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Evaluating the delay problems and solutions for active filters in Photovoltaic grid-connected

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Abstract:

An active power filter (APF) is one of the main ways to eliminate the harmonic quality of the grid, and LCL is currently the APF connected to the grid's common filters. To inhibit the resonance problem caused by the LCL filter, active damping based on capacitive current feedback is commonly used. Active damping can effectively inhibit the resonance caused by the LCL filter, and it can be equivalent to the resistance parallel to the filter capacitor under the simulation control, due to the stagnation of capacitive current. After that, the virtual resistance value will be negative, and the negative damping characteristics will be presented, which will affect the stability of the system. For this reason, this article aims to evaluate the delay problems and solutions for active filters in photovoltaic grid-connected, and four solutions were analyzed. The first method is modifying the sampling method, the second one is the delay compensation method for state estimation, the third one is the phase advance method and the fourth one is the Kalman Filter.

Keywords: active power filter (APF), digital delay, capacitance, current

1. Introduction

Since the beginning of the 21st century, with the increasingly serious environmental pollution and the continuous decline of fossil resources, the energy crisis has kicked off. In the face of this worldwide energy crisis, some countries are looking for new energy channels to solve the problem of energy decline. In recent years, China has vigorously developed photovoltaic power generation, from small household photovoltaic panels to large capacity grid-connected, and solar energy has been created. Among them, the "China Photovoltaic Industry Association" pointed out that from January to October 2022, China's new photovoltaic installed capacity was 58.24GW, a year-on-year increase of 98.7%, and as of the end of August 2023, the total installed capacity of photovoltaic was 349.9GW, second only to the total installed capacity of thermal power and hydropower[2]. The photovoltaic system has the advantages of a short construction period, less land space occupation, and low negative effects on the ecological environment,

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and it is a clean and sustainable energy type. The photovoltaic grid-connected system provides a new idea for energy depletion and environmental pollution, but it is susceptible to weather changes, the photovoltaic power generation is intermittent and the utilization rate is low. On the one hand, it is hoped that photovoltaic power generation can be widely utilized, and on the other hand, it is necessary to reduce the harmonics brought by photovoltaic systems to the power grid. With the widespread use of power electronics in photovoltaic grid-connected devices, a large number of harmonics are generated in the system, and the power quality is greatly reduced. In practical applications, due to the existence of harmonic sources, a large number of harmonics are introduced to the grid-connected system, which not only affects the normal operation of the load but also destroys the stability of the grid-connected inverter system. The active filter can effectively solve the problem of harmonic pollution, it can dynamically compensate the harmonic component, and the harmonic suppression effect is good, but there are also problems such as single function, high cost, not wide application, and delay in use. Therefore, the author hopes to carry out a project to find some way to solve or reduce the impact of the active filter delay problem on the power quality of photovoltaic grid-connected PV. In this way, it is hoped that harmonics can be filtered out more effectively, ensuring the safety of electricity consumption and improving the quality of electricity consumption in the power grid.

2. Literature review

In the literature review part, the author will first introduce the causes of harmonics and their harms. Then, give the definition, principle, and function of active filters. After that, the principle and function of the Photovoltaic Grid Connection are given. Lastly, introduce and analyze active filter delay problems.

2.1 The causes of harmonics and their harms

When the current flows through the nonlinear load of the power system in the power grid, there is a nonlinear relationship between the load voltage on the nonlinear load and the load current, that is, there is a nonlinear component, also known as harmonics. Harmonics is defined by Pichan[26] as the amount of electricity contained in the current is an integer multiple of the fundamental wave.

In addition to the nonlinear load, the frequent conduction and shutdown of the switching devices in the grid-connected photovoltaic power generation system will also produce harmonics and the dead-zone effect of the photovoltaic grid-connected converter and the fluctuation of the DC side[18] voltage when the light changes will even aggravate the harmonic pollution of the system, resulting in the decline of the power quality of the large power grid and the deviation of the electrical equipment on the user side from the ideal working state. In particular, the new energy power generation equipment connected to the grid may also be related to The problem of harmonic interaction caused by the harmonic source of nonlinear load, and the power supply quality of small-capacity distributed photovoltaic grid-connected equipment at the edge of the power grid is affected by this[17].

The ideal utility grid should supply power to users at a constant frequency, sine waveform, and standard voltage. When a current signal forms a non-sine wave current due to the presence of a nonlinear load, that is, the whole circuit generates a harmonic current signal. Harmonics will have a harmful impact on various types of power equipment, communication transmission equipment, and power systems, and in serious cases, they will cause serious damage to power equipment and even cause power system safety accidents. Before the widespread application of power electronic testing equipment, people carried out some in-depth research on power harmonics and their pollution hazards[8], and had a certain new understanding of them, but at that time, harmonics and their pollution did not attract enough social attention. In recent years, people have higher and higher requirements for power quality and equipment safety, and the harmonic control of the distribution network in the power system has also received great attention from society. The main hazards of harmonics are manifested in the following. According to previous studies, the disadvantages of harmonics are presented:

(1) As supported by Liu[21] Harmonics will bring additional losses to the equipment in the public power grid, make the equipment heat up, and reduce the efficiency of power generation, transmission, and other electrical equipment related to the power system in the power grid. The long-term existence of a large number of harmonics will cause a sharp increase in power loss, which will increase the maintenance cost of power equipment in the daily operation of power lines, thereby greatly increasing the expenditure of line electricity charges. The presence of a large number of harmonics can lead to overheating of power lines, and in severe cases, there is even the possibility of direct fire[8].

(2) Li [14] comments that when the harmonics are large, it will affect the normal operation of various civil building electrical equipment. The influence of harmonics on the motor of the equipment, in addition to directly causing some additional mechanical loss of the stator winding, rotor winding and stator and rotor core of the motor, will even directly produce mechanical vibration, noise, and

internal overvoltage of the motor[6], so that the parts of some motors are seriously worn locally, resulting in overheating of the motor, resulting in the failure of some motor equipment to work normally. Too high harmonics will also lead to overheating of electrical appliances, cables, and other insulating equipment, aging of insulating materials, and even greatly shortening the life of the insulating materials.

(3) The harmonic is too large will directly lead to the failure of relay protection and automatic device, and also lead to the real-time measurement of electrical equipment the real-time measurement of the instrument is inaccurate, and the relay protection device plays an extremely important role in the safe operation of the power grid, due to the existence of harmonics, may cause the mis operation or rejection of the relay protection device. The malfunction of the integrated automation device in the power system may cause the collapse of the local power grid, causing large-scale power outages and other vicious events. There have been many large-scale power outages and explosion accidents caused by power grid harmonics and negative sequence discharge in China, causing heavy losses to the national economy, which is supported by Zhou [40].

(4) Harmonic interference will cause great interference to the signal of the entire communication control system adjacent to the signal. Harmonic interference will produce radio frequency noise, reduce the quality of the entire communication system, and cause the temporary loss of radio frequency information when the impact is serious so that the entire communication control system can not work normally temporarily and this situation is supported by Luan[23]. Therefore, whether from the perspective of the stable operation of the large power grid or the safe operation of electrical equipment, the control of harmonic pollution has reached a moment when effective measures are urgently needed.

(5) Excessive harmonics can cause parallel resonance and local series resonance in some areas of the public power grid [38], which may amplify the entire harmonic range, which may greatly increase the safety hazards such as loss, noise, and equipment failure caused by harmonics[11].

In summary, Harmonics are extremely harmful to power safety and power efficiency and must be dealt with in time in the power grid. Solving the harmonic problem is very beneficial to the safe and efficient operation of the grid system, and the reduction of losses can also reduce the cost of electricity.

2.2 Overview of active filters

Due to the widespread promotion of smart distribution grids, power electronics technology has become an indispensable part of the power supply system and appears in various professional fields. However, power electronic devices are nonlinear, and they will also bring harmonics of various frequencies during operation, which will interfere with the stable and reliable operation of the power system. At present, active power filters play an important role in filtering out harmonics, isolating harmonics, and compensating for reactive power and load imbalance.

In the article[2], active power filters mainly have the following advantages: (1) they are easy to control and can respond quickly when the state changes; (2) The characteristics and properties are stable, not subject to the wave disturbance of various parameter changes in the power supply network, can track and curb harmonics of various frequencies, and at the same time, it is continuously compensated in real-time according to the reactive power of the system; (3) The volume weight is relatively small. Due to these advantages, the active power filter occupies an important position in the field of suppressing harmonics in the power system.

From the article[15], in order to eliminate the harmonic current of the active filter, it is necessary to detect the size of the harmonic current, so that the detected harmonic current value is used as the current instruction value to control the inverter circuit in the active filter, so that it can generate the compensation current signal with the same magnitude of the harmonic current and in the opposite direction, so the command current operation (i.e., harmonic current detection) and the compensation current control (i.e., the control method) are also the indispensable factors that need to be considered in the design of the active filter.

An active power filter (APF) is one of the main ways to eliminate harmonic quality problems in the power grid, LCL(L means resistance, C is a capacitor, and LCL refers to the structural form of the filter. The head is a set of inductors in series, and the middle part is a parallel security capacitance. A set of inductors connected in series) is currently a common filter that APF uses to connect to the photovoltaic grid. Therefore, this paper mainly focuses on LCL-type active filters.

In summary, the active filter is a kind of filter with high harmonic removal efficiency and low noise, which plays a huge role in photovoltaic grid connection.

2.3 Overview of active filters

Photovoltaic power generation is highly dependent on semiconductors, and solar energy is converted into electricity using the photocurrent and photovoltage generated by sunlight. There are many advantages of photovoltaic power generation owners, first of all, the power supply

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problem in remote areas can be solved by photovoltaic power generation, and it has great development prospects when used in roofs and other buildings combined. With the increasing competition in the photovoltaic industry, the cost of technology in photovoltaic power generation is getting lower and lower. At the same time, photovoltaic power generation can better transfer emissions and optimize the energy structure. The installation of grid-connected power generation systems in 10% of deserts can provide 10,0000 billion kilowatts of electricity per year, which is equivalent to 4~5 times the current annual electricity consumption in China[11].

The application of photovoltaic power generation will affect the voltage stability because of the change of voltage output power and the active and reactive load of the grid itself will change. At the same time, it will also affect the stability of the power angle[11]. The integration of the photovoltaic grid into the power grid will affect the failure of the distribution network to a certain extent, and the relay protection and automatic devices will be changed to a certain extent. At present, the scale of photovoltaic power generation connected to the power grid is getting larger and larger, and nonlinear loads continue to appear in the power grid, resulting in a great impact on the quality of power supply. With the increase of nonlinear load, the power grid inverter switch will be delayed, and the power output will appear harmonics, and with the extension of the grid-connected time, the harmonic changes will become more and more drastic. Therefore, the use of active filters in photovoltaic grid-connected has changed this status quo very well, and the active filters continue to change the filter frequency during use, which ensures the output quality of photovoltaic grid-connected more efficiently. However, due to the delay in the process of sampling and calculating the feedback, the filtering quality of the active filter decreases.

In summary, the active filter is a kind of filter with high harmonic removal efficiency and low noise, which plays a huge role in photovoltaic grid connection.

2.4 Active filter delay problems

The LCL filter has the characteristics of a third-order system, there is a resonance phenomenon between the filter capacitor and the filter inductance, and the resonance spike is generated at its resonant frequency, and at the same time, a large interference harmonic is generated, which makes the output current of the grid-connected inverter oscillate, and even causes the stability of the system to drop greatly in serious cases[16]. Therefore, solving the delay problem is of great help to the quality of photovoltaic grid-connected output power. In order to eliminate the problem of resonant spikes in LCL-type active filters, active damping is used, which does not introduce additional losses when suppressing resonant spikes. However, when active damping is used, the phase lag problem introduced in the digital control system will affect the stability of the grid-tied inverter. The core part of the active filter system of the inverter is of great significance for the stability of the active filter system, as well as the filtering performance and efficiency.

In order to solve the delay problem of active damping in the inverter, the compensation strategy needs to be studied. There are four main methods according to the articles:

1. Modify the sampling method, that is, the method of instant sampling of capacitive current, advance the sampling time of capacitive current, and reduce the delay control of active damping of capacitive current feedback, but high-frequency noise will be introduced into the peaks or troughs sampled at non-triangular carriers [37].

2. A delay compensation method for state estimation is proposed, which achieves the purpose of correcting phase lag through series estimation, but the change of circuit parameters in practical application will affect the prediction bias.

3. As mentioned by [5], the phase advance compensation link is introduced into the capacitor current feedback loop to eliminate the one-beat delay of the capacitor current control, but it will produce high-frequency noise at the Nyquist frequency amplification position.

4. The Kalman filter method is a more accurate and effective method in practical application. Active damping is adjusted by weighting the estimated and actual measured values of the system to produce a value with a small deviation.

Modifying the sampling method, prediction, and leading phase compensation all have their drawbacks. Modifying the sampling method and leading phase compensation will produce high-frequency noise while modifying the sampling method will deviate due to changes in capacitance parameters. Kalman filtering is an ideal method because it has a small deviation and does not produce noise. The existing research mostly wrote about the first three methods, but it is not integrated into the Kalman filter method. Therefore, this study intends to provide the method of Kalman filter.

3. Methodology

3.1 Literature research

In terms of literature research, this research has collected information on the hazards and causes of harmonics, including damage to power equipment, interference to electronic equipment, impacts on the safety of power equipment, power system operation, power quality on transmission efficiency, etc. At the same time, it also introduces the conversion of light energy into electrical energy through the photogenerated volt effect of semiconductors. The definition of active filter and the principle of real-time sampling for filtering are also understood, and finally, the delay problem of active filter, which is the main thing to be studied in this paper, is also understood. Specifically, it is a sampling delay problem with active damping to suppress resonance in LCL-type active filters. This information is used to solve the main delay problem in this research. By understanding the definition and hazards of harmonics, the author can deepen our author's understanding of the principle of active filters, and further prove the importance of the author's research and solution to the sampling delay problem, because the delay problem will seriously affect the performance of LCL filters in photovoltaic grid-connected, resulting in poor harmonic filtering effect.

By understanding the principle and structure of photovoltaic grid connection, can have a better understanding of harmonic generation and understand the necessity of the use of active filters in photovoltaic grid connection. Reading articles related to the mechanism of active filters will give the author a first-hand understanding of the principles of active filters and the root causes of sampling delays caused by active damping.

At the same time, the author read the article on the problem of active damping sampling delay in LCL-type active filters, which helped the author to understand more about the problem and find a variety of solutions. The above resources are all collected from credible platforms such as CNKI, and Google Scholar, thereby their credibility is ensured. In terms of data analysis, information will be obtained from the articles, and this study collected data on comparison after each method to solve the sampling delay compared to the use of the previous wave. The data will be used to discuss which method is the most effective and which method is most feasible in practice, and finally to arrive at the best solution to the problem of active damped sampling delay.

4. Results

The Kalman filter is a highly efficient recursive filter that estimates the state of a dynamic system from a series of incomplete and noisy measurements. The Kalman filter will take into account the joint distribution of each measurement at different times, and then produce an estimate of unknown variables, so it will be more accurate than the estimation method based on a single measurement quantity. The Kalman filter gets its name from Rudolf · Kalman, one of the main contributors.

As [19] supported, the Kalman filter algorithm is a two-step procedure. In the estimation step, the Kalman filter produces an estimate of the current state, which also includes uncertainty. As long as the next measurement is observed, it must contain some degree of error, including random noise. Estimates are updated by weighted averages, and the higher the certainty, the higher the weighted weight of the measurements. The algorithm is iterative and can be executed in a real-time control system, requiring only current input measurements, past calculations, an uncertainty matrix, and no other previous information.

As [27] supported, the Kalman filter is a recursive estimation, that is, an estimate of the current state can be calculated as long as the estimate of the state at the previous time and the observed value of the current state are known, so there is no need to record the historical information of the observation or estimate. The Kalman filter differs from most filters in that it is a pure time-domain filter, which does not need to be designed in the frequency domain and then converted to the time domain like a frequency-domain filter such as a low-pass filter.

Kalman filter is mainly divided into two parts: prediction and update, which requires the construction of the state equation and observation equation of the system, and the initial state of the system is known. In the prediction phase, the filter uses the estimate of the previous state to make an estimate of the current state. In the update phase, the filter uses observations of the current state to refine the predictions obtained in the prediction phase to obtain a new, more accurate estimate.

Carman filtering is a method that is optimal estimated by the system state through the linear system state equation. The system state is optimized. Because the observation data includes the impact of noise and interference in the system, the optimal estimation can also be regarded as the filter process. In simple terms, it is:

The predicted value calculated by the linear mathematical model + Sensor measurement value = More accurate measurement value[21].

Then derive the parameters of Karman filtering:

$\hat{x}_{[k]}$ represents the estimation of the state at time k

$\hat{x}_{[\bar{k}]}$ indicates the state of the known past k moments and predicts the state of the k+1 moment

$P_{[k]}$ is the covariance matrix of the posterior estimation error, which measures how accurate the estimate is

Linear Karman formula derivation:

Linear Karman's five formulas:

(1)Calculate the priority state estimation:

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$$\hat{x}^{-}_{[k]} = \hat{x}_{[k-1]} + Bu_{[k-1]}$$

(2)Calculate the priority state estimation:

$$P^{-}_{[k]} = P_{[k-1]} + Q_c$$

(3) Calculate Karman filter gain:

$$K_{[k]} = \frac{P^{-}_{[k]}}{P^{-}_{[k]} + R_c}$$

(4) After calculating the status estimation:

$$\hat{x}_{[k]} = \hat{x}^{-}_{[k]} + K_{[k]}(z_{[k]} - \hat{x}^{-}_{[k]})$$

(5) After the update, the status estimation error matrix:

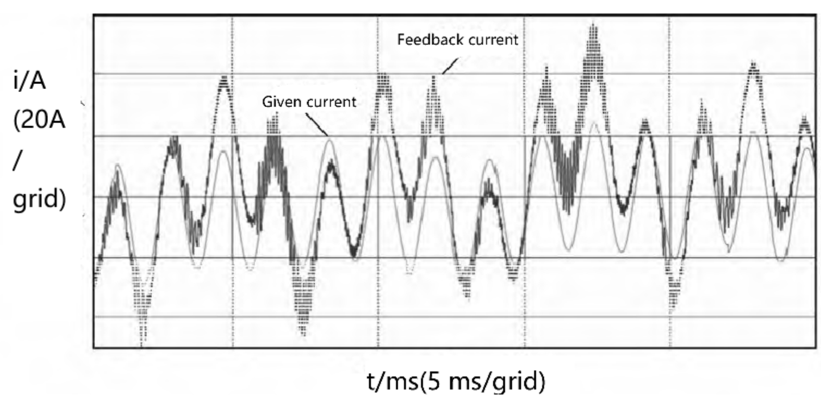
$$P_{[k]} = \left(I - K_{[k]}\right) P^{-}_{[k]}$$

In the prediction step, the state of the current moment is predicted based on the state and control quantity of the previous moment. This prediction is an estimate because it does not take into account the observations at the current moment. The error covariance matrix of the predicted value is calculated from the error covariance matrix and the system noise covariance matrix at the previous time. Formulas 1 and 2 are used for the prediction step.

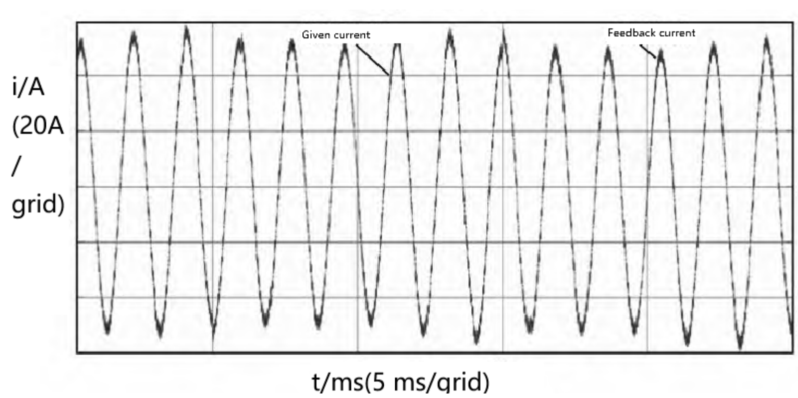
In the update step, an estimated state at the current moment is calculated based on the observed and predicted values at the current moment. This estimate is a more accurate estimate because it already takes into account the observations at the current moment. The error covariance matrix of the state estimate is calculated from the error covariance matrix, the observed noise covariance matrix, and the Kalman gain calculated in the prediction step. Equation Three, Formula Four, and Formula Five are used for the update step.

The optimal variance with the normal distribution error is the optimal $K^* = \frac{\sigma^2_{e_1}}{\sigma^2_{e_1} + \sigma^2_{e_2}} = \frac{Var(e_1)}{Var(e_1) + Var(e_2)}$ is consistent.

Using this coefficient K to weigh the valuation and measurement value, and finally, can get a more accurate result. Figure 1a is a detection diagram given by a given current and feedback current before using the Karman filtering method. Figure 1b is the detection diagram after use.



(a) before using



(b)after using

Figure 1 Given current and feedback current waveforms before and after using the Karman filtering method

It can be seen from the figure that the current after using Karman filtering is significantly more stable, and the resonance inhibitory effect is better.

5. Discussion

Modify the sampling method, that is, the method of instantaneous sampling of the capacitor current, the sampling time of the capacitance current will be advanced in advance, and reduce the delayed control of the source damping at the non-triangular wave. There is a deviation from the actual value of advanced sampling, and there are large defects in actual applications.

The delayed compensation method of state estimation can achieve the purpose of correcting phase lag through the section of the series of stagnation, but the changes in the circuit parameters in the actual application will affect the predicted deviation.

The introduction of phase is introduced to eliminate a delay in the control of capacitive current control, but high-frequency noise will be generated at the positioning position of the Nyquist frequency amplification.

The Karman filtering method proposed in this article considers the factors including noise and interference. Using probability theory and the Karman formula to make a weighted average of the prediction and actual detection values. The impact of reducing delay detection on resonance inhibitory performance is a low-cost, high-efficiency method in practical applications.

6. Evaluation

Of course, there are some limitations in the research. It is inevitable that the Karman filtering method has higher requirements for controlling the computing power of the chip. In practical applications, the solution needs to be adjusted according to the specific situation. However, the research has its highlight, In this study, the advantages and disadvantages of the four methods can be analyzed. In addition, the specific process of Calman filter parameters was listed in detail, and Dr. Pang of Tsinghua University was interviewed to confirm the superiority of the Karman filtering method. All research is authoritative.

7. Conclusion

On the basis of the analysis of traditional affordable damping strategies, this article uses the Karman filtering method to effectively reduce the effects of sampling delay on the stability of the system. First, analyze the structure of virtual impedance in the filter system. When the capacitor current is lagging behind, the system will have negative damping. The main analysis of the Karman filtering method, and compared with the remaining three methods to obtain the superiority of the Karman filter wave. At the same time, the data chart is referenced to prove the feasibility of this method.

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