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Optimization of LCL Filter Grid-Connected Inverters

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Abstract: The increasing use of grid-connected inverters in power systems, driven by renewable energy growth and high-voltage, high-power open-loop devices, poses challenges due to PWM modulation generating harmful high-frequency harmonic currents. Optimizing parameter selection becomes crucial.LCL grid-connected inverters, as third-order systems, suffer from insufficient damping, leading to oscillations. Active and passive damping techniques are employed for effective control. The optimization process involves analyzing the fundamental principles of LCL filters, selecting space vector modulation for PWM. Design focuses on controlling current ripple within limits by considering LCL filter parameter constraints.A comparison of passive and active damping methods favors a current dual-loop control system. Simulation models evaluate system performance, confirming successful implementation of the optimized design.

Keywords: LCL grid-connected inverter, Voltage Space Vector Control, Phase Locked Loop, Active Damping Control, Closed Loop Control.

1. Introduction

In recent years, China has made significant progress in the level of renewable energy generation, gaining recognition on a global scale. Extensive research efforts have been dedicated to enhancing the performance of photovoltaic (PV) cells, primarily focusing on monocrystalline and polycrystalline silicon PV cells. Monocrystalline silicon cells typically achieve efficiency levels ranging from 13% to 15%. Through experimentation, the optimal performance of monocrystalline silicon cells can reach around 24.4%. Polycrystalline silicon cells generally exhibit efficiencies between 12% and 14%, with the optimal performance reaching approximately 19.8%. Improvements in PV cell efficiency have positive implications for the advancements and development of grid-connected inverters, such as LCL inverters, contributing to the significant growth potential of PV systems. [1]

However, LCL filters present certain challenges. In voltage-type grid-connected inverter control, the control of grid-side currents is achieved through PWM control of the output grid voltage on the bridge side. Due to the addition of multiple capacitors in the new filter, the control system of the grid-connected inverter transitions from a first-order to a third-order system within a certain frequency range. This can result in resonance and ultimately affect system stability. This resonance phenomenon is typically caused by low system damping, necessitating a damping control strategy based on LCL filters for grid-connected inverters. This strategy is generally classified into active damping and passive damping methods.

Currently, research on LCL filter control strategies can be divided into two trends. One approach is to continue using L-filter-based grid-connected inverter strategies, enhancing system stability by incorporating active and passive damping. The other approach involves employing control strategies based on LCL filters, introducing damping resistors to suppress system resonance and enhance stability. Additionally, the impact of filter parameters on high-frequency harmonic suppression, damping losses, system filtering stability, and second harmonic attenuation can be compared. By satisfying the constraints of equivalent model relationships, optimization design solutions can be identified.[2]

In the current LCL grid-connected inverters, harmonic current issues still persist, despite significant filtering efforts. Even with extensive filtering, there remain substantial harmonic distortions. Therefore, new control algorithms have become a focus of future research to effectively eliminate harmonics and achieve superior waveform quality in the grid. The commonly used active control strategy employs voltage outer-loop and current inner-loop control. However, this approach still exhibits some level of error in the resulting waveform. To further improve the waveform, future research can explore the implementation of three-loop or multiple-loop control strategies for active filtering, aiming to achieve further waveform enhancement.[3]

2. Organization of the Text

2.1. LCL Three-Phase Grid-Connected Inverter

2.1.1. Topology Structure

VT1 to VT6 are configured in an anti-parallel manner to form a bridge inverter circuit, commonly using IGBTs or MOSFETs as the switching devices.The inductors Lb and Lg in the LCL filter are used to reduce harmonics and noise.[4]The capacitor Cf is used to convert the DC signal to an AC signal.The equivalent impedance of these inductors is used to limit the Q-factor of the resonant circuit.Together, these three components form a third-order resonant circuit.[5]

The control system in this study adopts a PI controller for regulation. PI control utilizes the error value between the reference input and the actual output, as well as the integral of the error, as input signals for PWM modulation. It is characterized by its simplicity and good robustness, making it one of the most commonly used control methods.PI control enables the adjustment of the DC control variable without static error. [6]Therefore, in the control system of a three-phase filter, the three-phase AC quantities in the stationary coordinate system are transformed into the DC quantities in the dq two-phase rotating coordinate system for more convenient control and better dynamic performance. The dq transformation is based on the principle that the combined rotating magnetic flux vector F, formed by the interaction of the three-phase AC components in the stationary coordinate system, is consistent with the magnetic flux vector formed by the interaction of the two-phase rotating components in the dq coordinate system. [7]The two-phase stationary coordinate system serves as an intermediate step in the transformation, where the three-phase stationary coordinates are converted to two-phase stationary coordinates and then to two-phase rotating coordinates through matrix transformations. This allows for easier analysis and control of the DC component in the resulting two-phase rotating coordinate system.

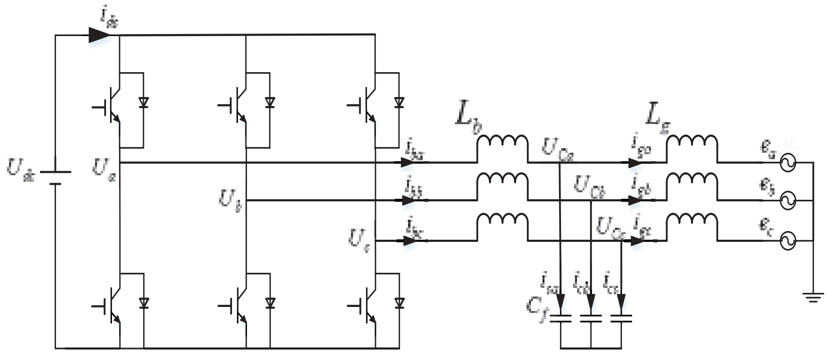

Figure 1. Main Circuit Topology Diagram

2.1.2. Phase-locked loop

Three-phase phase-locked loop (PLL) technology is based on the fundamental principle of a PLL, but it involves the transformation of the stationary coordinate system into a rotating coordinate system of a three-phase system. The control of the three-phase PLL is achieved through synchronization and locking in the rotating coordinate system.[8] The primary objective is to maintain synchronization between the output of the PLL system and the input, which is the grid voltage, in terms of both frequency and phase.

The PLL first determines whether the grid voltage and the vector U0 are aligned at the same angle by performing detection. Then, feedback is used to reduce the difference, allowing the grid and U0 to achieve phase synchronization. [9]In Figure 2, the grid voltage undergoes Clarke and Park transformations to convert the sinusoidal quantity into a DC quantity. When the output voltage vector aligns perfectly with the actual voltage vector, phase locking can be achieved by closing the control loop and minimizing the difference to zero. [10]

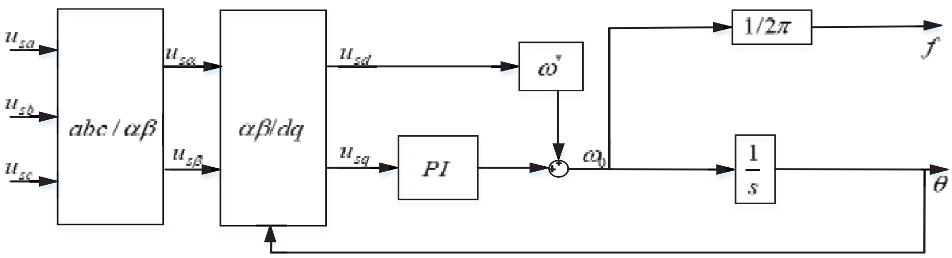

Figure 2. SSRF-SPLL Control Structure Schematic

2.2. Optimization of LCL Filter Parameters

2.2.1. Impact of LCL Filter Parameters on System Performance

Suppression of Bridge Current Ripple. LCL filter inductor parameters include bridge-side inductance and grid-side inductance. Although the harmonic standards for grid-connected inverters such as IEEE 519, IEEE 929, IEC 61000 focus on current and voltage harmonics at the grid connection point[11] the bridge current ripple also needs to be limited in terms of inverter design and control. Excessive ripple in the bridge arm current not only increases the losses in the filtering components but also subjects the power switching devices to higher switching stress. It can also affect the control of the grid-connected inverter. Therefore, the value of the bridge-side inductance should be relatively larger than the grid-side inductance.

Suppression of High-Frequency Harmonics by Filter Capacitor and Grid-Side Inductance.To suppress high-frequency components, adding filter capacitors in parallel helps bypass these frequencies from entering the grid.[12] The parallel connection of grid-side filter inductance and filter capacitor diverts harmonic currents. Increasing the capacitive impedance relative to the inductive impedance enhances the inverter's reactive current capacity. Controlling the grid-side inductance affects the low-frequency range, voltage drop, and power loss.

Effects of Inductance Ratio and Damping Resistance. Assuming the ratio of inverter-side inductance to grid-side inductance is denoted as k, and the damping resistance is denoted as Rd. Based on the Nyquist plots corresponding to different values of k and Rd (with the other variable held constant), it is observed that increasing Rd (while keeping k constant) enhances system stability. Conversely, as k increases (with Rd held constant), system stability decreases accordingly.

When the value of k remains constant, increasing Rd effectively suppresses the resonance peak, but the high-frequency filtering performance of the system gradually deteriorates. [13]On the other hand, when the damping resistance Rd remains constant, increasing the value of k reduces the frequency bandwidth, but significantly improves the attenuation rate of high-frequency harmonics.

Impact of Grid-Side Inductance on the Filter.In a grid-connected system, the grid itself typically has an inherent inductance, which is commonly considered as an increase in the grid-side filter inductance. Increasing the grid-side inductance enhances the ability of the filter capacitor branch to divert high-frequency currents. It also reduces the resonant frequency and the gain in the low-frequency range.

2.2.2. Design Requirements for LCL Filter Parameters

Designing the Upper Limit of Total Inductance. Firstly, the steady-state control performance of the grid-connected inverter for active and reactive power should be considered. When the grid-connected inverter meets the rated current output, the size of the filter inductance directly affects the magnitude of the voltage amplitude, which in turn affects the amplitude value of the grid-connected inverter's AC voltage vector U. [14]Therefore, for a grid-connected inverter with a predetermined maximum amplitude value of U, it is necessary to limit the value of the filter inductance to meet the corresponding vector amplitude requirements. For a grid-connected inverter operating in all four quadrants, when designing the upper limit of the filter inductance, the worst-case scenario should be considered, which is the pure inductive operation.

Designing the Upper Limit of Filter Capacitor Parameters.In an LCL grid-connected filtering system, the larger the value of the filter capacitor, the stronger its filtering ability for high-frequency currents. However, this also results in an increase in reactive power generation, thereby reducing the power conversion capability of the inverter. Therefore, in the design of the LCL filter for grid-connected inverters, it is common to limit the reactive power generated by the capacitors. Typically, engineering requirements dictate that the reactive power generated by the capacitors should not exceed 5% of the system's rated power.[15]

Designing the Upper and Lower Limits of Resonance Frequency.For grid-connected inverters of different power levels, their switching frequencies vary. When considering different switching frequency conditions for the grid-connected inverter, the design of the resonance frequency of the LCL filter needs to take into account two aspects. Firstly, the filter should adequately attenuate the switching frequency harmonics. Secondly, the control system should have sufficient control bandwidth and stability margin. Typically, the approximate design range of the LCL filter resonance frequency can be preliminarily determined based on the different switching frequency ranges.

Design Limitations of Passive Damping Resistance.In the design of the LCL filter for high-power grid-connected inverters, a damping resistor is often connected in parallel with the filter capacitors to improve the stability of the LCL grid-connected inverter. The design of the damping resistor requires a trade-off between system damping and losses. In engineering design of LCL filter parameters, the value of the damping resistor is generally chosen to be no more than one-third of the filter capacitor value at the resonance angular frequency.

2.2.3. Performance of LCL Filter Parameters

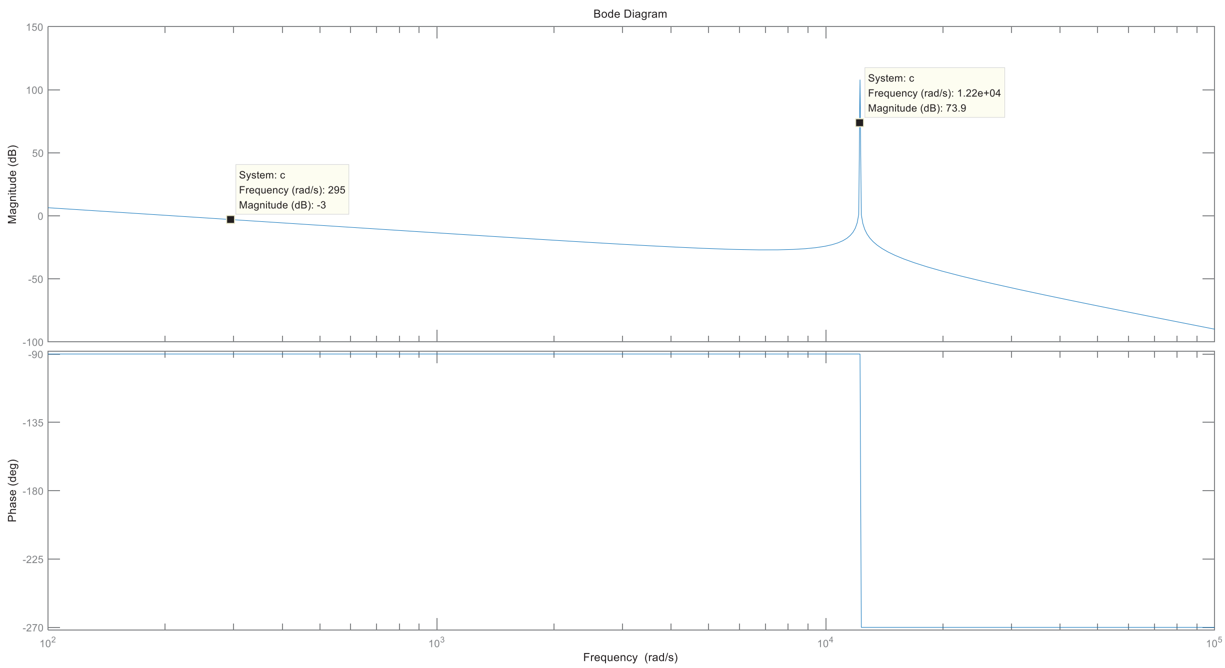

Figure 3. The Bode plot of an LCL filter

Based on the designed parameters, simulations were conducted, as shown in the figure. The results indicate that the LCL filter successfully achieves its filtering function. However, it is evident from the Bode plot that due to the presence of a high-order system, resonance occurs within a specific frequency range, which can have a detrimental impact on system stability. Therefore, it is necessary to incorporate damping control in the subsequent design to eliminate resonance and improve system stability.

2.3. Control Methods for LCL Grid-Connected Inverter Systems

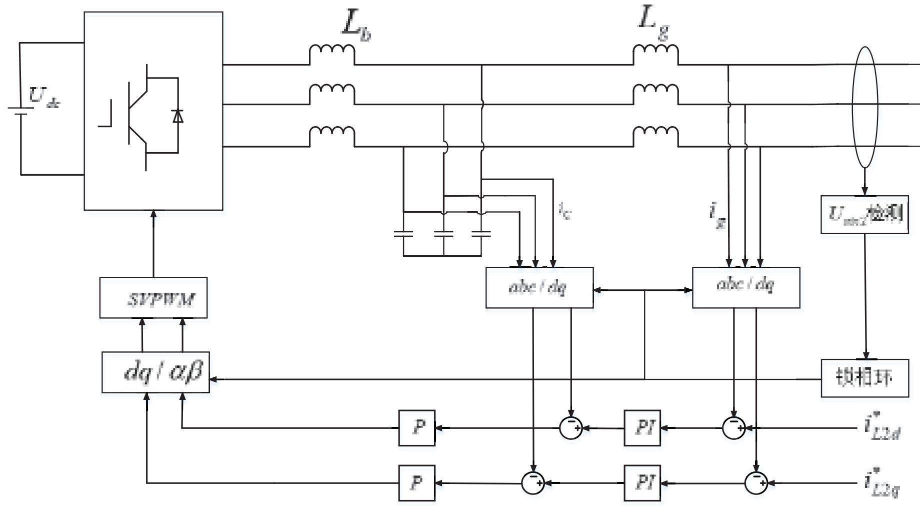

Figure 4. Block Diagram of LCL Grid-Connected Inverter Control System

The control system of the LCL grid-connected inverter is designed as a dual-current closed-loop system, where the inner loop controls the capacitor current using a proportional (P) controller, and the outer loop controls the grid current using a proportional-integral (PI) controller. [16]The reference current for the outer loop, after coordinate transformation, is combined with the SVPWM (Space Vector Pulse Width Modulation) technique implemented by the PI controller to control the switching states of the power switches. [17]The phase angle of the grid-side voltage is determined by the phase-locked loop system, ensuring that the d-axis in the coordinate transformation aligns with the direction of the grid voltage.[18] This alignment results in the output current of the grid-connected inverter having the same phase as the grid voltage, leading to a desirable output current waveform.

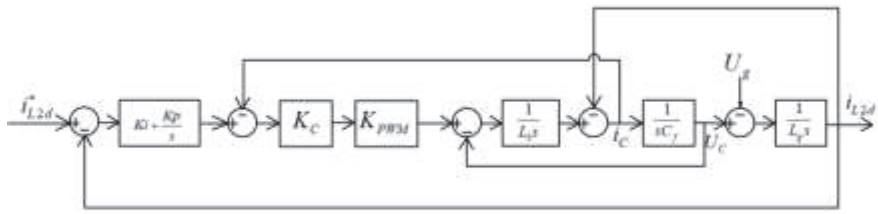

Figure 5. Dual-Loop Control System Diagram

The current dual-loop control strategy is a control approach that uses the capacitor current of the grid-connected inverter as the inner feedback variable and the grid current as the outer feedback variable. This strategy significantly improves the system's control capability over the grid current without introducing drawbacks such as power losses and heating caused by the presence of a damping resistor. It also preserves the excellent characteristics of the LCL filter system itself. [19]This superior current dual-loop control system meets the requirements of grid systems in various aspects. The purpose of using the capacitor current as the inner control variable is to suppress resonant peaks and eliminate high-frequency harmonic currents and other impurities through a closed-loop system. [20]If the system's precision level is not considered, this system already satisfies stability requirements. The inductor current, used as the outer control variable, ensures the tracking control of the inverter's output current.

3. Time-Domain Simulation Analysis

3.1. Active Power and Reactive Power Waveforms

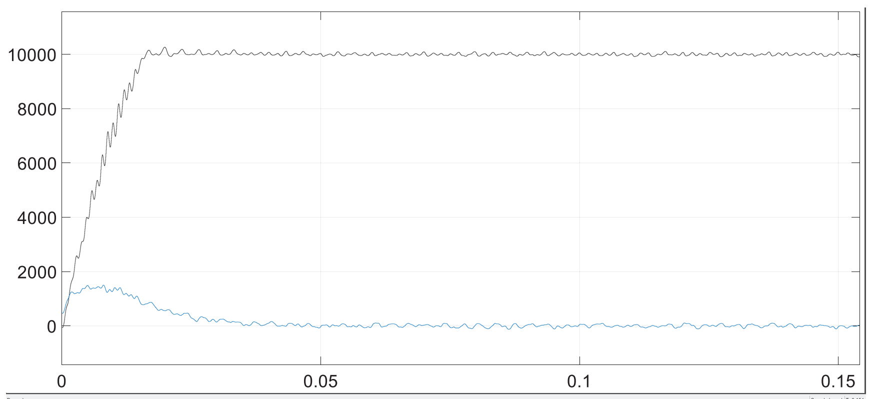

Figure 6. Active Power and Reactive Power Waveforms

Based on Figure 6, it can be observed that the active power output from the grid is 10 kW, and the reactive power is 0, which meets the requirements.

3.2. Voltage and current waveforms

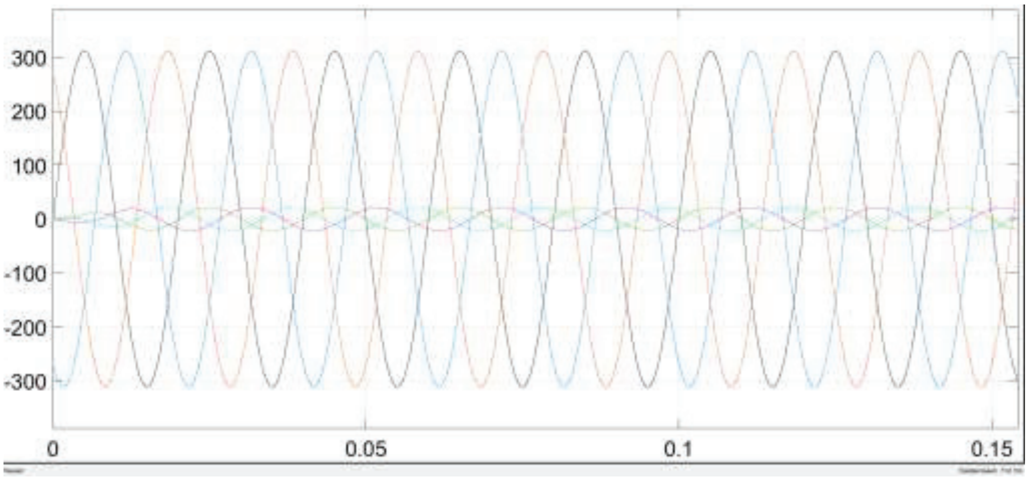

Figure 7. Grid voltage and current waveforms

As shown in the figure 7, the grid voltage and current are in phase and have the same frequency, consistent with the theoretical expectation. Although there is a transient period in the waveform at the beginning, it stabilizes afterwards and meets the requirements.

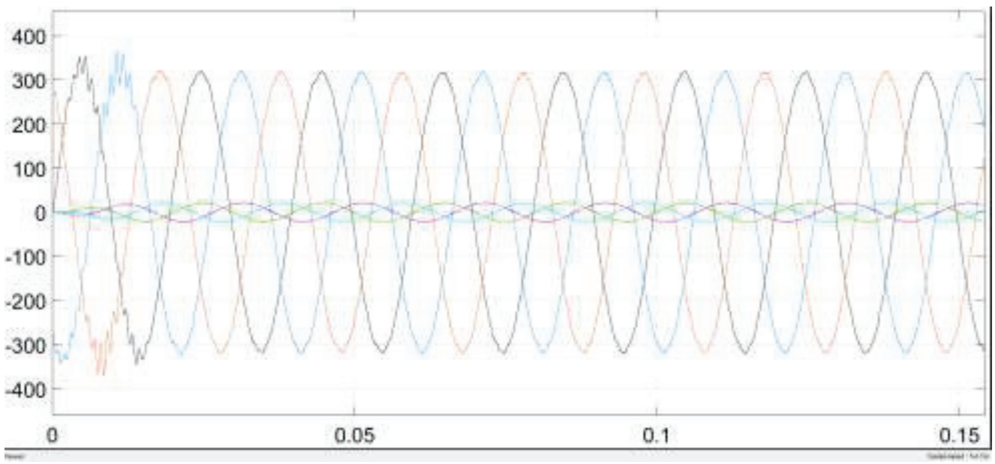

Figure 8. Inverter's voltage and current waveforms

As shown in Figure 8, the waveform of the inverter's output voltage and current is inferior to that of the grid-side voltage and current. Additionally, there are more harmonics present. It can be observed that the LCL filter indeed performs the filtering function, reducing errors and harmonics. The main reason for this improvement is the presence of two L filters, which further filters the output voltage and current of the inverter. As a result, the waveform is improved. This is one of the reasons why the LCL filter outperforms a single L filter.

3.3. Fourier analysis

From Figure 9, it can be observed that our grid-tied inverter system has successfully filtered out a majority of the harmonics. After an initial transient period, the waveform closely resembles the grid voltage waveform in terms of frequency and phase. The waveform exhibits minimal harmonic distortion, with a Total Harmonic Distortion (THD) of only 0.63% for the grid current after 0.1 seconds. This low level of harmonic distortion satisfies the system's requirements, indicating a successful implementation of the filtering strategy and achieving excellent output performance.

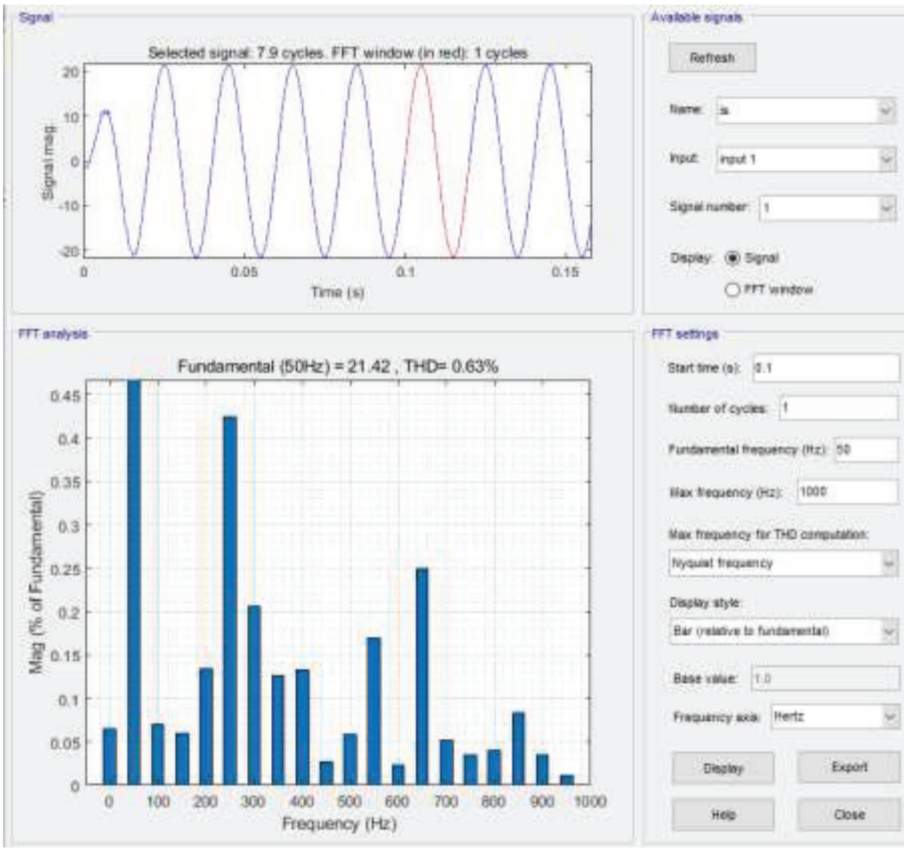

Figure 9. Fourier analysis

4. Summary

Under an active damping system, I selected a dual-current closed-loop control strategy for my current control design. By utilizing a voltage outer loop and a current inner loop, I achieved simpler adjustment, faster response, and greater stability. The system employed SVPWM modulation and a PI controller for AC-to-DC conversion. Through coordinate transformation and the use of a phase-locked loop, the grid voltage was aligned with the transformed d-axis. The system parameters were designed to meet the bandwidth requirements, starting with the capacitor current inner loop and then the grid current outer loop. The resulting design achieved excellent current tracking capability.

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