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A new approach to open-circuit fault diagnosis of MMC sub-module

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ABSTRACT
This paper is concerned with the open-circuit fault diagnosis of MMC sub-module. To estimate the arm current accurately in normal and fault cases, a sliding mode observer is designed based on Lyapunov theory. The residual between the estimation and measurement of the arm current will increase rapidly in fault cases, which can facilitate not only the open-circuit fault detection of the arm but also the identification of the fault type. Based on the open-circuit fault analysis of MMC sub-module, the fault feature is defined and calculated for the fault location of sub-module, which can remarkably promote the efficiency of fault diagnosis. To test the performance of the proposed approach, some simulation experiments are carried out and can confirm the effectiveness of the proposed approach for the open-circuit fault diagnosis of MMC sub-module.

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Fault diagnosis; modular multilevel converter; MMC; open-circuit fault

1. Introduction
Benefited from the advantages of modularity, extensibility and high-quality output, modular multilevel converter (MMC) has been widely used in high-voltage and high-power application fields since its birth (Deng et al., 2018; Gao et al., 2018; Lesnicar & Marquardt, 2003; Yang, Lin, Zheng, & You, 2013; Yang, Zheng, Xue, Lin, & Chen, 2016).

In practical engineering, the amount of MMC sub-module (SM) can reach up to several hundreds or thousands, which will make the fault of SM more likely arise in the complex and harsh circumstances (Xu, Xie, Yuan, & Yan, 2017; Zhang et al., 2017). The fault of SM mainly includes the short circuit fault (SCF) and open circuit fault (OCF) of power electronic switch (PES) (Yang, Qin, & Saedifard, 2016). In the case of SCF, the relay protection unit of the circuit will cut off the overcurrent to prevent further deterioration of the fault, so that the SCF will cause the OCF in the end. In the case of OCF, the fault circuit cannot be shut down immediately, so that it could result in more serious distortion on voltage and current, and finally damage the MMC system. Therefore, the open-circuit fault diagnosis of MMC sub-module is of critical importance for the reliable and stable operation of the MMC system, which will make the fault detection of MMC sub-module not only complex but also costly (Picas, Zaragoza, Pou, & Ceballos, 2017). Thus the software-based fault detection method is more prevalent in the fault diagnosis of MMC sub-module, including model-based method, signal processing-based method and knowledge-based method, among others. For example, a mixed kernel support tensor machine (MKSTM) has been proposed for the diagnosis and location of open-circuit fault of MMC sub-module in Li, Liu, Zhang, Chai, Xu (2019), where MKSTM is employed to train and classify the data samples extracted from AC current and internal circulation current in normal and open-circuit fault cases. In Yin, Duan, Shen, and Qu (2018), a novel method has been presented to diagnose the open-circuit fault of modular five-level inverter, where stacked sparse auto-encoder is applied to extract the fault feature from MMC. Though the fault can be detected more accurately by using the deep neural network-based classifier, it can only be located to one arm of the bridge rather than a specific sub-module. Besides, the diagnosis result is susceptible to parameter variation of the network. In Deng, Chen, Khan, and Zhu (2015), a Kalman filter-based method has been put forward to detect the open-circuit fault of MMC sub-module by comparing the state estimation with its measurement, while the diagnosis system is very complex and time-consuming. In Li, Zhao, Li, Zhang, and Zhai (2014), the detection of several kinds of faults can be completed by using the ratio of the theoretical

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and practical voltage values on the capacitor of SM. In Shao, Wheeler, Clare, and Watson (2013), a sliding mode observer-based method has been proposed for the open-circuit fault detection of MMC sub-module, where the disturbances from sampling error and parameter variation can be successfully avoided. Nevertheless, the methods in current literature are subjected to some intractable issues, such as heavy computational load and redundant measurement of capacitor voltage (Gao, Gu, Ma, & Zhang, 2020; Jiang & Bakran, 2019; Kiranyaz, Gastli, Ben-Brahim, Al-Emadi, & Gabbouj, 2019; Li et al., 2020). In summary, up to now, there is still much room to further improve the performance of the open-circuit fault diagnosis of MMC sub-module.

To shorten such a gap, a new approach is proposed in this paper to overcome the above-mentioned problems on the open-circuit fault diagnosis of MMC sub-module. The main contributions of this paper can be summarized as threefold. (1) The diverse cases on open-circuit fault of MMC sub-module are analysed according to the switch states and different directions of arm current. (2) A sliding mode observer is exploited to estimate the arm current, whose residual between estimation and measurement can not only be used to detect the open-circuit fault of the arm but also to identify the type of switch fault. Thus the fault sub-module can be located efficiently depending on the fault feature calculated by using capacitor voltage and arm current. (3) Some simulation experiments are carried out on the open-circuit fault diagnosis of MMC sub-module and can verify the effectiveness of the proposed approach.

The remainder of this paper can be outlined as follows. Section 2 presents the preliminary on modular multilevel converter. Section 3 details the open-circuit fault analysis of MMC sub-module in different cases. In Section 4, the proposed approach is elaborated for the open-circuit fault diagnosis of MMC sub-module. In Section 5, some simulation experiments are implemented to verify the effectiveness of the proposed approach. Finally, the paper is concluded in Section 6 and some future works are also provided.

2. Preliminary on modular multilevel converter

As sketched in Figure 1, a typical three-phase MMC is composed of six arms, each of which consists of one arm inductor (\( L \)) and several identical SMs. The circuit of SM has also been shown in Figure 2, which mainly contains one DC capacitor (\( C \)) and a half-bridge, which is composed of two complementary IGBT switches (\( T_1 \) and \( T_2 \)) and their anti-parallel diodes (\( D_1 \) and \( D_2 \)) (Deng et al., 2018). Note that \( L \) and \( C \) denote not only the inductor and capacitor components but also their values in this paper.

![Figure 1. Circuit model of three-phase MMC.](image1)

![Figure 2. Circuit model of MMC sub-module.](image2)

Note that each phase unit of MMC is comprised of two arms, i.e. the upper arm and the lower arm, whose currents are denoted as \( i_{uj} \) and \( i_{lj} \) (\( j = a, b, c \)) respectively. Besides, \( U_{dc} \) stands for the DC input voltage of MMC, and \( u_j \) indicates the AC output voltage of phase \( j \). Normally, the output voltage of \( i \)th SM (denoted as \( u_{sni} \), \( i = 1, 2, \ldots, 2n \)) can be expressed as follows:

\[
 u_{sni} = S_i u_{ci} 
\]

where \( u_{ci} \) denotes the capacitor voltage of \( i \)th SM; \( S_i \) is the corresponding switching function that depends on the
state of MMC sub-module. $S_1 = 1$ holds when the SM is in the ‘ON’ state, i.e. $T_1$ is conducted and $T_2$ is blocked. Otherwise, $S_1 = 0$ holds when the SM is in the ‘OFF’ state, i.e. $T_1$ is blocked and $T_2$ is conducted. Based on Kirchhoff’s voltage law, the voltage equation on each phase of MMC can be expressed as follows Wang et al. (2018):

$$L \frac{di_{uj}}{dt} = \frac{U_{dc}}{2} - u_{uj} - u_j,$$

$$L \frac{di_{ij}}{dt} = \frac{U_{dc}}{2} - u_{ij} + u_j,$$

where $u_{uj}$ and $u_{ij}$ represent respectively the voltage sums of SMs on the upper and lower arms of phase $j$, and can be calculated by

$$u_{uj} = \sum_{i=1}^{n} u_{smi} = \sum_{i=1}^{n} S_i u_{ci},$$

$$u_{ij} = \sum_{i=n+1}^{2n} u_{smi} = \sum_{i=n+1}^{2n} S_i u_{ci}.$$

### 3. Open-circuit fault analysis of MMC sub-module

The open-circuit fault of MMC sub-module can be divided into $T_1$ fault and $T_2$ fault, and the SM can be in ON ($S_1 = 1$) or OFF ($S_1 = 0$) state when any of the faults occurs. In this section, the open-circuit faults of MMC sub-module are discussed in terms of different cases encountered.

#### 3.1. Open-circuit fault of switch $T_1$

In the case of $T_1$ fault, the output voltage of SM (denoted as $u_{sm}$) is identical with the case of normal state if the SM is in OFF state.

In contrast, the output voltage of SM depends on the state of SM current (denoted as $i_{sm}$) if the SM is in ON state. To be specific, if $i_{sm} > 0$ (see Figure 2 for the reference direction of the current), the capacitor $C$ can be charged by the SM current through diode $D_1$ as normal, so that the output voltage of SM is the capacitor voltage, i.e. $u_{sm} = u_c$. Otherwise, as shown in Figure 3, if $i_{sm} < 0$, the capacitor cannot be discharged through switch $T_1$ due to its open-circuit fault, but the SM current through diode $D_2$ can be motivated. Thus the output voltage of SM is 0 rather than the expected $u_c$, i.e. $u_{sm} = 0$.

It is worth mentioning that the output voltage of SM cannot be used to diagnose the open-circuit fault of SM except the case that the SM is in ON state and $i_{sm} < 0$. That is because the capacitor $C$ cannot be discharged in this case, so that the output voltage of SM is obviously different from the normal case.

#### 3.2. Open-circuit fault of switch $T_2$

Similar to above analysis of $T_1$ fault, the open-circuit fault of $T_2$ will not affect the normal operation of SM when it is in ON state.

When SM is in OFF state, as shown in Figure 4, the SM current will flow through diode $D_2$ as usual in the case of $i_{sm} < 0$, so the output voltage of SM is 0, i.e. $u_{sm} = 0$. But in the case of $i_{sm} > 0$, because of the open-circuit fault of $T_2$, the SM current cannot flow through switch $T_2$ but charge the capacitor $C$ through diode $D_1$. In this case, the output voltage of SM is $u_c$ other than normal value 0, i.e. $u_{sm} = u_c$.

It is also worth noting that the output voltage of SM will stay in normal state except the case that SM is in OFF state and $i_{sm} > 0$. Obviously, the output voltage of SM will significantly differ from its normal value as a result of the abnormal charging of capacitor $C$, which can be employed for the diagnosis of open-circuit fault in the sections below.

For clarity, the output voltages of SM in different states are illustrated in Table 1 for both normal and fault cases.

#### 4. Open-circuit fault diagnosis of MMC sub-module

In this paper, the open-circuit fault diagnosis of MMC sub-module mainly include two steps, i.e. fault detection and fault location (Figure 4).
In the step of fault detection, the residual between the estimated upper/lower arm current and its measurement is calculated and compared with a threshold. Based on the comparison result, not only the open-circuit fault of arm can be detected on account of whether the threshold is exceeded, but also the type of fault (T1 or T2 fault) can be identified in terms of the sign of residual. Then, the fault SM can be determined according to the fault feature calculated by using capacitor voltage and arm current, which can be affected by the abnormally charged capacitor in fault cases.

### 4.1. Fault detection

In this step, a sliding mode observer is exploited to estimate the arm current of MMC. Take the upper arm for example. Denote $\hat{i}_{\text{ij}}$ as the estimation of upper arm current on one phase of MMC, and define sliding surface $S = \tilde{i}_{\text{ij}} - i_{\text{ij}}$. Omitting the arm resistance, the sliding mode observer can be built based on Equation (2) as follows:

$$\frac{d\hat{i}_{\text{ij}}}{dt} = -\frac{1}{L} \left( \sum_{i=1}^{n} S_i u_{ci} - \frac{U_{dc}}{2} + u_j \right) + K \text{sgn}(i_{\text{ij}} - \hat{i}_{\text{ij}}),$$

where $K$ is the gain of the observer; $\text{sgn}$ indicates the sign function; and other variables and parameters of Equation (6) can be explained as mentioned above.

To obtain the stability condition of the sliding mode observer, a Lyapunov function is selected as follows:

$$V = \frac{1}{2} S^T S.$$  

Obviously, the sliding mode observer can converge to the real value when $V = S^T S < 0$, i.e. $V = (\hat{i}_{\text{ij}})[-K \text{sgn}(\hat{i}_{\text{ij}})] = -K|\hat{i}_{\text{ij}}| < 0$, where $\hat{i}_{\text{ij}} = i_{\text{ij}} - \tilde{i}_{\text{ij}}$ is defined as the residual of upper arm current. Thus the estimation of the sliding mode observer will approach the measurement value when $K > 0$.

In fault cases, the real state of switch is not consistent with its expected state, which results in the deviation between the real arm current and its expectation. Thus, the state equation of upper arm can be expressed as follows:

$$\frac{d\hat{i}_{\text{ij}}}{dt} = -\frac{1}{L} \left( \sum_{i=1}^{n} S_i u_{ci} - \frac{U_{dc}}{2} + u_j \right) + f_1,$$

where $f_1$ stands for the deviation caused by SM fault, whose absolute value can vary between 0 and $(n/L)u_{ci}$ in accordance with the switch states of the $n$ SMs and the direction of arm current. Without loss of generality, we take $n = 1$ in the following discussion.

It is worth pointing out that the following conclusions can be deduced based on MMC circuit (Guo et al., 2017), i.e. $0 < f_1 < (1/L)u_{ci}$, $\tilde{i}_{\text{ij}} = i_{\text{ij}} - \hat{i}_{\text{ij}} > 0$ in T1 fault; and $-(1/L)u_{ci} < f_1 < 0, \tilde{i}_{\text{ij}} = i_{\text{ij}} - \hat{i}_{\text{ij}} < 0$ in T2 fault. From the difference between Equations (8) and (6), we get

$$\frac{d\hat{i}_{\text{ij}}}{dt} = f_1 - K \text{sgn}(i_{\text{ij}} - \hat{i}_{\text{ij}}).$$

In the case of T1 fault, we hope the residual will become large enough for sensitive fault diagnosis. With this consideration and Lyapunov theory in mind, we expect

$$\frac{d\hat{i}_{\text{ij}}}{dt} = f_1 - K \text{sgn}(i_{\text{ij}} - \hat{i}_{\text{ij}}) > 0.$$  

Therefore, considering the conclusion mentioned above, the gain of the observer should satisfy the following condition, i.e. $0 < K < f_1$. Similarly, the gain of the observer should satisfy the condition $0 < K < -f_1$ in the case of T2 fault. In summary, to ensure the stability of the sliding mode observer in normal case and the sensitivity of fault diagnosis in fault cases, the gain of the sliding mode observer should satisfy

$$0 < K < \frac{1}{L}u_{ci}.$$  

It should be highlighted that the fault arm can be detected according to whether the absolute of the residual exceeds the threshold $\tilde{i}_{\text{ij}}$, and lasts for a period of time. Besides, the fault type of SM, i.e. T1 fault or T2 fault, can also be identified depending on whether $\tilde{i}_{\text{ij}} > 0$ or not, which will significantly improve the efficiency of fault location in the following section.

### 4.2. Fault location

After the identification of fault arm and fault type, the specific fault SM can be determined in the fault location step. Based on the fault analysis mentioned above, the open-circuit fault of SM will lead to abnormal charging of SM capacitor, which can be utilized in SM fault location.
Because the cycle $T$ is very small in the control of MMC, the capacitor voltage can be considered to vary linearly with time (Li et al., 2016). Thus the theoretical increment of capacitor voltage can be calculated by

$$u_c(t+T) = u_c(t) + \frac{1}{C} \int_{t}^{t+T} S_i(t) \, dt$$

$$= u_c(t) + TS_i(t+T) + i_{isn}(t)$$

which can be transformed into Equation (13)

$$S_i = \frac{2}{T} \left( u_c(t+T) - u_c(t) \right) (12)$$

Note that the capacitor can only be charged when SM is in ON state, i.e. $S_i = 1$. While in OFF state, the capacitor voltage will remain constant. Denote

$$\alpha = \frac{S_i}{C} = \frac{2}{T} \left( u_c(t+T) - u_c(t) \right)$$

so the practical values of $\alpha$ can be calculated using the measurement of capacitor voltage and arm current (see the right of Equation (13)), and the theoretical values of $\alpha$ in normal and fault states are illustrated in Table 2 and explained as follows.

Take the ON state ($S_i = 1$) of SM for instance. When $i_{isn} > 0$, the value of $\alpha$ is $1/C$ in normal case. Meanwhile, in $T_1$ or $T_2$ fault, the capacitor can be charged as usual. In other words, the SM can be considered to be operating in normal state, so the value of $\alpha$ is still $1/C$ in these fault cases. However, when $i_{isn} < 0$, the capacitor cannot be discharged in the case of $T_1$ fault. Hence, the output voltage of SM is no longer $u_c$ but 0 as the fault analysis mentioned above, which is the value as same as the normal state of $S_i = 0$ and $i_{isn} < 0$. Thus the value of $\alpha$ in $T_1$ fault is 0 rather than $1/C$. While, the value of $\alpha$ will maintain $1/C$ in the case of $T_2$ fault, because $T_2$ fault cannot affect the normal operation of SM. Similarly, the value of $\alpha$ in the OFF state of SM can also be explained for the last two rows of Table 2. On the basis of above explanations, the fault SM can be located as long as the calculated practical $\alpha$ deviates its theoretical value.

Remark 4.1: The fault detection of MMC sub-module is completed via a sliding mode observer, which can estimate the arm current accurately in normal state. While in fault state, the residual between the estimation and measurement of the arm current can be used to not only detect the occurrence of fault but also identify the type of fault. Therefore, half of the computational load can be reduced for the fault location.

Remark 4.2: Based on the fault analysis of MMC sub-module, the fault location of MMC sub-module can be implemented by the calculated fault feature, which can change dramatically once the capacitor is abnormally charged. Thus the fault location is not a complicated task, which can be embedded in the control of MMC.

5. Simulation results

In this paper, several simulation experiments are carried out to verify the effectiveness of the proposed approach on open-circuit fault diagnosis of MMC sub-module. In the simulation, the MMC simulation model is built based on MATLAB/Simulink, where the strategies of carrier phase shift and voltage balance control are used for the MMC system.

The parameters of the simulation model are set as follows: the DC voltage is set as 5 kV; the capacitor value of

| SM state | Normal | $T_1$ fault | $T_2$ fault |
|----------|--------|------------|------------|
| $S_i = 1$, $i_{isn} > 0$ | $1/C$ | $1/C$ | $1/C$ |
| $S_i = 1$, $i_{isn} < 0$ | $0$ | $0$ | $1/C$ |
| $S_i = 0$, $i_{isn} > 0$ | $0$ | $0$ | $1/C$ |
| $S_i = 0$, $i_{isn} < 0$ | $0$ | $0$ | $0$ |
Figure 6. Estimation and measurement of arm current in $T_1$ fault case.

Figure 7. Time of fault detection and fault location in $T_1$ fault case.

SM is set as 4.7 mF; the arm inductor value is set as 5 mH; the sampling frequency is taken as 50 kHz; the gain of observer is taken as 20,000; and for simplicity, each arm of MMC is composed of 5 SMs.

Besides, the result of fault detection is significantly dependent on the threshold and duration of the current residual on the fault arm. A small threshold could promote the sensitivity of the system, but it is susceptible to sampling error and signal interference. To avoid the false alarm, a duration time is set for fault detection. Additionally, the deviation of $\alpha$ value will fluctuate around a threshold in the first cycle after the occurrence of fault, so
a threshold for the number of fluctuation is set for fault location. Bearing these ideas in mind, the parameters of fault diagnosis are set as follows: the threshold of current residual is set as 20 A; the duration time of fault detection is taken as 2 ms; and the thresholds of $\alpha$ deviation and its fluctuation number are set as 10 and 100 respectively.

To clearly demonstrate the fault diagnosis approach used in the following simulation experiments, a flowchart is depicted in Figure 5 for the fault SM’s detection and location steps, which are enclosed by two dotted boxes respectively. Note that the conditional branches have implied the corresponding additional conditions, such as duration time and the thresholds for the deviation and fluctuation number of $\alpha$, etc.

### 5.1. $T_1$ fault case

In $T_1$ fault simulation, the open-circuit fault of $T_1$, which is set in the first SM of the upper arm of phase $a$, is triggered at 0.8 s. The estimation and measurement of the arm current are depicted in Figure 6 with diverse line and colour styles.

As shown in the figure, owing to the excellent performance of sliding mode observer, there is nearly no difference between the estimation of arm current and its measurement before 0.8 s. However, when $T_1$ fault is triggered, the deviation between the estimated arm current and its measurement begins to appear and increase rapidly, which makes it an easy task to detect the open-circuit fault of SM. While, it is worth noting that the detection flag is not triggered immediately when $T_1$ fault occurs, but turns into 1 from 0 at 0.8055 s as shown in Figure 7. That is because the fault can only be detected when the arm current is in the theoretical negative half cycle and $S_1 = 1$ state. Additionally, to avoid false alarm, the trigger of detection flag is delayed 2 ms after the zero-crossing time.

When the fault is detected on the upper arm, the $T_1$ fault can be identified according to the sign of the residual, i.e. $\tilde{i}_{ua} = i_{ua} - \hat{i}_{ua} > 0$, which can be observed clearly in Figure 6. Then, the fault location can be completed depending on the calculated $\alpha$ value, whose deviation crosses the threshold 100 times at the 50 kHz sampling frequency in 2 ms after the detection flag is triggered.

### 5.2. $T_2$ fault case

In $T_2$ fault simulation, the fault $T_2$ is set in the third SM of the upper arm of phase $b$. As shown in Figure 8, when the fault is triggered at 1 s, the estimated arm current begins to deviate immediately from its measurement, which decreases rapidly and starts to fluctuate around zero. Based on the obvious deviation between the estimated arm current and its measurement, the open-circuit fault can be lightly detected and the detection flag is triggered at 2 ms after the occurrence of the fault as depicted in Figure 9. In contrast with above $T_1$ fault, the time for fault detection is shorter because the arm current is just in the theoretical positive half cycle and $S_3 = 0$ state when the $T_2$ fault occurs.

Similarly, the $T_2$ fault can be identified in accordance with the sign of the residual, i.e. $\tilde{i}_{ub} = i_{ub} - \hat{i}_{ub} < 0$, which
can be easily determined in Figure 8. Then, the fault location can also be accomplished according to the fluctuation number of the calculated $\alpha$ deviation in 5 ms.

6. Conclusion

In this paper, a new approach is proposed for the open-circuit fault diagnosis of MMC sub-module. A sliding mode observer is exploited to estimate the arm current of MMC in normal and fault cases. Based on the calculated residual between the estimation and measurement of the arm current, we can not only detect the open-circuit fault of the arm but also identify the type of fault according to the sign of the residual. Then, on the basis of open-circuit fault analysis of MMC sub-module, a calculated fault feature $\alpha$ is employed to locate the fault SM. Note that the efficiency of fault diagnosis can be remarkably promoted via the proposed approach. Finally, the effectiveness of the proposed approach can be verified by several simulation experiments on the open-circuit fault diagnosis of MMC sub-module.

In the future work, we will pay more attentions on the machine learning based fault diagnosis of MMC system (Li et al., 2019; Song, Xu, & Xu, 2019; Wang, Xu, Han, Elbouchikhi, & Benbuzid, 2015), as well as the hybrid approach of model and machine learning on the fault diagnosis of power electronic systems (Cui & Liu, 2017; Xu et al., 2018; Zhang, Song, & Zhao, 2017).

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