A non-invasive Fault Location Method for Modular Multilevel Converters under Light Load Conditions

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Abstract—This paper proposes a non-invasive fault location method for modular multilevel converters (MMC) considering light load conditions. The prior-art fault location methods of the MMC are mostly developed under full load conditions. However, it is revealed that the faulty arm current will be suppressed to be unipolar when the open-circuit fault happens on the submodule switch under a light load. This leads to the capacitor voltage of the healthy and faulty submodules rising or falling with the same variations, increasing the difficulty of fault location. The proposed approach of injecting the second-order circulating current will rebuild the bipolar arm current of the MMC and enlarge the capacitor voltage deviations between the healthy and faulty SMs. As a result, the fault location time is significantly shortened. The simulations are carried out to validate the effectiveness of the proposed approach, showing that the fault location time is reduced to 1/6 compared with the condition without second-order circulating current injection.

Keywords—Circulating current injection, Fault location, Light load, Modular multilevel converter, Open-circuit fault.

I. INTRODUCTION

The modular multilevel converter (MMC) is one of the most promising multilevel converters in high-voltage applications thanks to its modularity, superior AC performance, and scalability to meet any voltage level [1]. The half-bridge (HB) submodule (SM) has the simplest structure and lowest power losses, becoming the most popular SM for the MMC. In general, there are even hundreds of identical SMs and massive power switching devices in the MMC, which have a high malfunction rate threatening the reliability of the MMC [2]. Therefore, it is necessary to detect and locate the fault quickly so that further measurements can be taken to protect the MMC from being broken down.

Open-circuit and short-circuit are two typical faults of power semiconductor switches. The short-circuit fault detection is easier and faster to be realized and is usually embedded into the commercial gate driver circuit [3]. However, the open-circuit fault would not cause obvious damage immediately [4]. Once an open-circuit fault happens in one or multiple SMs, the output performance of the MMC will deteriorate because the actual output voltage of the faulty SM does not match the required output modes. Moreover, the capacitor in a faulty SM will be overcharged if the faulty SM is not detected and isolated in time. Then the capacitor voltage will be increased exceeding the safe threshold and, at last, breaking down the whole MMC system [5].

The existing methods of faulty SM location for the MMC are mainly classified into two types, i.e., the hardware-based and software-based methods. The hardware-based method can realize the fault location within short time. In [6], the voltage sensor is employed to measure the arm voltage and detect the faulty arm. However, it can only be used to locate the defective arm, not the faulty SM. Two voltage sensors are used in each SM in [7] to accurately locate the faulty SM. One voltage sensor is parallel with the capacitor to realize the voltage balancing control, and the other is paralleled to the lower power switch to detect the SM output voltage and be compared with the reference switching signal. However, the cost of the voltage sensors is significantly increased since the number of SMs is usually large. In [8], the two voltage sensors are reduced to one in each SM and the voltage sensor is re-configured to be parallel connected with the upper power switch. The cost is not increased, but the extra voltage observer is required to acquire the capacitor voltage, making the control more complex. Moreover, the above voltage observer will lose the accuracy with the SM capacitance aging, negatively affecting the normal MMC operation. Therefore, concerning the system cost and operation robustness, the hardware-based approaches to faulty SM locations in [7] and [8] are not the best choice.

The software-based methods are proposed for the HBSM MMC without changing the converter structure or sensor configuration. There are three types of software-based methods, namely signal-based methods, model-based methods, and data-based methods. In the signal-based methods [9], the detected signal is compared with the reference signal, and the fault can be located once the signal deviation exceeds the threshold and last for a certain time. In model-based methods [10], voltage or state observers are demanded to compare the estimated and actual values. Besides, an appropriate threshold is required but difficult to satisfy the requirements under different power levels. In the data-based methods [11], the data feature of the SM capacitor voltage is extracted to detect the error data and derive the error possibility. This method depends on the capacitor voltage deviations between the faulty and healthy SMs. Above all, the aforementioned software-based approaches perform well under the rated power level but are not well evaluated under light load conditions.

The arm current will be distorted to be unipolar or even zero by the SM open-circuit faults when the MMC operates under light load [12]. In this case, the capacitor voltage of the healthy and faulty SMs will vary similarly, and the voltage deviations are quite small or even disappear. This will cause the failure of the existing software-based methods since they are all achieved by extracting the capacitor voltage difference between the healthy and faulty SMs. In this paper, a software-based fault location method is proposed for the MMC under light load conditions to accelerate the fault location speed. First, the mechanism of the unipolar arm current under fault is analyzed. Second, the circulating current injection is enabled after the faulty arm is detected so that the arm current recovers to the bipolar variations. The amplitude and phase of the reference second-order circulating current are selected for
different types of faults. Finally, the simulations are performed to verify the effectiveness of the proposed methods.

II. OPEN-CIRCUIT FAULT OF MODULAR MULTILEVEL CONVERTERS

A. Configuration of MMC

Fig. 1 shows the configuration of the three-phase MMC, where each phase consists of upper and lower arms. Each arm contains one arm inductor and \( N \) identical HBSMs. In each HBSM, \( u_{\text{HBSM}} \) represents the capacitor voltage. \( u_{\text{SM}} \) is the output voltage of the SM, having + and 0, namely the insert and bypass states, respectively. \( i \) is the numbering of each SM in each arm, having \( i=1,\ldots,N \). \( u_x \) denotes the summation of HBSM output voltage in the \( y \) arm of phase \( x \), where \( x=a, b, c, y=a, b, c, \ldots \). The arm voltage and current of each arm are expressed as

\[
\begin{align*}
    u_y &= \frac{U_m}{2} \sin(\omega t + \varphi_y), \\
    i_y &= \frac{I_m}{3} \sin(\omega t + \varphi_y + \varphi)
\end{align*}
\]

where only DC and fundamental components are included in the arm currents with the higher-order currents suppressed. According to the power balancing between the DC and AC sides, the DC and AC current have the relations of

\[
I_{\text{dc}} = \frac{3m}{4} I_m \cos \varphi
\]

B. Open-circuit Fault

Fig. 2 shows two types of open-circuit faults on \( T_1 \) and \( T_2 \). In Fig. 2(a), the SM cannot be inserted under \( i_{\text{ap}}<0 \) when the upper switch \( T_1 \) is faulty, and the arm current can only flow through the freewheeling diode \( D_2 \). Therefore, the faulty SM cannot be discharged under \( i_{\text{ap}}<0 \), leading to over-voltage of the SM capacitor. In Fig. 2(b), the SM cannot be bypassed by \( T_2 \) under \( i_{\text{ap}}>0 \) with open-circuit occurrence on \( T_2 \). In this case, the arm current flows via the freewheeling diode \( D_1 \) and charges the SM capacitor. As a result, the capacitor voltage of the faulty SM keeps increasing. This will also cause over-voltage of the faulty SM.

Based on the above analysis, the open-circuit fault of \( T_1 \) or \( T_2 \) will both cause an abnormal increase of the corresponding SM capacitor voltage. Also, as the faulty SM cannot output the voltage required by the switching signal, the arm voltage is distorted, causing circulating and arm current distortion. This fault of arm current or circulating current is used to detect the faulty arm or phase. But the specific faulty SM must be located by distinguishing its own capacitor voltage or other information inside each SM.

III. IMPACT OF LIGHT LOAD ON IGBT OPEN-CIRCUIT FAULT LOCATION

This section clarifies the impact of the system parameters and operation conditions on the faulty arm current. It emphasizes the high risk of the unipolar arm current under the light load condition, which has the negative impact on the fault location of the MMC.

A. Unipolar arm current under \( T_1 \) and \( T_2 \) fault

Assume that the faulty SM exist in SM1 of the upper arm. Under the open-circuit fault of \( T_1 \), SM1 cannot be inserted but only be bypassed by the diode \( D_2 \) with \( i_{\text{ap}}<0 \). Then the actual arm voltage is

\[
\begin{align*}
    u_{\text{ap},f1} = \begin{cases} 
        \left| \frac{u_{\text{ap}} - S \cdot U_C}{i_{\text{ap}}^{*}} \right| & i_{\text{ap}} < 0 \\
        \frac{U_C}{i_{\text{ap}}} & i_{\text{ap}} > 0
    \end{cases} (3)
\end{align*}
\]

where \( S \) is the reference switching function of the faulty SM, having \( S=0.1 \).

Fig. 3 illustrates the equivalent circuit under \( T_1 \) fault. The faulty voltage deviation under \( T_1 \) fault is given by

\[
\Delta u_{\text{ap},f1} = u_{\text{ap}} - u_{\text{ap},f1} = \begin{cases} 
    \frac{S \cdot U_C}{i_{\text{ap}}^{*}} & i_{\text{ap}} < 0 \\
    0 & i_{\text{ap}} > 0
\end{cases} (4)
\]

Here we assume that the faulty SM capacitor voltage is not changed too much and is still limited to the safety zone without over-voltage before it is located.

In Fig. 3(a), the faulty arm current \( i_{\text{ap},f1} \) is composed of the normal component \( i_{\text{ap}}^* \) and the faulty component \( i_{\text{ap},f1} \), which is given as

\[
\begin{align*}
    i_{\text{ap},f1} &= \Delta i_{\text{ap},f1} + i_{\text{ap}}^* \quad i_{\text{ap},f1} < 0
\end{align*}
\]

In Fig. 3(c), \( \Delta u_{\text{ap},f1} \) is evenly distributed on the two arm inductors. Then the faulty current component under \( T_1 \) is

\[
\Delta i_{\text{ap},f1} = \frac{S \cdot U_C}{2L} dt > 0 \quad i_{\text{ap}} < 0
\]

Since the faulty component in (6) is positive, the negative part of the arm current might be suppressed under the \( T_1 \) fault.

If the following prerequisite is satisfied, the negative part of the arm current will be canceled out, leading to the unipolar faulty arm current with only the nonnegative part.
As a result, all the SMs cannot be discharged and have the same voltage variations as the faulty SM. This will cause the failure to locate the faulty SM quickly.

To make sure that (8) is satisfied in each switching period, the left term is approximated as

$$I_m = \frac{U_{dc}}{(2 - m \cos \varphi)} \frac{1}{N_f L_s}$$  

(10)

In case of the multiple faulty SMs, $N_f$ refers to the number of SMs with $T_1$ fault. Then (10) is written as

$$I_m = \frac{U_{dc} \cdot N_f}{(2 - m \cos \varphi)} \frac{1}{N_f L_s}$$  

(11)

which means that, if the AC current amplitude is lower than the right side, the faulty arm current will become nonnegative. As a result, all the SMs cannot be discharged and have the same voltage variations as the faulty SM. This will cause the failure to locate the faulty SM quickly.

Similar to the analysis of $T_1$ fault, the equivalent circuit of $T_2$ fault is illustrated in Fig. 4. The condition where the unipolar arm current occurs under $T_2$ fault is:

$$I_m = \frac{U_{dc} \cdot N_f}{(2 + m \cos \varphi)} \frac{1}{N_f L_s}$$  

(12)

where $N_f$ is the number of SMs with $T_2$ fault. When the AC current amplitude is lower than the right term of (12), there will be a high possibility of nonpositive arm current.

The criterion in (11) and (12) are derived with certain simplifications. It shows that whether the faulty arm current will become unipolar is affected by various factors, i.e., the

\[ \Delta u_p \leq \max \left( \left| \Delta i_p \right| \right) = \frac{I_p - I_{dc}}{3} i_p < 0 \]  

(7)

Combined with (2) and (6), the criterion in (7) is given as

$$\int (S)dt = \left( \frac{1}{2} \frac{m \sin (\omega t)}{m \cos \varphi} \right) \frac{2I_m L_s}{U_c}$$  

(8)

To make sure that (8) is satisfied in each switching period, the carrier and switching frequency.

Combining (8) and (9), the condition to generate the unipolar arm current is approximately expressed as

$$I_m = \frac{U_{dc}}{(2 + m \cos \varphi)} \frac{1}{N_f L_s}$$  

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cases are carried out under the fixed DC bus voltage, and the corresponding parameters are changed based on Table I. Under the different number of SMs, the corresponding value of \( I_m \) indicates the maximum values of the currents which would cause the unipolar arm current. Higher values of \( I_m \) curve mean higher risk of unipolar arm current.

From Figs. 5-8, the following conclusions can be drawn. The \( I_m \) threshold is increased when the arm inductance and modulation index are decreased, and also increased when the power factor and number of faulty SMs are increased. In Figs. 5-8, the \( I_m \) threshold of \( T_1 \) fault is higher than \( T_2 \). In other words, the faulty arm current of \( T_1 \) fault is easier to be unipolar under the same AC current level. Also, with the increase of the total SM quantity, the \( I_m \) threshold decreases, meaning that lower SM voltage is easier to trigger the unipolar arm current.

### IV. PROPOSED FAULT LOCATION METHOD

#### A. Mechanism of the proposed method

The existing software-based fault location methods are realized by distinguishing the faulty SM capacitor voltage from the healthy SM capacitor voltages. However, under the unipolar faulty arm current, the faulty and healthy SM capacitor voltage will rise or fall similarly. For example, the faulty arm current becomes nonnegative under \( T_1 \) fault, then all of the SM capacitors cannot be discharged and the faulty SM is hidden. Similarly, \( T_2 \) fault cannot be located under non-positive faulty arm current. Therefore, to ensure that all of the existing approaches can be well used without being degraded by the faulty unipolar arm current, the point is to produce bipolar arm current under \( T_1 \) or \( T_2 \) fault.

#### B. Proposed solution to unipolar arm current

This paper proposes the second-order circulating current injection approach as a solution to unipolar faulty arm current. The injected circulating current can rebuild the arm current to be bipolar so that the capacitor voltage deviations between the healthy and false SMs will be generated or enlarged under light load conditions.

Fig. 9 shows the implementation of the proposed fault location methods based on the circulating current injection. In Fig. 9(a), the fault location approach is performed in three steps.

**Step 1:** The fault diagnosis is performed to detect the faulty arm and type of faults, i.e., \( T_1 \) fault or \( T_2 \) fault. The approach in [13] can be directly used according to the characteristics of faulty circulating current.

**Step 2:** The circulating current injection is only enabled after the arm fault is detected and the criterion in (11) or (12) is satisfied. The injected circulating current is given as

\[
i_{inj} = I_{2nd} \sin (\alpha + \varphi_{2nd})
\]

where \( I_{2nd} \) and \( \varphi_{2nd} \) are the amplitude and phase of the second-order circulating current, respectively. Specifically, the phase is determined by the fault type, i.e., \( T_1 \) or \( T_2 \) type, which is

\[
\varphi_{2nd} = \begin{cases} 
\frac{\pi}{2} & \text{For } T_1 \text{ fault} \\
\frac{\pi}{2} & \text{For } T_2 \text{ fault}
\end{cases}
\]

In this way, the missing negative/positive interval of the faulty arm current could be compensated to the maximum extent. The amplitude of the injected second circulating current is decided by the current rating of the power device. Then the circulating current control in [14] is adopted to inject the second order circulating current; however, the injected circulating current cannot follow the reference value due to the false switching of the faulty SM. Nevertheless, the point is producing bipolar arm current rather than the accurate circulating current track. Note that the healthy phase should also be compensated by the circulating current so that the DC link current will not be too severely distorted.

**Step 3:** After the circulating current is injected, the fault location is conducted, as shown in Fig. 9(b), where the classic method in [4] is adopted. The capacitor voltage of the detected SM is compared with the average voltage of the rest SMs \( u_{off} \) and the calculated voltage deviation \( \Delta u \) is compared with the given threshold \( u_{th} \). If \( u_{off} > u_{th} \) lasts for \( \Delta T \), then SMf can be detected as faulty SM and bypassed by the outer bypass breaker. \( \Delta T \) is set as 5 ms in this paper.

### V. VERIFICATIONS

The simulation verifications are carried out in Simulink/ Matlab on a three-phase MMC with the parameters shown in Table I. The carrier phase shift-based pulse width modulation approach is adopted to realize the voltage balancing for individual SM. The SM1 in the upper arm of phase a is assumed to be faulty. The simulation results are presented for the \( T_1 \) and \( T_2 \) fault under the power level \( P = 750 \) kW (0.1 p.u.) with \( I_m = 50 \) A. According to the given criterion in (11) and
Fig. 10. Faulty SM location under $T_1$ fault and light load, without second-order circulating current injection. (a) SM capacitor voltage. (b) Arm currents and circulating current. (c) SM1 capacitor voltage and reference value. (d) Comparison with threshold. (e) Fault flag of SM1.

Table II Fault location time under light load condition

| Fault case | Circulating current injection |
|------------|------------------------------|
|            | Without | With  |
| $T_1$ fault| 130 ms  | 17 ms |
| $T_2$ fault| 135 ms  | 20 ms |

In Fig. 13, the second-order circulating current is injected at $t=0.1$ s, and the arm current becomes bipolar. Then the faulty SM capacitor voltage rises fast because it cannot be bypassed under positive arm current. As a result, $\Delta u_i$ rises quickly to surpass the threshold, and the fault is located at $t=0.11$ s. The fault location time is shortened to 20 ms.

Table II compares the fault location time with and without circulating current injection for the two types of faults. It justifies the effectiveness of the proposed approach of second-order circulating current injection.

**VI. CONCLUSION**

This paper proposes a non-invasive fault location method for MMC to accelerate the fault location process under the light load operation. The arm current is suppressed to be unipolar when the open-circuit fault happens on the SM switch under light load. The approach of injecting the second-order circulating current will rebuild the bipolar arm current and enlarge the capacitor voltage deviations between the healthy and faulty SMs. As a result, the fault location time is...
significantly shortened. The simulations are carried out to validate the effectiveness of the proposed approach, presenting that the fault location time is reduced to 1/6 compared with the condition without using the second-order circulating current injection.

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