base values at rated power are shown in TABLE I. The above five types of AC input side faults were simulated, and the overvoltage and overcurrent levels (p.u.) are shown in TABLE II. The "-" in the table indicates no overvoltage or overcurrent.

TABLE I. BASE VALUES OF VOLTAGE AND CURRENT AT RATED POWER

Observations	G_1	G_2	G_3	G_4	G_5	G_6	G_7
Base Values	10.5kV	0.204kA	±10kV	0.125kA	±0.375kV	3.333kA	2kV

TABLE II. OVERVOLTAGE AND OVERCURRENT LEVELS UNDER AC INPUT SIDE FAULTS

Faults\Observations	G_1	G_2	G_3	G_4	G_5	G_6	G_7
F_{11}	—	11.91	—	7.36	—	—	1.38
F_{12}	—	11.91	—	7.06	—	—	1.37
F_{13}	1.72	—	1.81	—	—	—	—
F_{14}	—	3.26	1.12	2.02	1.03	1.04	1.30
F_{15}	1.48	3.33	1.47	1.96	1.04	1.04	1.30

As can be seen from TABLE II, the interphase short circuit fault and the interphase short circuit grounding fault will result in serious overcurrent in AC side compared with single-phase grounding fault. The input overcurrent protection action should be triggered to disconnect circuit breaker (CB) of AC input side, and the MMC should be blocked so as to avoid excessive damage to the power switches caused by overcurrent in the bridge arms.

B. MV DC Side Faults

The fault types of the MV DC bus mainly include single-pole grounding fault F_{21}, pole-to-pole short circuit fault F_{22} and single-pole disconnection fault F_{23}. The positive and negative DC buses are similar in the analysis process under the single-pole grounding fault and the single-pole disconnection fault. In this paper, the positive DC bus was taken as an example to analyze, and the short circuit contact resistance and grounding resistance were both 0.01Ω.

The pole-to-pole short circuit fault was token as an example to analyze in this paper, which is the most serious fault type in MV DC side. The sub module discharge path of the DC side pole-to-pole short circuit fault is shown in Fig 4, and the single-phase equivalent model is shown in Fig 5. The UL, UC and UR indicates the voltage of bridge arm inductance, the equivalent voltage of sub module capacitor, the equivalent resistance voltage of discharge circuit, respectively.

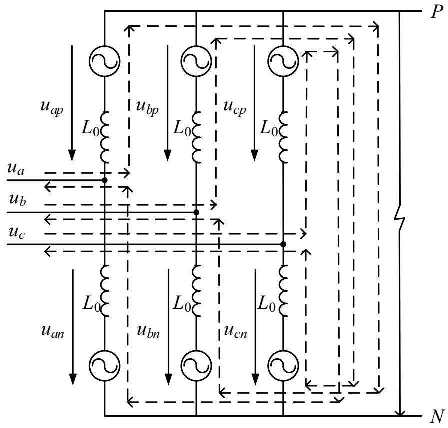

Figure 4. Sub module discharge circuit of MMC

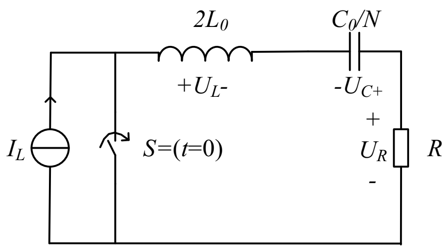

Figure 5. Single-phase equivalent circuit

According to the analysis of [14], the capacitor voltage and discharge current can be expressed as:

$$
\begin{cases} U_C = \dfrac{\omega_0 U_{dc}}{\omega} e^{-\delta t}\sin(\omega t+\beta) - \dfrac{N I_L}{\omega C_0} e^{-\delta t}\sin(\omega t) \\ I = \dfrac{U_{dc}}{2\omega L_0} e^{-\delta t}\sin(\omega t) + \dfrac{\omega_0 I_L}{\omega} e^{-\delta t}\sin(\omega t-\beta) \end{cases} \tag{4}
$$

$$
\delta = \frac{R}{4L_0} \tag{5}
$$

$$
\omega = \sqrt{\frac{N}{2L_0 C_0} - \delta^2} \tag{6}
$$

$$\omega_0 = \sqrt{\delta^2 + \omega^2} \tag{7}$$

$$\beta = \arctan \frac{\omega}{\delta} \tag{8}$$

As can be seen from (4), the discharge current after the fault is a process of vibration attenuation. As the current can be fed from AC input side into MV DC side in the case of MMC unblocked, the short circuit current after attenuation will eventually be stable at a certain value.

The simulation results of the pole-to-pole short circuit fault are shown in Fig 6, and the fault was triggered at 0.3 seconds. After the fault, the capacitor of the MMC sub module is rapidly discharged through the short circuit path of the DC side, so the voltages of the sub module and the DC bus are rapidly reduced to zero. The MV DC bus and the AC input side are seriously overcurrent, causing the power switches in the bridge arm subjected to huge electrical stress. The power transmission between the input stage and the isolation stage of PET will be terminated with the voltage of AC side input pulled down, which is similar to the three-phase short circuit fault in AC input side. Due to the pole-to-pole short circuit fault in the DC side, the MMC bridge arms and AC input line endure serious overcurrent. The sub module overcurrent protection should be opened and the CB of AC input side should be disconnected so as not to endanger the AC system.

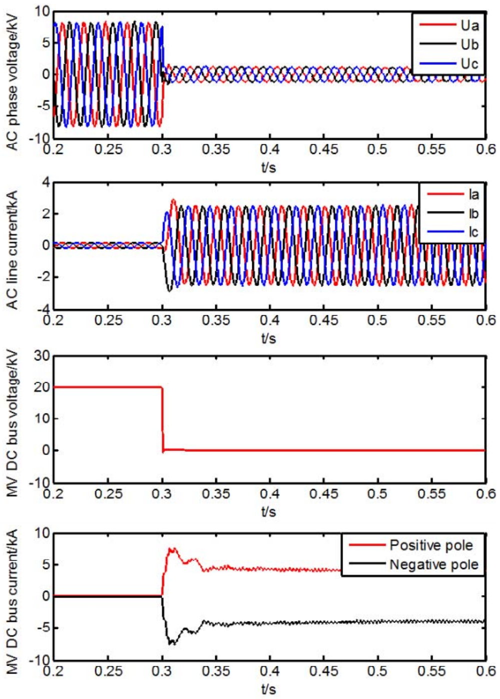

Figure 6. Waveforms for pole-to-pole short circuit fault in MV DC side

The overvoltage and overcurrent levels of the selected observations under the above three types of MV DC side faults are shown in TABLE III, and the base values have been given in TABLE I.

TABLE III. OVERVOLTAGE AND OVERCURRENT LEVELS UNDER MV DC SIDE FAULTS

Faults\Observations	**G_1**	**G_2**	**G_3**	**G_4**	**G_5**	**G_6**	**G_7**
F_{21}	2.15	3.79	2.13	5.60	1.04	1.04	2.00
F_{22}	—	14.36	—	60.40	—	—	—
F_{23}	1.08	—	1.06	—	—	—	1.10

In the case of single-pole grounding fault, the zero sequence current path is formed between the grounding transformer and the fault point, which causes overcurrent in AC input side and MV DC bus. At this time the MMC bridge arm overcurrent protection should be action to block MMC, and it is necessary to disconnect the CB of AC input side if the fault is permanent. Because of the constant DC voltage control of MMC, the DC bus voltage is kept constant after the single-pole disconnection fault. This type of fault is usually permanent, and the power transmission has been terminated so the CB of AC input side should be disconnected to maintain.

C. LV DC Side Faults

The LV DC side fault types are similar to those of MV DC side, which mainly include single-pole grounding fault F_{31}, pole-to-pole short circuit fault F_{32} and single-pole disconnection fault F_{33}. The three types of faults in LV DC side were simulated and analyzed, and the short circuit contact resistance and grounding resistance were both 0.01Ω. The overvoltage and overcurrent levels of the selected observations under the above three types of LV DC side faults are shown in TABLE IV, and the base values have been given in TABLE I.

TABLE IV. OVERVOLTAGE AND OVERCURRENT LEVELS UNDER LV DC SIDE FAULTS

Faults\Observations	**G_1**	**G_2**	**G_3**	**G_4**	**G_5**	**G_6**	**G_7**
F_{31}	1.04	2.60	1.13	4.80	2.08	9.37	1.21
F_{32}	—	17.50	—	13.76	—	14.95	1.59
F_{33}	1.07	—	1.05	—	1.04	—	1.09

The short circuit path in the LV DC bus is formed after the pole-to-pole short circuit fault, which causes the voltage dropping rapidly and produces serious overcurrent in the MV DC bus and AC input side. At this time the LV DC overcurrent protection should be operated before the current is higher than the allowable value. Single-pole disconnection fault immediately terminates the power transmission, resulting in a short period of DC voltage fluctuations without serious overvoltage and overcurrent. However, with the power transmission termination of output stage, the CB of LV DC side needs to be disconnected to maintain. If there are DC loads in the LV DC bus, PET can still run normally. When a single-pole grounding fault in LV DC side occurs, the fault location forms a short circuit path with the capacitors because the LV DC side adopts the way that the capacitors are grounded in neutral point. The voltage of grounding DC bus is rapidly reduced to zero as the grounding side capacitors discharged quickly with serious overcurrent, which will result the voltage of healthy DC bus up to 2 p.u.. The discharge current of the LV DC side can also cause overcurrent in MV DC side and AC input side. The voltage of LV DC bus is only supported by the capacitors on the healthy bus side, so the voltage of the capacitors increased to 2 p.u.. It is necessary to configure the overvoltage protection of the LV DC capacitors, so as to avoid damage caused by overvoltage. The simulation results of the single-pole grounding fault in LV DC side are shown in Fig 7, and the fault was triggered at 0.3 seconds.

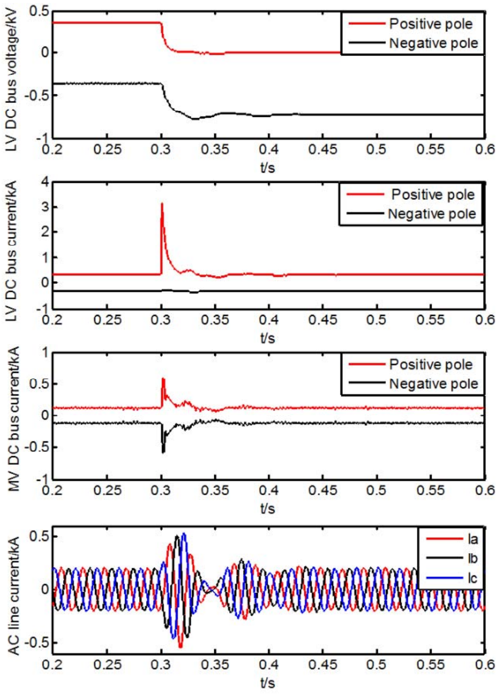

Figure 7. Waveforms for single-pole grounding fault in LV DC side

D. Power Switch Faults

The main fault types of power switch are short circuit fault and open circuit fault. The fault location includes the sub module of MMC, the primary and secondary H bridge of HFT and the inverter of output stage. The following fault types were selected in accordance with the number of components specified in Fig 1: T_{11} or D_{11} short circuit F_{41}, T_{11} open circuit F_{42}, T_{12} open circuit F_{43}, D_{11} open circuit F_{44}, D_{12} open circuit F_{45}, T_{21} or D_{21} short circuit F_{46}, T_{21} open circuit F_{47}, T_{21} and D_{21} open circuit F_{48}; T_{31} or D_{31} short circuit F_{49}, T_{31} and D_{31} open circuit F_{410}, D_{31} open circuit F_{411}; T_{41} or D_{41} short circuit F_{412}, T_{41} open circuit F_{413}, D_{41} open circuit F_{414}. The overvoltage and overcurrent levels of the selected observations under the above power switch faults are shown in TABLE V, and the base values have been given in TABLE I.

TABLE V. OVERVOLTAGE AND OVERCURRENT LEVELS UNDER POWER SWITCH FAULTS

Faults\Observations	G_1	G_2	G_3	G_4	G_5	G_6	G_7
F_{41}	1.07	2.16	1.22	3.52	1.04	1.05	1.47
F_{42}	—	1.09	1.08	1.54	—	—	1.09
F_{43}	—	1.02	1.06	1.50	—	—	1.07
F_{44}	1.04	1.27	1.23	1.67	—	—	1.52
F_{45}	—	1.96	1.25	1.94	1.03	1.03	1.72
F_{46}	—	17.60	1.08	5.80	—	34.86	1.99
F_{47}	—	—	—	—	—	1.71	—
F_{48}	—	—	—	—	—	1.71	—
F_{49}	—	16.32	—	10.56	—	93.18	1.65
F_{410}	—	1.09	—	1.15	—	1.57	—
F_{411}	—	1.07	—	1.14	—	1.52	—
F_{412}	—	15.88	1.11	19.55	1.52	25.03	1.38
F_{413}	—	1.54	—	2.56	1.34	3.74	1.12
F_{414}	—	1.27	—	1.50	1.11	1.94	1.04

As shown in TABLE VI, T_{21} or D_{21} short circuit, T_{31} or D_{31} short circuit and T_{41} or D_{41} short circuit cause serious overcurrent in the AC input side, the MV DC bus and the LV DC bus. The essence of this type of fault is that it will cause short-through of converter leg, resulting in a short circuit path to discharge rapidly in the connected capacitors or DC bus. T_{11} or D_{11} short circuit will form the discharge circuit of the MMC sub module capacitor, resulting in the voltage of the sub module decreasing rapidly, which will cause the overvoltage fluctuation of the MV DC bus. The short circuit faults of power switch usually develop rapidly, so it is difficult to realize the protection in time by the method of software protection and necessary to adopt the method of hardware protection, such as the short circuit and over temperature protection of IGBT.

Compared with the short circuit faults, the open circuit faults may not cause the system to be shut down immediately, and it will run for a period of time under the abnormal condition. However, the open circuit faults may cause other normal power switches in the PET to withstand overvoltage and overcurrent stresses.

IV. CONCLUSION

According to the possible fault types of PET based on MMC, including AC input side faults, MV DC side faults, LV DC side faults and power switch faults, the theory and simulation analysis were carried out, and the fault characteristics of PET were pointed out in this paper.

- The interphase short circuit faults and the interphase short circuit grounding faults will result in serious overcurrent. The single-phase grounding fault will form a zero sequence current loop between the fault location and the AC input side grounding transformer. Since the input line voltage is constant, the PET is still running for some time. However, the insulation level of the MV DC bus should be considered, and the corresponding protection measures should be taken according to the current duration of neutral point of grounding transformer.
- The single-pole grounding fault in MV DC side will also form a zero sequence circuit between the fault location and the grounding transformer, which will cause overcurrent in the AC input side and MV DC bus. Pole-to-pole short circuit is the most serious type of fault in MV DC side. The MMC sub module capacitors are discharged rapidly through the short circuit path accompanied with serious overcurrent.

- The single-pole grounding fault and pole-to-pole short circuit fault in LV DC side will both form the discharge circuit of support capacitors in LV DC side, which will cause serious overcurrent phenomenon. In addition, single-pole grounding fault will also make the voltage of capacitors on the healthy DC bus side up to 2 p.u..
- T_{21} or D_{21} short circuit, T_{31} or D_{31} short circuit and T_{41} or D_{41} short circuit will cause short-through of converter leg, resulting in serious overcurrent in AC input side, MV DC side and LC DC side. The open circuit faults may cause other normal power switches in the PET to withstand overvoltage and overcurrent stresses.

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