

Stability and Fault Detection Algorithm of Grid-Connected Inverter in Complex Power Grid Environment

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Abstract. In order to improve the stability, this paper designs a control strategy based on adaptive grid impedance. By monitoring the grid impedance in real time and dynamically adjusting the inverter control parameters, the influence of grid impedance change on inverter stability is effectively reduced. At the same time, LCL filter is introduced, which significantly filters out the higher harmonics in the inverter output current and improves the output waveform quality. In addition, a voltage compensation device is applied to quickly generate a compensation voltage signal when the grid voltage fluctuates to ensure the stability of the inverter output voltage. In the aspect of fault detection, a data-driven fault detection algorithm is proposed, which combines machine learning and real-time monitoring technology to realize early detection and accurate diagnosis of inverter faults by collecting and analyzing inverter operation data. The experimental results show that the algorithm performs well in the detection of power switch device faults, sensor faults and other types, and has high classification accuracy. The research shows that the control strategy based on adaptive grid impedance, the addition of LCL filter and the application of voltage compensation device have significantly improved the stability of grid-connected inverter in complex grid environment. The proposed data-driven fault detection algorithm provides strong support for rapid fault location and accurate treatment of inverter.

Keywords: Complex Power Grid Environment; Fault Detection; Grid-connected Inverter.

1. Introduction

In modern power system, grid-connected inverter not only undertakes the task of converting DC energy into AC energy and injecting it into the power grid, but also maintains the stable operation and power quality of the system. However, with the increasing complexity of power grid structure and the improvement of power electronization, the stability and fault detection of grid-connected inverter in complex power grid environment have become particularly prominent [1].

Complex grid environment is often accompanied by multiple factors such as uncertainty of grid impedance, harmonic interference, voltage fluctuation and flicker, which pose a severe challenge to the stable operation of grid-connected inverter. Once the inverter fails or becomes unstable, it will not only affect the safe connection of local power supply, but also threaten the stability of the whole power system [2]. Therefore, it is of great significance to study the stability of grid-connected inverter in complex power grid environment for improving the reliability and security of power system. At the same time, in order to quickly locate and accurately handle the faults of grid-connected inverters, effective fault detection algorithms are particularly important. Traditional fault detection methods mostly rely on fixed thresholds or simple logical judgments, which are difficult to adapt to the complex and changeable power grid environment [3]. Therefore, exploring a new data-driven fault detection algorithm to realize real-time monitoring and intelligent diagnosis of inverter operation state has become a hot research topic at present.

This paper discusses the influence of complex power grid environment on inverter stability, and puts forward corresponding stability improvement measures; A data-driven fault detection algorithm is studied and designed, and its effectiveness and accuracy are verified by experiments.

2. Stability Analysis of Grid-connected Inverter in Complex Power Grid Environment

2.1 Influence of Weak Current Network Characteristics on Stability of Grid-Connected Inverter

Weak current network refers to the power grid environment with large impedance, high voltage fluctuation and high harmonic content. In this environment, the interaction between grid-connected inverter and power grid becomes more complicated, thus affecting the stable operation of inverter.

The grid impedance in weak current network is large, which will lead to a large voltage drop of inverter output current on the grid impedance, and then affect the output voltage and power factor of inverter [4]. When the power grid impedance changes, the output voltage and current waveforms of the inverter may be distorted, and even lead to inverter instability in serious cases. Therefore, when designing and operating the grid-connected inverter, it is necessary to fully consider the influence of grid impedance to ensure the stable operation of the inverter under various grid conditions.

Voltage fluctuation and harmonic content in weak current network will also affect the stability of grid-connected inverter. Voltage fluctuation may lead to the fluctuation of inverter output power, and then affect the control performance and stability of inverter [5]. However, the higher harmonic content may cause the resonance problem between the inverter and the power grid, further aggravating the stability problem of the inverter. In order to solve these problems, filters and harmonic suppression devices are added to the inverter control system to reduce the influence of voltage fluctuation and harmonics on inverter stability.

Variability and uncertainty in weak power grid are also important factors affecting the stability of grid-connected inverter. Because the parameters such as power grid impedance, voltage fluctuation and harmonic content may change with time and operating conditions, the inverter needs to have strong adaptability and robustness to meet the stability challenges brought by these changes.

2.2 Measures to Improve the Stability of Grid-Connected Inverter

Aiming at grid-connected inverter in complex power grid environment, a control strategy based on adaptive power grid impedance is designed in this study. This strategy can reduce the influence of grid impedance on inverter stability by monitoring the change of grid impedance in real time and dynamically adjusting the control parameters of inverter.

Using advanced sensing technology and signal processing algorithm, the amplitude and phase of power grid impedance can be monitored in real time [6]. According to the monitored power grid impedance information, the current loop and voltage loop control parameters of the inverter are dynamically adjusted, including proportional coefficient, integral coefficient and filter coefficient.

The relationship between inverter output voltage V_{inv} and grid voltage V_{grid} is expressed as:

$$V_{inv} = V_{grid} + Z_{grid} \cdot I_{inv} \quad (1)$$

Where Z_{grid} is the grid impedance and I_{inv} is the inverter output current.

In order to reduce the influence of harmonics on the stability of grid-connected inverter, this study proposes to add LCL filter to the output of inverter [7]. LCL filter is composed of inductance, capacitance and inductance, which can effectively filter out higher harmonics in inverter output current and improve the quality of output power.

After the LCL filter is added, the transfer function $H(s)$ of the filter is expressed as:

$$H(s) = \frac{1}{L_1 s + \frac{1}{C_s} + L_2 s} \quad (2)$$

Where L_1, L_2 is the inductance of the filter and C is the capacitance of the filter.

Aiming at the influence of grid voltage fluctuation on inverter stability, this study proposes to add voltage compensation device to grid-connected inverter system. The device monitors the fluctuation of grid voltage in real time, and generates corresponding compensation voltage signal, which is superimposed on the output voltage of inverter to offset the influence of grid voltage fluctuation on inverter output.

3. Research on Fault Detection Algorithm of Grid-connected Inverter

3.1 Fault Types of Grid-connected Inverter

Grid-connected inverter is the key equipment to connect distributed energy and power grid, and its stable operation is very important for the reliability of power system. However, in actual operation, grid-connected inverters may encounter a variety of faults, which not only affect the performance of inverters, but also may adversely affect the whole power system.

Power switching device is the core component of grid-connected inverter, which is responsible for realizing the conversion of electric energy. These devices may be damaged due to overvoltage, overcurrent, overheating and other factors, resulting in the inverter can not work normally. A large number of sensors are used in grid-connected inverter to monitor key parameters such as voltage, current and temperature. Sensor failure may lead to distortion of monitoring data, and then affect the control accuracy and stability of inverter. The control circuit is responsible for generating the pulse signal to drive the power switching device according to the sensor signal. The fault of control circuit may lead to abnormal pulse signal, which may lead to distortion or shutdown of inverter output waveform. Capacitors in grid-connected inverters are mainly used to smooth DC voltage and filter out harmonics. Capacitance fault may lead to instability of inverter output voltage and increase of harmonic content. The connection line is responsible for transmitting the output power of the inverter to the power grid. A line fault may cause the inverter to fail to connect to the grid or cause a power grid fault.

Bad environmental conditions may lead to accelerated aging of components in the inverter, thus increasing the risk of failure. Shortcomings in inverter design may lead to problems in actual operation of equipment. Poor manufacturing process may lead to sub-standard performance of components or potential defects, which may lead to failure. Lack of regular maintenance may lead to problems such as dust accumulation and poor heat dissipation in the inverter, and then affect the stable operation of the equipment. The complex power grid environment may pose a challenge to the stable operation of the inverter, thus increasing the possibility of faults.

3.2 Fault Detection Algorithm based on Data Drive

A data-driven fault detection algorithm is proposed, which combines machine learning and real-time monitoring technology to realize accurate monitoring and fault diagnosis of grid-connected inverter. By collecting inverter operation data, the data model is constructed, and the data is analyzed and learned by machine learning algorithm, so as to realize early detection and accurate diagnosis of inverter faults. Traditional fault detection usually depends on a fixed threshold, but this algorithm sets the threshold adaptively through the output probability of machine learning model, which is more flexible and accurate.

The key operation data of grid-connected inverter, including voltage, current, power, temperature and other parameters, are collected in real time through sensors and monitoring systems. The collected original data are cleaned, denoised and standardized, and the features related to the operation state of the inverter are extracted from the preprocessed data by wavelet transform. Based on the extracted features, a support vector machine (SVM) model is constructed. By training the model, it can learn the data characteristics of inverter in normal operation and fault state.

The SVM decision function is expressed as:

$$f(x) = \text{sign} \left(\sum_{i=1}^n \alpha_i y_i K(x, x_i) + b \right) \quad (3)$$

Among them, x is the sample to be classified, x_i is the sample in the training set, y_i is the category label of the sample, $K(x, x_i)$ is the kernel function, which is used to map the sample to a high-dimensional space to improve the classification performance, α_i is the Lagrange multiplier, which is obtained through training, and b is the bias term.

Finally, the data collected in real time are input into the trained model for condition monitoring and fault diagnosis. The model can output the current operating state of the inverter and give an alarm when an abnormality is detected.

4. Experimental Analysis

In order to deeply study the stability and fault detection algorithm of grid-connected inverter in complex power grid environment, an experimental platform of grid-connected inverter is built to simulate complex power grid environment. The platform can simulate various complex working conditions such as power grid impedance change and voltage fluctuation.

The experimental results show that the inverter can still keep stable output when the grid impedance changes after adopting the control strategy based on grid impedance adaptation, which verifies the correctness of the strategy. At the same time, the addition of LCL filter effectively filters out the high-frequency harmonics in the inverter output and improves the waveform quality. The voltage compensation device can respond quickly when the grid voltage fluctuates, and generate corresponding compensation voltage signals to ensure the stability of the inverter output voltage. Figure 1 shows the signal spectrum difference before and after adding LCL filter, which directly reflects the significant influence of LCL filter on the harmonic content of inverter output signal.

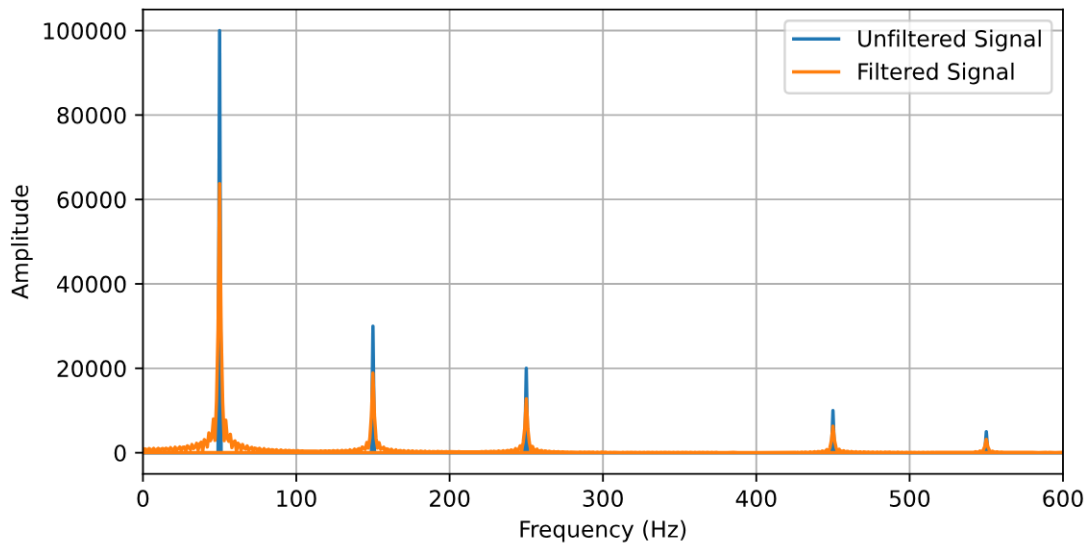


Figure 1. Changes of harmonic content before and after adding LCL filter

There are several peaks in the spectrum, corresponding to the fundamental wave (50Hz) and its higher harmonics (150Hz, 250Hz, 450Hz and 550Hz). The spectrum of unfiltered signal shows a wide range of frequency components contained in the inverter output, especially the significant existence of high-frequency harmonics. Compared with the unfiltered signal, the amplitude of the filtered signal in the high frequency region ($> 200\text{Hz}$) is significantly reduced, which indicates that the LCL filter effectively attenuates the high frequency harmonics. The amplitude of the fundamental wave (50Hz) and its lower harmonics have little change, which shows that the LCL filter has little

influence on the low-frequency signal and maintains the basic characteristics of the signal. LCL filter significantly improves the quality of output signal by attenuating high-frequency harmonics.

The classification performance of SVM model in fault detection task of grid-connected inverter is shown in Figure 2. 80 samples that are actually in normal operation are correctly classified as normal operation, which shows that the model has strong recognition ability in this category. 60 samples which are actually faults of power switching devices are correctly classified, which shows that the model has certain accuracy in identifying such faults. 68 samples which are actually sensor faults are correctly classified, which is the highest classification accuracy among the three categories, indicating that the model performs well in detecting sensor faults. On the whole, the classification accuracy of the model in the three categories is relatively high, but there is still room for improvement. Especially for the distinction between normal operation and power switching device failure, the model seems to have some confusion. This needs to be solved by further optimizing model parameters, adjusting feature selection or increasing training data.

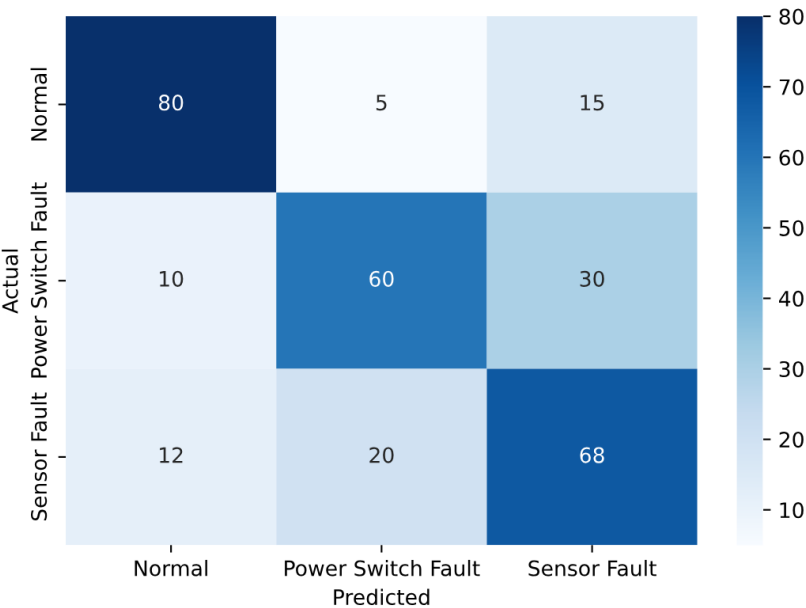


Figure 2. SVM model confusion matrix for inverter fault detection

The control strategy based on adaptive grid impedance, the addition of LCL filter and the application of voltage compensation device can effectively improve the stability of grid-connected inverter in complex grid environment. The fault detection algorithm based on data-driven is excellent in practical application, which can realize early detection and accurate diagnosis of grid-connected inverter faults. The future work will further optimize the control strategy and fault detection algorithm to improve the stability and reliability of grid-connected inverter in more complex power grid environment. At the same time, it will explore the application potential of more advanced machine learning technology in the field of inverter fault diagnosis.

5. Conclusion

In order to enhance the adaptability and robustness of the inverter, a control strategy based on grid impedance adaptation is proposed, and it is verified by experiments that the strategy can effectively cope with the change of grid impedance and maintain the stability of inverter output. In addition, the introduction of LCL filter significantly reduces the high-frequency harmonic content and improves the power quality, while the voltage compensation device effectively counteracts the influence of grid voltage fluctuation on inverter output. In the aspect of fault detection, this paper introduces a data-driven fault detection algorithm, which combines machine learning technology and real-time monitoring technology, and realizes real-time monitoring and intelligent diagnosis of grid-connected

inverter by constructing SVM model. Compared with the traditional method relying on fixed threshold, this algorithm based on machine learning can detect faults more flexibly and accurately. The experimental results show that this method is effective in practical application, and can find and accurately diagnose inverter faults at an early stage. This study not only improves the stability of grid-connected inverter in complex power grid environment, but also enhances its fault response ability through innovative fault detection algorithm, which provides strong technical support for improving the reliability and security of power system. The future work will further optimize the control strategy and fault detection algorithm, and improve the reliability and safety of grid-connected inverter in more complex power grid environment.

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