A Novel Fault Diagnosis Strategy of MMC Battery Energy Storage System Based on SPVD

Tao Yibin¹²³, Yin Shi*, Zhan Xin⁴, Li Guanjun¹³, Liu Zhong⁴

¹National Key Laboratory on Operation and Control of Renewable Energy and Energy Storage, China Electric Power Research Institute Co., Ltd, Nanjing, Jiangsu, 210003, China
²School of Electric Power, South China University of Technology, Guangzhou, Guangdong, 510640, China
³State Key Laboratory of New Energy and Energy Storage Operation Control, Nanjing, Jiangsu, 210003, China
⁴Yangzhou Power Supply Company, State Grid Jiangsu Electric Power Co., Ltd, Yangzhou, Jiangsu, 225000, China

*Corresponding author’s e-mail: yinshi@epri.sgcc.com.cn

Abstract. With the vigorous development of renewable energy, high-power energy storage systems have become a key technology for energy transformation. Electrochemical energy storage systems based on modular multilevel converters have become a hot and difficult research topic due to their modular design, fast dynamic response, and excellent output quality. The MMC-BESS system contains a large number of sub-modules, each of which is a potential fault point. How to quickly diagnose and locate faults is the main research content of this article. First, the mathematical model of MMC-BESS is established, and the observer is constructed to judge whether the system is in a fault state. Second, the changing trend of the fault status of the sub-module is analyzed, and a fault location strategy based on port voltage discrimination is proposed. Finally, the experimental verification of the proposed diagnostic strategy proves the effectiveness and feasibility of the diagnostic strategy.

1. Introduction

In recent years, new energy power generation represented by wind power and photovoltaics has developed rapidly. The electrochemical energy storage system has the characteristics of two-way energy flow and rapid action response. Therefore, it has received extensive attention in areas such as large-scale new energy consumption, grid frequency and voltage regulation, and power supply for important loads. Modular multilevel converter (MMC) has the advantages of easy expansion, modularization, and low harmonic content, and is widely used in large-capacity high-voltage flexible DC transmission occasions. Combining MMC with battery energy storage can give full play to the excellent dynamic response characteristics of the energy storage system, while reducing system losses, and it can also be applied to AC/DC hybrid connection systems[1-5]. In order to solve the problems of long online diagnosis time, many observation objects, heavy calculation load, and limited diagnosis fault types in the existing fault diagnosis methods of MMC battery energy storage system (MMC-BESS), this paper proposes a sub-module port voltage discrimination based on sub-module port voltage discrimination (SPVD) fault
diagnosis method. First, a mathematical model of the MMC-BESS to analysis the typical fault status and fault characteristics of the MMC system are established. Secondly, based on the linear discrete mathematical model of the MMC-BESS system, the observer is designed to avoid the adverse effects of system process noise and sensor noise. The convergence of the observed variables and observed values of the system is evaluated online to realize effective monitoring of the system status. At the same time, based on the analysis of the open-circuit and short-circuit fault characteristics of the sub-module power devices, an effective criterion for the location of the fault point is proposed, and the online and accurate location of the fault point is realized by discriminating the sub-module port voltage. Finally, the fault diagnosis method proposed in this paper is simulated and experimentally analyzed to prove the rapidity, effectiveness and feasibility of the proposed fault diagnosis method.

2. Basic working principle of MMC energy storage system

The MMC energy storage system is a three-phase symmetrical common bus topology structure. Each phase is divided into two upper and lower bridge arms. Each bridge arm is composed of several sub-modules with the same structure in series and the bridge arm inductors, as shown in Figure 1. The sub-module is the power unit of the system, and the bridge arm inductance plays the role of restraining the circulating current and buffering the fault currents.

Referenced to Kirchhoff current law, when the MMC converter is operating under normal operating conditions, the following relationships exist among the converter bridge arm current, AC side current and circulating current:

\[ i_{c,p,n} = \pm \frac{i_{x,p}}{2} + i_{z,x} \]  

(1)

Due to the complex structure of the MMC-BESS and the large number of sub-modules, in order to facilitate analysis, the system model needs to be simplified, and each bridge arm is equivalent to a variable voltage source \((v_{x,p, n})\). The output voltage of each bridge arm is determined by the switching status of its subsidiary sub-modules.

\[ v_{x,p,n} = \sum_{n=1}^{n} S_{x,m,p,n} \frac{V_{dc}}{n} \]  

(2)

The relationship between the port voltage of each bridge arm and the AC and DC side variables of the MMC converter is as follows
\[ v_{x,p/n} = \frac{V_{dc}}{2} + v_{x} - R i_{x,p/n} - L_i \frac{d i_{x,p/n}}{dt} \]  

(3)

Since the equivalent resistance of the bridge arm is small, it can be approximated as \( R = 0 \), and the relationship between the circulating current of each phase and the output voltage of the upper and lower bridge arms and the DC bus voltage and other variables can be obtained by sorting the above formula.

\[ 2 L_i \frac{d i_{x}}{dt} = V_{dc} - v_{x,p} - v_{x,n} \]  

(4)

It can be seen from equations (2)(3)(4) that the switching state of the sub-module not only directly determines the AC side voltage and current of the MMC-BESS, but also has a strong coupling relationship with the circulating current of each phase. Therefore, by planning the switching states of the sub-modules of each bridge arm, coordinated control of multiple variables such as the output voltage, current, sub-module capacitor voltage and internal circulation current of the MMC converter can be realized.

3. Basic working principle of MMC energy storage system

3.1. Fault state detection of MMC-BESS

With reference to equations (1) and (4), it can be seen that there is a strong coupling and similar linear relationship between the circulating current of each phase of the MMC system and the AC side current, bridge arm port voltage, sub-module capacitor voltage and other system variables. Therefore, the internal circulating current of each phase is selected as Observation object. This method can quickly determine whether the system is in a fault state, and realize the preliminary location of the fault location.

The observer is based on the discrete domain mathematical model of the MMC-BESS system, and uses the state estimate of the previous control cycle and the input variables and measured state variables at the current moment to obtain the observed state variables. The nonlinear state equation of the observer can be expressed as

\[
\begin{aligned}
\dot{x} &= A(x) \cdot \hat{x} \cdot B \cdot u + K \cdot (y - \hat{y}) \\
y &= C \cdot \hat{x}
\end{aligned}
\]  

(5)

The observer-based MMC-BESS status monitoring link is divided into two parts: status prediction and measurement correction. The calculation process is as follows

(1) State prediction

Calculate the state prediction error covariance matrix:

\[
\hat{P}(k) = A_{k-1} \cdot \hat{P}(k-1) \cdot A_{k-1}^T + Q
\]

\[ A_{k-1} = 1 - R_s (L_i f_i)^{-1} \]  

(7)

Calculate the predicted value of the circulating current state variables of MMC-BESS:

\[
\hat{i}_{x,s}(k) = A_{k-1} \cdot \hat{i}_{x,s}(k-1) + B_{k-1} \cdot u(k-1)
\]

\[ B_{k-1} = (L_i f_i)^{-1} \]  

\[ u = V_{dc}/2 - v_{x,p} - v_{x,n} \]  

(9)

(2) Measurement correction

Calculate the gain matrix of the observer:

\[
K(k) = \hat{P}(k) \cdot [\hat{P}(k) + R]^{-1}
\]

Calculate the optimal state error covariance matrix:

\[
\hat{P}(k) = [1 - K(k)] \cdot \hat{P}(k)
\]  

(12)

State observation correction:
3.2. Fault location of MMC-BESS

If the MMC-BESS sub-module power switching device $T_1$ has an open circuit fault and $S_{sm}=1$ & $i_{arm}<0$, the sub-module port voltage is not equal to the expected output voltage; if $S_{sm}=0$, the MMC converter system When the sub-module power switching device $T_2$ has an open-circuit fault and $i_{arm}<0$, the sub-module port voltage is not equal to the expected output voltage but $v_c$. When a short-circuit fault occurs in a sub-module power device, its port voltage may also not match the expected voltage. Therefore, in the fault diagnosis mechanism, the sub-module can sample the port voltage, and the $S_{sm}$, the ideal port voltage and the actual sampling port voltage can be used as the basis for judging whether the sub-module is faulty.

In order to simplify the structure of the converter system and control the engineering cost, while maintaining the number of voltage sensors, the sub-module port voltage and capacitor voltage are obtained at the same time, so as to achieve healthy voltage balance and accurate fault location. For this reason, in the system design process, the structure of the traditional sub-module needs to be optimized, as shown in Figure 2.

Taking the residual of the sub-module port voltage sampling value and the expected value and the duration of the fault state as the criterion, the fault location link of the sub-module is designed, as shown in Figure 2. The specific steps are as follows:

$$\hat{i}_{z,s}(k) = i_{z,s}(k) + K(k) \cdot (i_{z,s}(k) - \hat{i}_{z,s}(k))$$

(13)

4. Experimental verification of MMC-BESS fault diagnosis based on SPVD

In order to verify the correctness and feasibility of the above-mentioned MMC-BESS system fault diagnosis method, a three-phase MMC-BESS experimental platform was built. The DC bus voltage of the sub-module is 200V. The core controller adopts the DSP+FPGA digital processing system architecture, the DSP28335 chip is used as the main controller to complete the core algorithm, and the
FPGA3S500E is used as the coprocessor to complete auxiliary functions such as AD sampling and dead zone protection.

4.1. Sub-module open circuit fault diagnosis experiment

The following figure shows the dynamic experimental waveform of the open circuit fault of the sub-module of the MMC converter. As shown in the figure, before the fault occurs, the residual error between the EKF circulation observation value and the measured value converges to zero. After the sub-module open circuit fault occurs, the residual error of the observation circulation is greater than the threshold. 10ms after the fault occurs, the state monitoring link determines that the system is in a fault state and can initially locate the faulty phase unit. The fault diagnosis system quickly enters the location link after obtaining the fault state signal. As shown in the figure below, if an open-circuit fault occurs in the MMC converter sub-module, the residual difference between the output voltage of the port and the expected output voltage is large and the number of fault cycles is greater than the pre-set threshold. The fault location link is through simple logic operations and status. The storage can capture the serial number of the faulty sub-module and complete the precise location of the fault point within 3ms after the fault signal is obtained.

Figure 4. Dynamic diagnosis experimental waveform of open circuit fault of sub-module

4.2. Sub-module short circuit fault diagnosis experiment

Figure 5 shows the dynamic experimental waveform of the short-circuit fault of the MMC converter sub-module. As shown in the figure, if a short-circuit fault occurs in the system sub-module, the difference between the observed value of the internal circulation and the measured value also does not converge to zero, which can effectively monitor the fault state of the MMC system. Different from the traditional method of logically judging the sub-module capacitor voltage, the fault location method based on the sub-module port voltage discrimination proposed in this article can not only locate the open-circuit faulty sub-module, but also quickly capture the short-circuit faulty sub-module. The location, and the positioning time is maintained within 5ms, effectively improving the safe and stable operation of the MMC converter.

Figure 5. Dynamic Diagnosis Test Waveform of Sub-module Short Circuit Fault
5. Conclusion
This paper proposes a fault diagnosis method based on sub-module port voltage discrimination for MMC-BESS system. By establishing a system-like linear discrete mathematical model, the internal state transformation of the system after the sub-module open circuit and short circuit faults are analyzed. Through the research and design of the MMC-BESS fault diagnosis system, the following conclusions can be drawn. The design of the fault monitoring link based on the observer can realize the online monitoring of the system and quickly determine whether the system is in a fault state. It can avoid the influence of system process noise and sampling noise on the diagnosis result. The port voltage location method can realize precise location of different types of fault points of open circuit and short circuit of the sub-module without adding additional sensors, which provides a design idea for the optimization of the system fault diagnosis method.

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