Theory and Practice of Science and Technology
2025, VOL. 6, NO. 3, 49-52
DOI: 10.47297/taposatWSP2633-456908.20250603

A review of the research on fault detection, prediction and health management strategies of three-phase inverters under the background of Grid 2.0

Xiaomin Hong

Department of Electrical engineering and automation, Jilin Jianzhu University, Changchun, Jilin, 130022, China

ABSTRACT

Under the requirements of today's Grid 2.0 background, more intelligent power electronic converters are needed, and three-phase inverters are one of them. The function of the three-phase inverter is to convert DC into AC and convert the AC power in the grid into DC power. Three-phase inverters are inevitably used when the grid is running. Various faults may occur in the three-phase inverter during use, so fault detection, prediction and health management of three-phase inverters have become necessary. This research direction mainly reviews the various situations of three-phase inverter faults and how to detect and avoid faults to keep the three-phase inverter in a healthy state.

KEYWORDS

Three-phase inverter; Fault detection and prediction; Health management

1 Introduction

With the rapid development of modern power electronics technology, three-phase inverters have attracted widespread attention due to their wide application in the power field, solar energy systems, electric vehicle charging, industrial applications, and portable electronic devices. In the power field, three-phase inverters are widely used in industrial control, variable frequency drive, etc. In the field of electric vehicles, the DC power provided by the battery is converted into the AC power required to drive the motor. In the solar photovoltaic power generation system, the direct current generated by the solar panel is converted into alternating current that can be used by the home or the power grid. With the advancement and development of science and technology, it is particularly important to maintain the healthy operation of the three-phase inverter and repair the faults in it in a timely manner. Therefore, it is necessary to efficiently detect and manage the faults of the three-phase inverter.

2 Three-phase inverter

The three-phase inverter is an electronic device that converts direct current (DC) into alternating current (AC). It is a converter that converts direct current power (battery, storage battery) into constant frequency and voltage or frequency-modulated and voltage-regulated alternating current (generally 220V, 50Hz sine wave). The core components of the three-phase inverter include the DC input terminal, the inverter unit, the control circuit, the filter, and the protection circuit. Its circuit structure is shown in Figure 2.1.

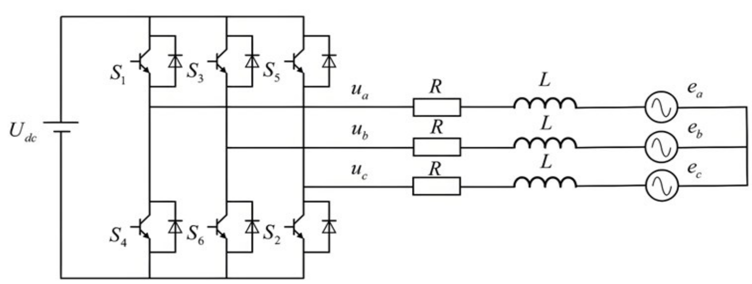

Figure 2.1 Schematic diagram of the three-phase inverter circuit structure

In the three-phase inverter, the power switching device is the component with the highest probability of failure. This causes the three-phase inverter to not only damage the power device itself under abnormal working conditions, but also increase the stress on the voltage and current of other power devices. If the corresponding fault detection is not carried out in time, it may cause secondary faults, eventually leading to abnormal operation status or even serious damage, affecting the safety and reliability of the system, and causing serious economic losses.

2.1 Open circuit fault of three-phase inverter switch device

Three-phase inverter switch device faults are usually divided into open circuit faults and short circuit faults. This article first introduces open circuit faults. The open circuit fault of the three-phase inverter switch device refers to the failure of the inverter's power switch (such as IGBT or MOSFET) in a certain channel, causing the switch to be unable to turn on. This will cause the output voltage of this phase to fail to be generated normally, which may cause an imbalance in the inverter output. In Figure 2.1, Udc is the DC voltage; S1-S6 are power switch tubes; R is the load resistor; L is the filter inductor. Taking S1 open circuit as an example, the upper bridge arm cannot be turned on normally, and the positive voltage of ua cannot be output normally; ua can only output negative voltage when S4 is triggered. Therefore, starting from the open circuit fault of S1 tube, ea has no positive output current and can only output negative current. The three-phase current imbalance caused by S1 circuit breaker is that under normal circumstances, three switch tubes should be triggered at the same time at every moment. The setup may include a single switch tube in the upper arm and a pair in the lower arm, or alternatively, two switch tubes in the upper arm and a single switch tube in the lower arm, enabling normal current flow.

2.2 Open circuit fault detection of three-phase inverter switch devices

The open circuit fault detection of switch tubes in three-phase inverter switch devices can be divided into two categories from the perspective of detection variables [2]: current value-based detection method and voltage value-based detection method. Reference [2] simulated the open circuit fault of the inverter by taking the open-loop V/F induction motor control system and the permanent magnet synchronous motor vector control system as examples, and analyzed the voltage and current patterns referred to by the fault detection method. Based on the simulation results, the principles of each fault detection method are introduced and compared. Among them, the method based on current signal uses the existing current sensor of the system. Although no additional hardware is required, the detection time is long and is easily affected by external factors. The method based on voltage signal determines the fault state by measuring the internal voltage change of the inverter. It has a faster detection response speed and is applicable to a variety of control strategies.

In order to accurately detect open circuit faults, reference [1] adopts a three-phase inverter fault detection method based on a time convolutional neural network. First, the parameters of each layer in the network are trained to obtain a detection network for a specific fault object. Then, the trained network is used to discriminate and classify the test data. Finally, the fault type is compared to obtain the detection result. In order to detect inverter faults, the TCN neural network model in deep learning is employed online to identify inverter faults. Following extensive theoretical study and learning in programming, an 8-layer TCN model has been developed. This model is capable of precisely identifying various inverter circuits, achieving optimal simulation outcomes, and attains a specific level of accuracy. Through the examination and juxtaposition of fault categorization outcomes for fundamental and various dynamic circuits, the practicality and efficacy of the developed TCN model in classifying inverter circuit faults are confirmed, leading to the attainment of highly accurate fault classification in optimal conditions.

Reference [3] mainly introduces CS and wavelet theory, and conducts detailed analysis from three aspects: signal sparse representation, signal compression measurement and signal reconstruction, and focuses on the optimization method of the measurement matrix. The literature represents the fault voltage signal of the three-phase inverter on the DCT sparse basis, and uses the measurement matrix optimized by the fused Gram matrix and the fast iterative shrinkage threshold algorithm (FISTA) to project it, and conducts simulation research. The influence of the Toeplitz matrix and the OST matrix on the reconstruction error before and after optimization is compared and analyzed. The denoising effects of the two methods of wavelet analysis and wavelet packet decomposition are compared, and then the energy characteristics of the fault frequency band are extracted through db3 decomposition. Finally, the results show that the optimization algorithm in this paper has a better effect on the reconstruction error. Under various measurement numbers, the reconstruction error of the optimized OST matrix is smaller than that of the Toeplitz matrix, which effectively reduces the reconstruction error of the fault voltage signal and retains the important information of the uncompressed voltage signal.

Literature [4] proposes a single-switch and dual-switch open-circuit fault diagnosis method for three-phase inverters based on phase current value analysis. First, the influence of each switch tube on the output value of the phase current after an open-circuit fault occurs is analyzed. After the switch tube has an open-circuit fault, the maximum value of the output value of the phase current will not exceed 1/3 of the rated amplitude. The current characteristics of the open-circuit fault of the dual switches on the same side of the inverter are analyzed and summarized into a table, which effectively eliminates the misdiagnosis problem encountered in the previous current-based diagnosis method. The current waveform affected by each switch tube is used as the fault detection waveform. The fault detection waveform corresponding to each switch tube can be obtained by detecting the starting zero point. Then, the open-circuit fault of the inverter switch is quickly detected by counting whether the number of sample values of each fault detection wave meets the condition of the judgment function. The experiment of the open-circuit fault of the three-phase inverter is carried out on the semi-physical simulation platform to verify the effectiveness and accuracy of the method. The experiment carried out the diagnosis of different types of open-circuit faults of the three-phase inverter switch tubes. The experimental results show that the method can accurately locate different types of open-circuit faults of the three-phase inverter, and also shows high robustness for fault diagnosis under load change operation. The method has the characteristics of fast fault detection, accurate fault location and low computational burden.

Reference [5] proposes a T-type three-level fault diagnosis method based on the DC side capacitor voltage residual and the inverter three-phase voltage residual. Through the characteristics of the neutral point clamping of the T-type three-level inverter, the core device of the APF, the residual values of the upper and lower capacitor voltages of the T-type three-level inverter and the residual values of the inverter command voltage and output voltage are extracted, and the cycle average value is calculated as the basis for power device fault diagnosis. At the same time, after extracting the voltage parameters, a complete fault location method is proposed to gradually locate the fault through various judgment bases. Finally, a simulation model and an experimental platform are built to verify the proposed fault diagnosis method. The simulation and experimental results prove the effectiveness of the fault diagnosis method.

2.3 Short-circuit fault detection of three-phase inverter switching devices

In normal operation, S1 is the switch tube responsible for controlling the output voltage of phase A. Taking the short circuit of S1 as an example, it will always be in the on state, causing the phase A circuit to short-circuit, and the current will flow directly from the DC power supply through S1, thereby generating a large current. Due to the short circuit of S1, the current is no longer modulated and controlled, but is affected by the DC power supply voltage and circuit impedance, causing the current to increase sharply, which may cause damage to S1 or other switch tubes.

In reference [7], a proposed scheme for current limitation was suggested, relying on the existing inner loop command to restrict the inverter's three-phase three-bridge structure during an asymmetric short-circuit fault, which would result in voltage limiting phenomenon, thus leading to the problem of incomplete control of the short-circuit current. The mechanism of output voltage limiting when an asymmetric short-circuit fault occurs is theoretically analyzed, an existing solution is introduced, and its shortcomings are analyzed in detail. Consequently, we suggest a strategy for current limitation that relies on virtual impedance. The fundamental concept behind this approach is to diminish the equivalent load impedance through the parallelization of virtual impedance, thereby preventing limitations in output voltage. The technique eliminates the need to assess the fault phase, significantly easing the process of designing and executing. Furthermore, this document presents the method for implementing virtual impedance in a control system and outlines the selection principle for virtual impedance, focusing on both preventing voltage limitations and maintaining system stability. Ultimately, comparative studies have confirmed the efficacy of the existing limiting approach.

3 Health management strategy of three-phase inverter switch devices

Three-phase inverter switch devices will inevitably fail during operation. In order to avoid the failure to handle the failure in time, it is necessary to manage the health of the three-phase inverter switch devices. Reference [8] proposed an online health status monitoring method for single-phase inverters based on common-mode components based on the analysis of the current flow path. By superimposing the common-mode components on the original modulation wave and clamping the inverter output to a specific level, the online health status monitoring can be completed without affecting the output current of the single-phase inverter. Moreover, under any modulation index, this method can provide a sufficiently long time window for online health status monitoring. Then, for the more widely used three-phase inverter, an online health status monitoring method based on the intermittent pulse width modulation strategy is proposed. By comparing different types of DPWM modulation strategies, the advantages of the DPWMA modulation strategy in online health status monitoring are demonstrated, and the constraint relationship between the monitoring time and the modulation index is analyzed. Finally, an online monitoring system suitable for three-phase three-level ANPC inverters is designed, and offline and online experimental platforms are built. The linear relationship between the junction temperature and the saturation voltage drop under low current is calibrated through experiments, verifying the feasibility of the proposed online health status monitoring method.

4 Conclusion and Outlook

In the context of Grid 2.0, with the widespread access of renewable energy and distributed generation, three-phase inverters are important devices that connect the grid and power system. The research on fault detection, prediction and health management strategies is particularly important. This paper reviews the existing technologies of fault detection and prediction of three-phase inverters, analyzes various fault modes and their impacts, and explores data-driven and model-driven fault diagnosis methods. By comparing the advantages and disadvantages of different algorithms, a health management framework suitable for practical applications is proposed.

At present, fault detection and prediction methods have gradually shifted from traditional empirical methods to intelligent diagnosis technologies based on machine learning and artificial intelligence. Especially with the support of advanced algorithms such as deep learning and neural networks, the diagnostic accuracy and prediction advance of inverter faults have been significantly improved. However, existing research still faces challenges such as insufficient data annotation, high real-time requirements, and insufficient robustness in complex system environments.

With the continuous advancement of Grid 2.0 technology, intelligent health management of three-phase inverters has become an important direction for future research. Current research shows that fault detection methods based on data-driven and artificial intelligence have gradually replaced traditional empirical methods and improved diagnostic accuracy. However, there are still challenges such as insufficient data annotation and high real-time requirements. Future research should further combine big data, cloud computing and edge computing technologies to build a more intelligent and efficient health management system to improve the reliability and stability of the power system.

In short, the fault detection and health management technology of three-phase inverters will play a vital role in the process of power grid intelligence. In the future, we should focus on intelligence, real-time, robustness and multi-functional integration to promote the sustainable development of power electronic systems.

References

[1] Li Jing. (2023). Fault Diagnosis and Location Method of Three-phase Inverter (Master's thesis, Jilin University). Master's degree https://link.cnki.net/doi/10.27162/d.cnki.gjlin.2023.002319doi:10.27162/d.cnki.gjlin.2023.002319.

[2] An Q. T, Sun L, Sun L. Z, Zhao K. Research progress in fault diagnosis methods for three-phase inverter switches. Transactions of China Electrotechnical Society, 26:135-144

[3] Li Wenjie. (2022). Research on Fault Diagnosis Method of Three-phase Inverter Based on Signal Processing (Master's thesis, Xi'an University of Technology) Master's degree https://link.cnki.net/doi/10.27391/d.cnki.gxagu.2022.000361doi:10.27391/d.cnki.gxagu.2022.000361.

[4] Luo Y, Chen C.Y, Shi Y.C, Zeng X.J. Open-circuit fault diagnosis method of three-phase inverter switch tube based on current value analysis. Journal of Railway Science and Engineering. 21: 4370-4382

[5] Zhang Y, Shi L.P, Wen C, Han L. A fault detection method for T-type inverter based on voltage residual. 2022, China University of Mining and Technology. 56: 4-7

[6] Zhan G.X, Liu G.Y, Ji Z.M, Yu S.E, Wang R.F. Health monitoring method of grid-connected inverter based on model parameter identification. Electric Power Science and Engineering, 39: 1-8

[7] Gao Bofeng. (2018). Research on Three Phase Inverter Digital Control Technology and Short Circuit Current Limiting Strategy (Master's thesis, Huazhong University of Science and Technology). Master's degree https://kns.cnki.net/kcms2/article/abstract?v=i_LPdPvRpB6wA7CJh3OSCS6GODIIPp7jXSY0Q5VWK1B_vpsZOF1gNtaFvdfbpTneROpcTo738rQTR__ajSsjENOgl2hXlMCJ80m-7HvnL05EKJuhMaNLzNK2iydR5lj5PdguTV7J_fb7A3Y3qIP-Yxk1bb9Rneo68cyLtEvWNyssS81BpAZpaLc7h2IIXbAAowCv9Bt9UtY=&uniplatform=NZKPT&language=CHS.

[8] Chen Zhaoxiang. (2023). Research on the online health condition monitoring for IGBT power modules in three-level NPC/ANPC inverters (Master's thesis, Hefei University of Technology). Master's degree https://link.cnki.net/doi/10.27101/d.cnki.ghfgu.2023.000369doi:10.27101/d.cnki.ghfgu.2023.000369.