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Resonance Mechanism Analysis of Large-scale Photovoltaic Power Plant*

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Abstract: To analyze the resonance mechanism of a photovoltaic (PV) power plant, a simplified impedance model of the PV power plant is first established. The structure of the PV power plant is then introduced, and the reason for the resonance is obtained by analyzing the on-site situation and measured data of the PV power plant. Finally, a simple and effective solution is proposed based on the structure of the PV power plant and its existing facilities. The results of the engineering experiments and the stable operation of the PV power plant verify the effectiveness of the proposed method.

Keywords: Large-scale PV plants, impedance analysis, system stability, power quality

1 Introduction

With technological improvements in renewable energy generation, PV plants are gradually developing toward a larger scale [1-4]. Large-scale PV plants usually embed a grid-connected PV inverter as an interface between the PV power generation unit and the grid to achieve a controllable current injection into the power grid. A large number of grid-connected inverters and power grid constitute a dynamic interconnected system, and their interaction may make the system unstable. Therefore, the interconnection of large-capacity PV plants has brought about challenges to the stable operation of the power grid, and has become an important topic in renewable energy research [5-9].

The methods used to analyze the interaction between the renewable energy grid-connected system and the grid can be divided into two types, the control system modeling analysis and the impedance analysis [10-12]. The control system modeling analysis takes the coupling relationship between several links in the controller into consideration. This type of analysis usually considers the stability of a grid-connected system under multiple working conditions using stability methods such as root locus, time or frequency domain analysis. However, this method mainly focuses on the stability of the inverter controller, and the process used in the stability analysis is usually complex. Based on this, some scholars have proposed an analysis method based on the impedance stability. This method aims to study the stability of the interaction between the grid-connected inverter and the power grid. After establishing the impedance model of grid-connected inverters and the power grid, the impedance stability criterion is used to analyze the stability of the system. Compared with the former method, the latter reduces the dependence on the internal parameters of the grid-connected system, and has therefore been widely used [13-16].

To avoid the potential resonance issues in large-scale PV plants, some studies have improved the

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control strategies of PV inverters. In Ref. [17], the authors put forward a virtual impedance control strategy to reshape the impedance of the grid-connected inverter, which can enhance its adaptability under a weak grid. Owing to the inevitable delay in the digital controllers, a control strategy to eliminate delay was proposed to enhance the stability of the system under variations of the grid impedance in Ref. [18]. In addition, after considering the limitations of the traditional control strategies, a control strategy with high robustness in a complex power grid was proposed in Ref. [19]. To improve the control strategy of the inverter itself, some studies have also put forward a scheme for reforming a PV grid-connected system. In Ref. [20], a power quality management scheme of PV plants was put forward based on the inductively filtered method, the effectiveness of which is verified through actual engineering applications. The transformer integrated filtering method was originally used in the large-power rectifier system[21], which greatly improves the integration level and can effectively prevent the harmonic amplification. Although many researchers have studied the possible resonance of PV plants theoretically, few have analyzed the resonance mechanism or proposed corresponding solutions based on the resonance problems occurring in a large-scale PV plant.

In this paper, the equivalent simplified model of a large-scale PV grid-connected system is established and the factors causing the system instability are revealed based on the impedance stability criterion. Then, combined with the on-site problems and measured data on the PV power plant, the reason for the resonance of the PV power plant is analyzed. Finally, a simple and effective solution is proposed to reduce the economic loss. The results of engineering experiments and the stable operation of photovoltaic power plants demonstrate the effectiveness of the proposed method.

2 System stability analysis

2.1 Impedance stability criterion

Impedance stability criterion is a practical analysis method, the remarkable advantage of which is the ability to judge the system stability based on the impedance values of two subsystems through a linearization method instead of fine modeling. In Ref. [10], the traditional impedance stability criterion is modified, and the impedance stability criterion for a grid-connected system based on power electronic inverters is established. In the case of an unknown or complex internal structure, this method is usually used to judge the stability of a grid-connected system and is therefore suitable for large-scale PV power plants.

The power grid can be modeled using its Thevenin equivalent circuit, which consists of an ideal voltage source and an output impedance in series. It is worth noting that the power supply itself is assumed to be stable under no load. The stability of this type of power supply mainly depends on whether the ratio of the output impedance to the load input impedance meets the Nyquist stability criterion.

However, a grid-connected PV inverter is usually controlled to inject the desired current into the grid, and thus it is inappropriate to equate it as a voltage source. Considering that there are many PV inverters applied in parallel in large-scale PV plants, the differences among these inverters can be ignored for the sake of simplicity. Therefore, an entire PV power plant can be equivalent to a Norton equivalent circuit rather than a Thevenin equivalent circuit, which contains an ideal current source and an inverter impedance in parallel. Similar to the Thevenin equivalent circuit, the stability of the Norton equivalent circuit also has the following conditions: (1) When the load shorts, the current source itself is stable; (2) the load is stable under ideal current supply; and (3) the ratio of the load input impedance to the output impedance of the power supply satisfies the Nyquist stability criterion.

2.2 System impedance model

Based on the above analysis, the power grid can be equivalent to an ideal voltage source V_g in series with the grid impedance Z_g, and the PV plant can be equivalent to a current source connected in parallel with an output impedance Z_{inv}. The equivalent circuit of the entire grid-connected system is shown in Fig. 1.

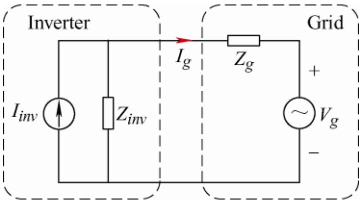


Fig. 1 Equivalent circuit

Assuming that the PV grid-connected system does not exist, the grid voltage is stable. When the grid impedance is 0, the output of the PV grid-connected system is stable. Given that the current direction flows from the PV power plant to the power grid, it is easy to deduce that the expression of the grid-connected current $I_g(s)$ is

$$I_g(s)=\frac{I_{inv}(s)Z_{inv}(s)}{Z_g(s)+Z_{inv}(s)}-\frac{V_g(s)}{Z_g(s)+Z_{inv}(s)} \tag{1}$$

To simplify the analysis process, Eq. (1) can be rewritten as

$$I_g(s)=\left(I_{inv}(s)-\frac{V_g(s)}{Z_{inv}(s)}\right)\frac{1}{1+Z_g(s)/Z_{inv}(s)}= G_1(s)G_2(s) \tag{2}$$

where, $G_1(s)$ and $G_2(s)$ are expressed as

$$G_1(s)=I_{inv}(s)-\frac{V_g(s)}{Z_{inv}(s)} \tag{3}$$

$$G_2(s)=\frac{1}{1+Z_g(s)/Z_{inv}(s)} \tag{4}$$

Eq. (2) can be divided into two parts. Based on the assumption above, $G_1(s)$ can be considered stable. Therefore, the stability of the grid-connected system depends on whether the ratio of the grid impedance $Z_g(s)$ to the output impedance $Z_{inv}(s)$ of the PV plant satisfies the Nyquist criterion. According to the analysis of the impedance, it can be concluded that with an increase in the grid impedance, the handover frequency of the grid and inverter impedance will be lower, which means the phase angle margin between the inductive grid impedance and the capacitive inverter impedance will be lower. The entire system tends to be unstable. By contrast, the high output impedance of the grid-connected system means that the stability of the system can be guaranteed when the grid impedance varies within a wide range.

3 Problem analysis

3.1 Structure of the PV plant

The Pingjiang PV power plant is located in Hunan Province, China, with a total capacity of 49 MW. The power plant is connected to the grid through the 110 kV Cangwu line. Fig. 2 shows a photograph of the PV power plant.

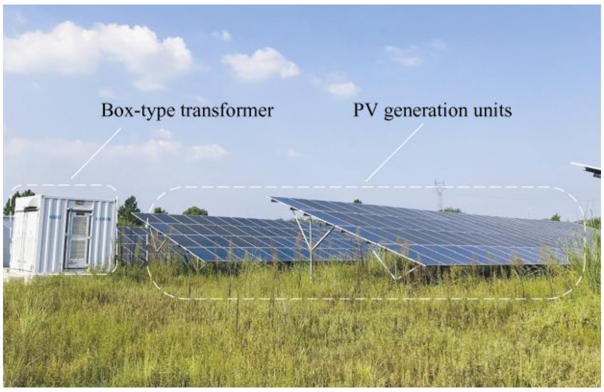


Fig. 2 Large-scale PV plant

Fig. 3 shows the structure of the PV power plant. As indicated in Fig. 3, the main transformer is an inductively filtered transformer whose connection group is YNd11+d11, the specific parameters of which are shown in Tab. 1.

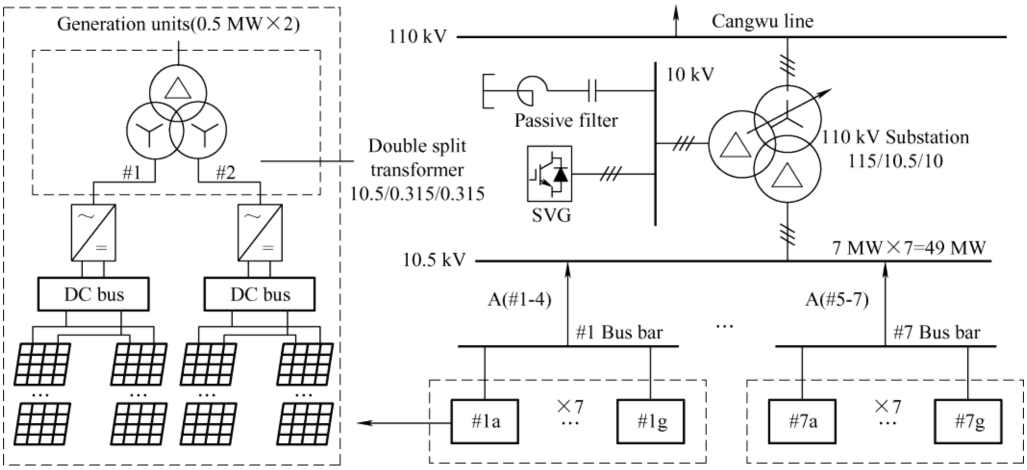


Fig. 3 Structure of PV power plant

Tab. 1 Specific parameters of the inductively filtered transformer

Parameter	Grid side winding	Filter side winding	Load side winding
Rated voltage/kV	115	10	10.5
Rated capacity/MVA	50	12	50
Equivalent impedance(%)	6.74	0.09	3.89
No-load loss/kVA	231.543		

The compensation system is composed of a single-tuned passive filter and a 5 MW static var generator (SVG) connected to the transformer through a filter winding. The passive filter is tuned at the fifth harmonic frequency, and the values of inductance and capacitance are 2.64 mH and 153.517 μF, respectively. The equivalent circuit model of the inductively filtered system composed of an inductively filtered transformer and fully tuned filters is shown in Fig. 4. At a specific harmonic frequency, the harmonics can be canceled out between the load winding and the filtering winding, and thus no harmonic is transferred into the grid winding. Different from traditional passive filtering technology, inductively filtered technology makes the best of the filtering potential of the transformer, which can reduce the effects of the harmonic components on the transformer.

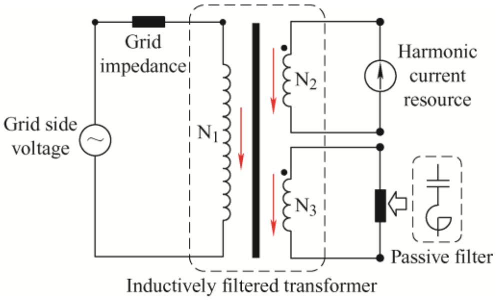


Fig. 4 Equivalent circuit model of inductively filtered system

The power plant adopts the power generation mode of the centralized interconnection after the decentralized inverter. Seven bus bars in the PV power plant are connected to the load winding of the main transformer. The full power plant is divided into groups A and B, which contain four and three collecting lines, respectively. Seven box-type transformers with Dy11y11 connection groups and the transformer ratio of 10/0.315/0.315 access to one collecting line. Each box-type transformer contains two 0.5 MW generating units.

3.2 Measured data analysis

During operation, two problems occur in the PV power plant: (1) The inverters in group B often trip and (2) the noise of the main transformer obviously increases. Transformer noise is usually caused by the harmonic flux, which is excited by the harmonic current. Three PW-3198 power quality analyzers were connected to the high-voltage bus of the main transformer, the low-voltage bus, and the output side of the inverter to test the power quality.

Figs. 5 and 6 show the waveforms and corresponding frequency spectrum on the 110 kV bus of the PV power plant, respectively. It can be clearly seen that during the normal power generation process, the power grid contains a large amount of 23rd harmonic voltage and current. It is therefore judged preliminarily that the problems in the power plant are related to the 23rd harmonic resonance.

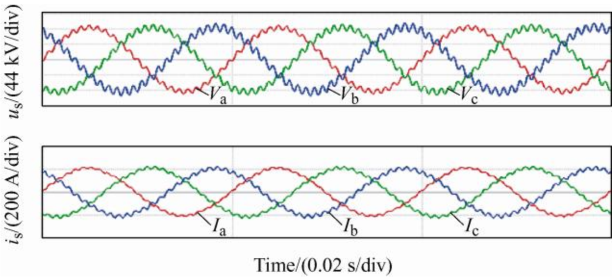


Fig. 5 Voltage and current waveforms during normal operation of PV power plant

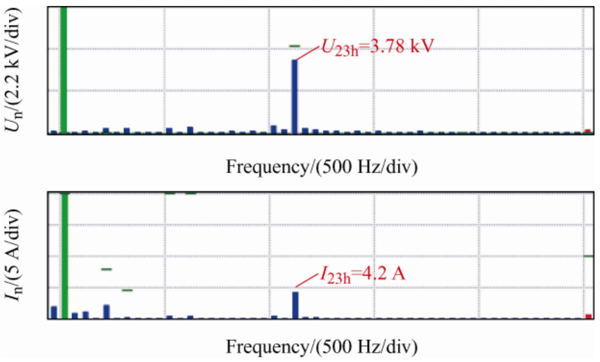


Fig. 6 Frequency spectrum of voltage and current during normal operation of PV power plant

To further identify the source of the 23rd harmonic, the background harmonic voltage of the power grid is measured when the generated power of the PV power plant reaches near zero. Figs. 7 and 8 show the 110 kV bus waveforms and the frequency spectrum, respectively, when the power generated is approximately zero. It can be determined from the figures that the grid contains little 23rd background harmonic voltage. Because other power electronic devices such as an SVG have not been used during the operation of the PV power plant, the 23rd harmonic is more likely to be generated by the photovoltaic inverter.

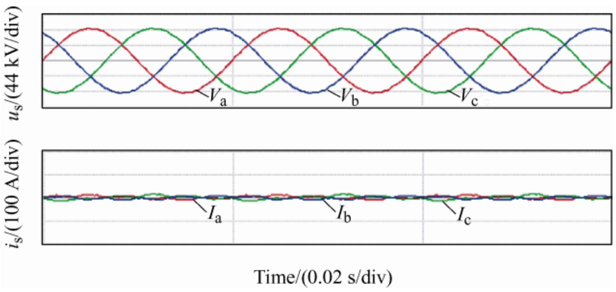


Fig. 7 Voltage and current waveforms when the generated power is approximately zero

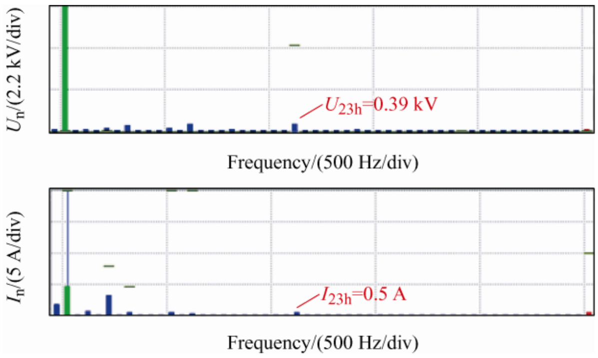


Fig. 8 Frequency spectrum of voltage and current when the generated power is approximately zero

Furthermore, Figs. 9 and 10 show the waveforms and frequency spectrum measured from the output side of the inverter, respectively. It can be concluded that the 23rd harmonic current of the inverters excited the system resonance.

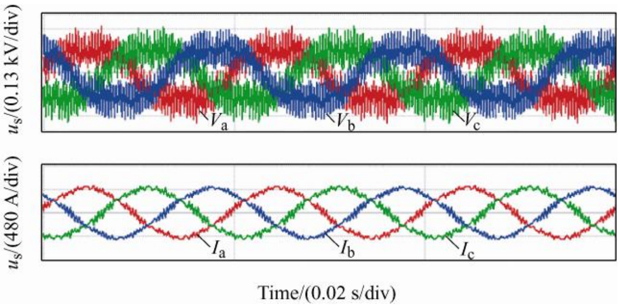


Fig. 9 Voltage and current waveforms of the inverter

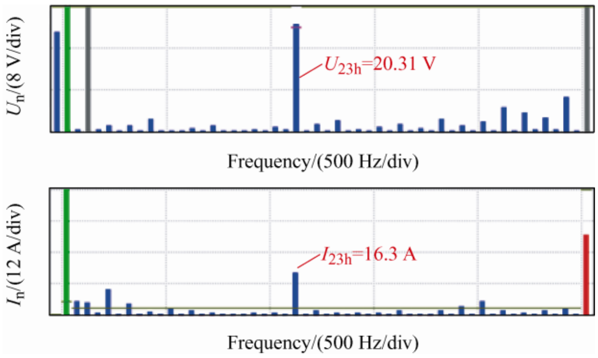


Fig. 10 Frequency spectrum of inverter output voltage and current

Fig. 11 shows the power variation curve on the 110 kV bus of the PV grid-connected system before and after the inverters have tripped. There is a power sag shown at 14:14:45 in the figure, which indicates that the inverter has undergone a process from tripping to reclosing.

The voltage and current waveforms before and after the trip are shown in Fig. 12. The content of the 23rd harmonic voltage and current reduced after the inverters tripped. In addition, the noise of the main transformer was also significantly reduced. It is therefore clear that the two problems mentioned above are caused by the 23rd harmonic resonance.

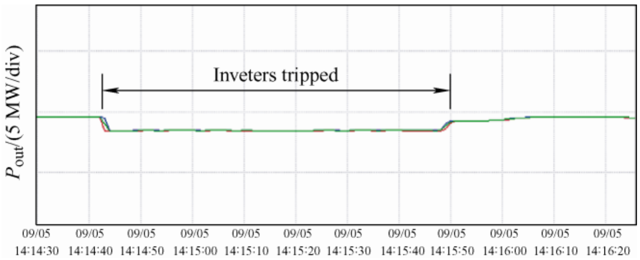
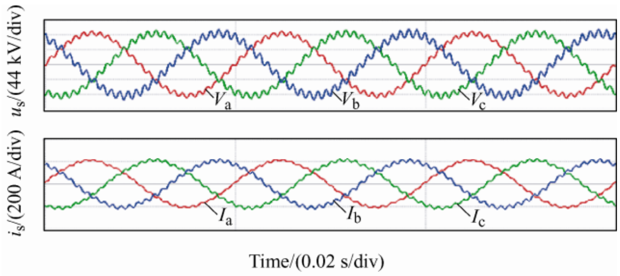
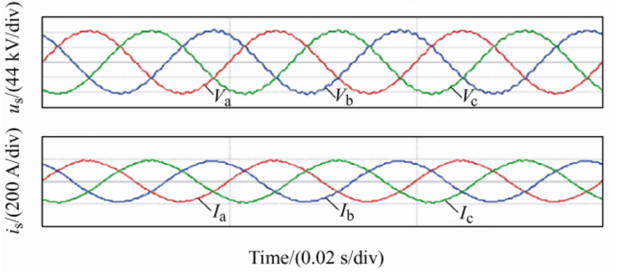


Fig. 11 Output power curve of the PV power plant



(a) Before the inverters tripped



(b) After the inverters tripped

Fig. 12 Voltage and current before and after inverters tripped

As shown in Fig. 13, the power factor of the inverters is approximately 0.78, which is quite different from their rated power factor of −0.9 to 0.9. The tests were conducted under good light conditions, and similar conclusions were drawn. This means that the PV grid-connected system injected a large amount of reactive power into the grid, which may lead to an increase in grid voltage and further aggravate the risk.

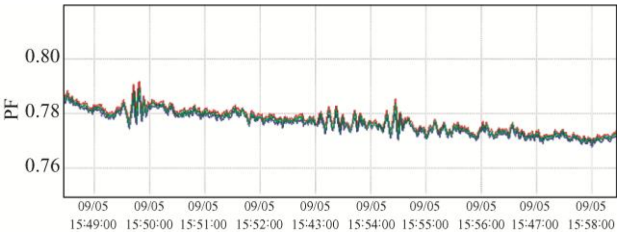


Fig. 13 Power factor of the inverter

4 Engineering experiment results

With an increase in the installed capacity of large-scale PV power plants, the key factor in the interaction between large-scale PV power plants and the power grid is the grid impedance. According to the conclusions in Ref. [22], in a parallel system of *n* inverters with a similar performance, the grid impedance connected to each grid-connected inverter is equivalent to being amplified by *n* times. The grid impedance is mainly composed of two parts: (1) line impedance and (2) leakage impedance of the transformer.

Based on the above conclusions, the system stability can be improved by increasing the output impedance amplitude of a PV grid-connected system or reducing the grid impedance. Although many studies have modified the control strategy to increase the output impedance or to compensate for the phase margin, these methods usually require a complicated debugging process, which is impractical. It is hoped that a simpler method can be used to change the overall parameters of the line to suppress the 23rd harmonic resonance.

The special structure of the inductively filtered transformer makes it better than conventional methods in a renewable energy grid-connected system. According to the conclusion in Ref. [18], when an inductively filtered scheme is adopted in renewable energy generation, compared with the traditional scheme, the harmonic resonance is better suppressed when the grid parameter fluctuates significantly. When considering the 23rd harmonic, the adoption of the passive filter is equivalent to a change in the grid impedance, which improves the phase margin of the impedance ratio and avoids the system from forming 23rd harmonic resonance.

Figs. 14 and 15 show the 110 kV bus waveforms and frequency spectrum before placing a passive filter on the low-voltage bus of the inductively filtered transformer into operation. The system exists under excitation conditions of the 23rd harmonic resonance, which may destabilize the entire system. In addition, distortion of the 110 kV bus voltage will affect the power supply quality of the grid.

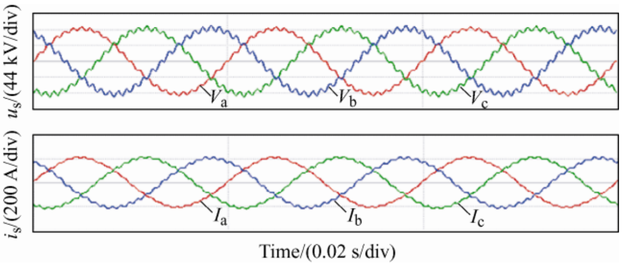


Fig. 14 Voltage and current waveforms without a filter

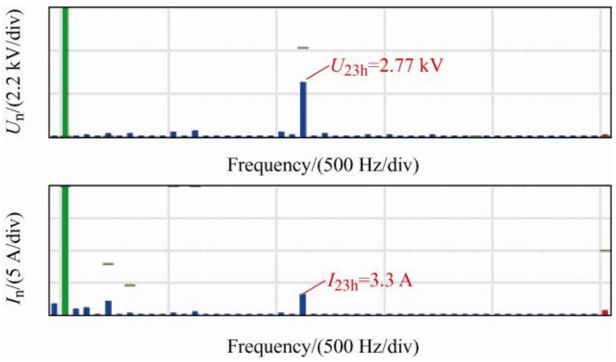


Fig. 15 Frequency spectrum of voltage and current without a filter

Figs. 16 and 17 show the 110 kV bus waveforms and frequency spectrum, respectively, after placing the passive filter on the low-voltage bus of the inductively filtered transformer into operation. It can be concluded from the figures that the 23rd harmonic has been effectively suppressed, and the whole system has difficulty forming such resonance.

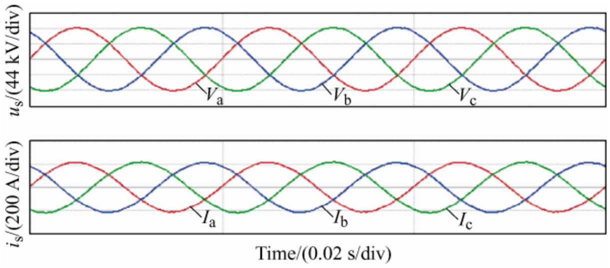


Fig. 16 Voltage and current waveforms with a filter

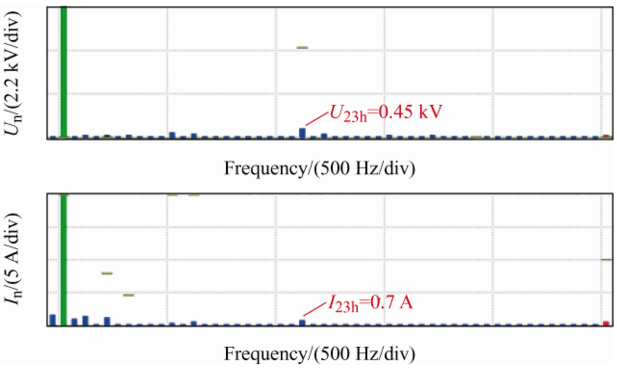


Fig. 17 Frequency spectrum of voltage and current with a filter

In addition, it is necessary to adjust the power factor of the inverter in the PV power plant to improve the efficiency and reduce the reactive power injected into the system.

Although the method proposed in this paper may not be the best solution, it damped the 23rd harmonic resonance effectively. After using the proposed method, the stable operation of the PV power station has also verified its effectiveness.

5 Conclusions

This paper takes a PV power plant as the research background and establishes a simplified model of a large-scale PV grid-connected system. Through the proposed simplified model, the influence of impedance on the system stability is analyzed. The structure of the PV power plant is then introduced and a detailed analysis of the measured data on the PV power plant with harmonic resonance problems is conducted. The measured data indicate that the problems are related to the 23rd harmonic resonance. Finally, based on the theoretical analysis and the existing equipment, a simple and effective method is proposed to avoid the formation of the 23rd harmonic resonance. A detailed model and analysis of multiple inverters used in the plant is another key issue, which will be discussed in future research.

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