Research on Optimization Strategies for Immersive Communication Experience in Metaverse Scenarios

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Abstract: The widespread deployment of nonlinear loads in low-voltage power distribution systems has led to increasingly severe harmonic pollution. Passive filters have become the mainstream mitigation solution due to their cost-effectiveness and reliability; however, in practical operation, factors such as component parameter drift, grid frequency fluctuations, and temperature variations often cause filters to deviate from their designed resonant frequency, resulting in detuning issues. This not only diminishes the filtering effectiveness but can also induce parallel resonance, amplifying harmonic currents. This paper systematically analyzes the causes of detuning and its impact on system safety and energy efficiency. Building upon this analysis, we propose an integrated solution that combines dynamic detection, adaptive tuning, and intelligent compensation techniques. Through real-time parameter identification, variable reactance adjustment, and coordinated control strategies, the filter is enabled to continuously track the actual harmonic frequency, ensuring optimal filtering performance at all times. The research findings demonstrate that adaptive tuning and compensation technologies can effectively address the challenges posed by detuning, providing a reliable technical pathway for harmonic mitigation in low-voltage power distribution systems.

Keywords: Harmonic Mitigation; Detuning; Adaptive Tuning; Dynamic Compensation

1. Introduction

With the rapid advancement of power electronics technology, the proportion of nonlinear loads in low-voltage power distribution systems has been steadily increasing; as a result, the resulting harmonic issues have become one of the core factors affecting power quality. Passive filters are widely employed in harmonic mitigation due to their simple structure, low cost, and reliable operation. However, in practical applications, factors such as the natural degradation of capacitor capacitance, the drift in reactor inductance, grid frequency fluctuations, and variations in ambient temperature often cause the actual resonant frequency of the filter to deviate from its design value, leading to detuning. This detuning not only significantly diminishes the filtering effectiveness but can also induce local parallel resonance, amplifying harmonic currents and posing a serious threat to equipment safety and system stability. Traditional fixed-parameter filters are ill-equipped to adaptively respond to these dynamic changes; therefore, there is an urgent need to explore novel mitigation approaches featuring active tuning capabilities. This paper conducts a systematic analysis of the causes and impacts of detuning and proposes a synergistic strategy combining adaptive tuning and dynamic compensation, aiming to provide theoretical support and technical reference for harmonic mitigation in low-voltage power distribution systems.

2. Harmonic Characteristics and Mitigation Requirements for Low-Voltage Distribution Systems

2.1 Sources of Harmonics and Their Impact on Power Distribution Systems

Harmonics in low-voltage distribution system mainly come from frequency converter UPS、Nonlinear loads such as rectifier equipment, LED drive and switching power supply inject a large number of odd harmonics into the power grid, with the 5th, 7th and 11th harmonics being the most significant. Harmonic current produces voltage drop on the system impedance, causing additional loss and torque ripple of motor, eddy current loss of transformer aggravates temperature rise, skin effect of cable accelerates insulation aging, and may lead to misoperation of relay protection device. More seriously, when the system impedance matches the harmonic source frequency, it will cause parallel or series resonance, which will amplify the harmonic current several times or even dozens of times, directly endangering the equipment insulation and system operation safety.

2.2 The Central Role of Passive Filters in Harmonic Mitigation

Because of its simple structure, reliable operation, low cost and convenient maintenance, passive filter plays a leading role in harmonic control in medium and low voltage distribution systems. Its typical forms include single tuned, double tuned and high pass filters, and attenuation is achieved by providing low impedance shunt channels for specific harmonics. Compared with the active filter, the passive filter does not need external control power supply and complex power devices, and operates reliably and has a long life under rated conditions. In addition, its capacitor outputs capacitive reactive power under fundamental wave, and has the function of reactive power compensation. It is widely used in various low-voltage scenarios such as industrial plants, data centers and commercial buildings.

2.3 Basic Principles of Filter Design and Parameter Tuning Methods

The design of passive filter is based on resonance theory, and its resonance frequency is determined by L and C. during the design, the capacitance is determined according to the reactive power demand, and then the reactance value is calculated according to the target harmonic number[1]. The selection of quality factor should take into account the selectivity sensitivity and the fault tolerance of parameter deviation. In the project, the shunt design is carried out according to 70% -90% of the target harmonic current, and the constraints such as capacitor terminal voltage, reactor temperature rise and parallel resonance point are checked. The grouping switching scheme needs to match the load change law. Although a margin will be reserved for aging and temperature at the design stage, it is difficult to cover all working condition changes, laying a hidden danger for the problem of detuning.

3. Causes and Impact Mechanisms of Filter Design Dissonance Issues

3.1 Definition of Misalignment, Characterization Parameters, and Engineering Manifestations

The detuning shows that there is a deviation between the actual resonant frequency of the filter and the design target frequency, and its essence is that there is an offset accumulation effect between the inductance or capacitance of the LC loop and the design value. In engineering, the degree of detuning is generally used to quantitatively describe the degree of deviation, which is defined as the ratio of the difference between the actual resonant frequency and the design resonant frequency to the design frequency, and its unit is percentage. When the detuning degree is greater than 1/2 of the passband bandwidth of the filter, the target harmonic impedance of the filter increases sharply, the shunt capacity decreases significantly, and the filtering effect becomes significantly worse. Detuning refers to a series of observable phenomena in the project site, such as a significant decline in harmonic filtering efficiency from the design value, abnormal heating of capacitor banks, and even expansion deformation. When the reactor generates abnormal electromagnetic noise, the fluctuation of system power factor increases. In some cases, the harmonic current recorded by the protection device is larger than the value before the input filter. These performances do not occur alone, are often interrelated, and are gradually degraded. It should be pointed out that slight detuning is a common and difficult problem to completely avoid in engineering, and the key is whether the degree of detuning is within the acceptable range; Once the allowable boundary is exceeded, the filter will not only lose its original role, but also become the source of harmonic amplification, which will pose a substantial threat to the safe operation of the system.

3.2 Analysis of Key Factors Contributing to Dissonance

The causes of filter detuning can be divided into two types according to the time scale: long-term gradual change type and short-term fluctuation type. The factors affecting the capacitance attenuation of power capacitor and the inductance drift of reactor are of long-term gradual change type. The capacitor is affected by many factors such as electric field stress, temperature cycle and chemical aging of dielectric materials during operation. The capacitance decreases slowly year by year, and the attenuation rate is generally annual average~annual average, and the longer the operation period, the cumulative attenuation can reach annual average or higher. The inductance of reactor is offset by the change of core permeability and the slight change of geometric size caused by winding temperature rise. The short-term fluctuation factors are represented by grid frequency fluctuation and environmental temperature change - the allowable frequency deviation of public power grid is ± 0.2~± 0.5 Hz, which is equivalent to about 1%~2.5% equivalent frequency deviation for the fifth harmonic (250 Hz); The dielectric constant of capacitor and the magnetic characteristics of reactor core will be affected by the temperature change, especially in the area with obvious seasonal temperature difference, the parameter drift caused by temperature can not be ignored. When the number of filter input groups changes, the change of the equivalent impedance of the system will also have an indirect impact on the real resonance point of each filter branch, and the condition correlation makes the problem of gain and detuning more complex.

3.3 The Detrimental Impact of Mismatch on Filtering Performance and System Safety

Detuning produces multidimensional and cascading effects in low-voltage distribution systems. In terms of filtering performance, detuning will cause the impedance characteristic curve of the filter to shift, and the original low impedance point will no longer align with the true harmonic frequency, resulting in the increase of harmonic shunt impedance and the nonlinear reduction of filtering efficiency[2]. Through simulation analysis and field measurement, we find that when the detuning degree reaches the range of 3%~5%, the filtering efficiency of single branch will drop sharply from more than 90% to 50% or less, which indicates that a large number of harmonic currents still flow into the upper system, resulting in the bus voltage distortion rate exceeding the standard. The more serious problem is the safety - the change of the capacitive reactance and inductive reactance of the filter after the detuning at the fundamental frequency makes the equivalent impedance of the system exhibit negative damping characteristics and induces parallel resonance at some frequency points. In the resonant state, even small harmonic source current can produce extremely high harmonic voltage on the system impedance, which not only threatens the insulation performance of the capacitor and reactor of the filter itself, but also may affect other grid connected equipment. In the detuning state, the capacitor has withstood the effect of large harmonic current for a long time, and the calorific value increases with the square of the effective value of the current, which accelerates the development of dielectric aging and partial discharge, and finally causes the Breakdown Failure of the capacitor, even the explosion accident, resulting in the loss of equipment and unplanned power failure.

4. Principles and Implementation Approaches of Adaptive Tuning Technology

4.1 Basic Architecture and Control Logic for Adaptive Tuning

The core idea of adaptive tuning technology is to make the filter actively sense the change of operation state and automatically adjust its parameters, so that the resonance frequency of the filter can track the real harmonic frequency at any time to maintain the optimal filtering performance. The basic structure of this technology includes three parts: signal detection unit, central processing unit and execution regulation unit, forming a closed-loop system. The signal detection unit collects the bus voltage and filter branch current signals from the voltage transformer and current transformer in real time, and enters the digital signal processor after pre filtering and synchronous sampling. The central processing unit uses the spectrum analysis algorithm to extract the amplitude and phase information of each harmonic and compare it with the set resonant frequency to calculate the current detuning degree and the expected parameter adjustment. A hierarchical strategy is adopted in the control logic. The outer layer determines the target tracking frequency based on the change of the harmonic distribution of the system, while the inner layer generates adjustment instructions based on the deviation of the actual resonant frequency from the target frequency. An execution adjustment unit is used to drive the variable reactor or the adjustable capacitor to change parameters to complete the tuning action after receiving the command. The whole control process is carried out in a fixed cycle, which ensures that the filter has the ability of rapid response and continuous tracking to system state changes, thus realizing the transition from static design to dynamic adaptation paradigm.

4.2 Dynamic Tuning Technology Based on Variable Reactors

As the core executive device to realize the sustainable adjustment of filter inductance, the technical scheme of variable reactor is divided into magnetic control type, thyristor control type and mechanical adjustment type. The magnetically controlled variable reactor changes the permeability at the working point of the core through DC bias, so as to realize the continuous and smooth adjustment of the equivalent inductance. It has the advantages of large adjustable range, faster response speed and no mechanical wear, but its control circuit is relatively complex and has some additional losses. The thyristor control scheme adopts the method of changing the thyristor conduction angle to adjust the access inductance value equivalently, which has the characteristics of flexible control and fast response, and will produce the switching frequency harmonic problem in addition to the characteristic subharmonic, which should be paid attention to in the design. The mechanical regulating type uses the change of winding tap or the position of moving iron core to realize the change of inductance. Although it has high linearity and good reliability, its response speed is limited by the mechanical action time. Due to the characteristics of continuous regulation and moderate cost, the magnetic control scheme has received more attention in practical engineering applications. When the variable reactor and fixed capacitor form a resonant loop, the control system adjusts the reactor control current or trigger angle according to the detuning deviation signal detected in real time, so that the equivalent inductance value changes along the detuning reduction direction until the actual resonant frequency is close to the target harmonic frequency[3]. In the process of adjustment, it is necessary to set a reasonable step size and dead zone to ensure the tracking accuracy and avoid system oscillation caused by frequent adjustment.

4.3 Real-time Frequency Detection and Parameter Identification Method

Real time frequency detection and parameter identification provide information basis for adaptive tuning technology. The accuracy and real-time performance of tuning directly determine the upper limit value of tuning effect. The current mainstream technology is based on the digital phase locked loop technology to extract the fundamental frequency of the power grid, and then combined with the harmonic frequency to calculate the actual frequency value of each target harmonic. The digital phase-locked loop uses closed-loop feedback for phase tracking, and can still maintain good measurement accuracy in the case of frequency fluctuation, noise interference and so on. To identify the actual resonant frequency of the filter, it is generally to inject small signal scanning or passive impedance measurement. The injection scanning method injects the sweep signal with small amplitude into the filter branch, and uses the minimum value of the impedance amplitude of the detection branch to judge the resonant frequency. This method has high accuracy, but it needs to add a signal injection device. The passive measurement method uses the inherent harmonic background of the system as the excitation source to analyze the phase relationship and amplitude ratio of the voltage and current of the filter branch at different frequencies, and indirectly deduces the position of the resonant point, which has the advantages of no additional disturbance and simple implementation. Adaptive notch filter and recursive least squares algorithm have also been introduced into modern digital signal processing technology. It can converge rapidly in dynamic environment and continuously track the changes of parameters, so as to provide reliable information such as frequency and detuning degree for tuning control.

5. Dynamic Compensation and Coordination Control Strategy

5.1 Coordination Mechanism for Combined Reactive Power and Harmonic Compensation

In the low-voltage distribution system, there is a close electrical coupling between reactive power compensation and harmonic control. The coordination of the two is the prerequisite to ensure the system performance to achieve the best state. When the filter capacitor filters out harmonics, it outputs the fundamental capacitive reactive power to the system, which is conducive to improving the power factor. However, it causes the over compensation phenomenon under light load conditions, resulting in the increase of bus voltage and the deterioration of the economic operation state of the transformer. The adaptive tuning scheme adopts a hierarchical control architecture in the compensation coordination mechanism, and the upper layer takes the system power factor and bus voltage deviation as the optimization objective to determine the total reactive power output requirements of each filter branch; The lower layer allocates the total reactive power demand for each adjustable filter branch and meets the harmonic filtering at the same time. The control strategy gives priority to adjusting the number of filter banks that have been put into operation when the reactive power demand of the system changes, and then allocates reactive power output between groups through reactance fine-tuning, avoiding the large deviation of resonant frequency caused by the adjustment of a branch. For the system with multiple harmonic sources coexisting, the filter branches with inconsistent tuning frequencies need to work together according to the set priority to avoid harmful harmonic interaction between the branches, so as to achieve the dynamic balance between harmonic suppression and reactive power support[4].

5.2 Dynamic Compensation Response Characteristics and Stability Constraints

As a key index of engineering applicability, the response characteristics of dynamic compensation system need to consider the requirements of rapidity and stability at the same time. In terms of response speed, the system has the interference of sudden load change or harmonic source switching. The tuning control system should complete the frequency detection, deviation calculation and output of regulation command in several power frequency cycles, and then the actuator can complete the parameter adjustment in tens of milliseconds to hundreds of milliseconds to make the filter return to the resonant state. The response time needs to match the time scale of system harmonic change - the faster the response to the step change caused by the start and stop of power electronic devices; The response rate can be appropriately reduced for the slow change process of load change or temperature drift, so as to avoid control action over frequency. The limitation of stability is that the control system needs sufficient amplitude margin and phase margin to avoid overshoot oscillation or limit cycle phenomenon in the process of closed-loop regulation. Therefore, the control parameter setting needs to consider the factors such as detection link delay, actuator inertia and system impedance change range, and if necessary, introduce low-pass filtering partial smoothing deviation signal or adopt integral separation strategy to improve the dynamic quality. In the selection of adjustment step size, the variable step size strategy can consider the requirements of fast approaching target and fine adjustment at the same time, which not only reduces the adjustment time, but also ensures the steady-state accuracy.

5.3 Multi-branch Collaborative Adaptive Tuning Strategy

In order to deal with harmonics with different frequencies and meet the grouping requirements of reactive power compensation in actual distribution projects, multiple filter branches with different tuning frequencies are usually installed, which leads to the problem of multi branch cooperative control[5]. The core of the adaptive control tuning strategy of multi branch cooperative operation is to reasonably configure the harmonic filtering task and reactive power compensation share of each branch to avoid coupling oscillation or competitive regulation between branches. In the actual operation process, each branch divides the main filter frequency according to the designed target frequency. For example, the main task of the 5th branch is to filter out the 5th harmonic, while the 7th branch is mainly for the 7th harmonic. At the same time, each branch also has a certain bypass effect on other frequency harmonics. Collaborative logic stipulates that in the process of adjusting its internal parameters, each branch must obtain the real-time state information of other branches to avoid the overall decline of filtering performance due to separate adjustment. From the control algorithm level, the master-slave coordination strategy can be adopted to take the total distortion rate of bus harmonic voltage as the global performance index, and the master controller can uniformly calculate the regulation quantity of each branch and then send it to the implementation, so as to avoid the spear and shield caused by the independent decision-making of each branch. For the operation conditions with significant changes in harmonic spectrum distribution, the collaborative strategy should have the function of branch role reallocation - adjust the target resonant frequency of a branch when necessary, so that the filtering resources tend to the most serious harmonic frequency, dynamically optimize the configuration and governance ability, and maximize the potential of existing hardware to deal with the complex and diverse harmonic environment.

6. Conclusion

The harmonic control of low-voltage distribution system is facing the practical challenge of detuning. The conventional fixed parameter filter is difficult to maintain its best performance under the condition of aging components, frequency fluctuations and environmental changes. This paper systematically analyzes the causes and damage characteristics of detuning, and puts forward a comprehensive solution combining adaptive tuning and dynamic compensation. In this scheme, the real-time frequency detection and parameter identification method is used to accurately grasp the working condition of the filter, and the dynamic adjustment of resonant frequency is realized by using variable reactor and other executive devices, and a perception decision implementation closed-loop governance system is formed by coordinating and controlling the filtering and reactive power compensation and other multi-objective requirements. Adaptive tuning makes the filter change from static "notch filter" to dynamic "frequency tracker", which fundamentally overcomes the limitation of detuning on filter performance, and provides a feasible technical way for the treatment of power quality in low-voltage distribution system.

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