IMPEDANCE MODEL BASED STABILITY ANALYSIS OF GRID-TIED INVERTERS

Lappeenranta–Lahti University of Technology LUT

Bachelor’s Programme in Electrical Engineering, Bachelor's thesis

2024

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ABSTRACT

Lappeenranta–Lahti University of Technology LUT
LUT School of Engineering Sciences
Your degree programme: Electrical Engineering
In co-operation with partner university: Hebei University of Technology

DI GAO

Impedance model based stability analysis of grid-tied inverters

Bachelor’s thesis
Year of completion of the thesis: 2024
38 pages, 17 figures, 0 tables and 0 appendices
Examiner(s): Professor Qing Liu, Assistant Professor Niko Nevaranta
Keywords: deadbeat (DB) control, grid-tied inverters, impedance model, small signal injection method, spectrum analysis, stability

This Bachelor's thesis investigates the stability of single-phase LCL grid-connected inverters through an impedance model approach, establishing impedance as a key stability factor. It introduces the DB-DB-PI controller, a tailored triple-loop control strategy for enhancing inverter performance by integrating single-phase voltage source inverters with LCL output filters. This controller combines dual dead-beat (DB-DB) internal loops with an external proportional-integral (PI) loop for precise regulation of inverter output current, filter capacitor voltage, and grid-injected current. The dead-beat internal loop's quick response facilitates a wider adjustment bandwidth for the external loop, boosting system dynamics and stability. MATLAB/Simulink simulations and the small signal injection method were used to analyze output impedance and validate the control strategy's effectiveness through Bode plot comparisons, offering insights for developing efficient and stable grid-connected inverters.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to my mentors Professor Qing Liu and Assistant Professor Niko Nevaranta for their valuable guidance, support, and encouragement throughout the entire process of my bachelor's thesis "Impedance model based stability analysis of grid-tied inverters". Their professional knowledge and insights played an important role in completing this research.

Professor Qing's profound knowledge and pursuit of excellence in the field of power electronics have made significant contributions to the depth and quality of my work. Her guidance in the theoretical aspects of impedance modeling and stability analysis is indispensable. In addition, Professor Qing's assistance in reviewing and understanding relevant literature has enriched my research and broadened my academic perspective. I am very grateful for her patience, enthusiasm, and the countless time she spent reviewing and suggesting my work.

I am also very grateful to Assistant Professor Niko Nevaranta for his careful guidance on the format and structure of my paper. His professional knowledge in academic writing and attention to details greatly enhance the presentation and coherence of my work. Assistant Professor Niko Nevaranta provided constructive feedback and practical suggestions in organizing my research findings, which is crucial to ensuring that my paper meets the highest academic standards.

Their joint guidance not only promoted my academic growth but also laid a solid foundation for my future academic endeavors. I feel privileged to have had the opportunity to learn from such wonderful, supportive mentors.

I would like to thank my family and friends for their support and encouragement during my studies.

This paper demonstrates the collective effort and support of many people, to whom I am deeply grateful. I am grateful for the opportunity I had to work under the guidance of such dedicated educators, and I am grateful for the knowledge and experience I gained at Lappeenranta University of Technology and Hebei University of Technology.

SYMBOLS AND ABBREVIATIONS

d	duty cycle
i_g	grid side current
V_{DC}	nominal DC link voltage
f_{sw}	switching frequency
L	filter inductance
ESR_L	equivalent series resistance
C_O	output capacitance
L_F	line inductance
ESR_{L_F}	equivalent series resistance
V_G	nominal grid voltage (RMS)

Abbreviations

DB	Dead-Beat
DG	Distributed Generation
P	Proportional
PID	Proportional-Integral-Derivative
PD	Passive Damping
PCC	The Point of Common Coupling
FFT	Fast Fourier Transform
PLL	Phase-Locked Loop
VSG	Virtual Synchronous Generator
PWM	Pulse Width Modulation
SVPWM	Space Vector Pulse Width Modulation

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Abstract

(Acknowledgements)

(Symbols and abbreviations))

1 Introduction

In recent decades, with the rapid development of renewable energy technology and the continuous development of power systems, grid-connected inverters, as key equipment connecting renewable energy systems and the power grid, have received widespread attention due to their stability and efficiency. In particular, single-phase LCL grid-connected inverters have been widely used in residential photovoltaic systems, small wind power generation and distributed energy systems due to their excellent filtering performance and efficient energy conversion capabilities. However, the introduction of LCL filters also brings challenges in control complexity and system stability, especially in the face of grid disturbances and load changes.

Distributed generation (DG), as one of the main ways to utilize renewable energy, plays an important role in improving the economic efficiency of power grid operation, enhancing the safety of power systems, and building environmentally friendly power systems [1]. Grid connected inverters are key equipment that connects distributed generation systems with the public power grid. Their main responsibilities are not limited to transmitting electricity from renewable energy sources to the grid, while also ensuring the stable operation of distributed generation systems. In view of this, the stability research of grid connected inverters is particularly crucial [2-4].

In the process of analyzing the stability of inverter grid connected systems, the first step is to identify the topology configuration of the system, which includes the design of three-phase inverters and grid connected interface filters. Next, construct an impedance model to accurately describe the transmission behavior of the inverter. Subsequently, scientific methods are used to evaluate the stability of the system connected to the inverter and power grid, in order to identify key factors that affect the stable operation of the system.

The design of filters in grid connected inverters and their impact on system stability has always been a concern for many scholars. The output filter is mainly used to filter out the switching frequency and its nearby integer harmonics. At present, the widely used filter types for grid connected inverters are L and LCL filters. The L-filter is mainly used in low-power grid connected scenarios, while the LCL filter is mainly used in high-power scenarios. The main reason is that the switching frequency of high-power grid connected inverters is generally not too high. The L-filter, due to its only -20dB attenuation, requires a large inductance to filter out the switching frequency and its nearby integer harmonics, thereby increasing system volume and cost while reducing system dynamic performance; The LCL filter has a attenuation of -60dB after the turning frequency, so achieving the same filtering effect can use a smaller inductance, resulting in good dynamic performance of the system. However, the LCL filter has resonance problems. When using grid side inductance current control for grid connected inverters based on LCL filters, reference [5] derived the characteristic equation of the system and analyzed the impact of LCL and filters on system stability using the RoutHurwitz criterion. For such systems, regardless of whether proportional (P) or proportional-integral-derivative (PID) control is used in the current loop, the system is unstable. The corresponding solution is provided in the article, which is to form passive damping (PD) by serially connecting resistors to the LCL filter, thereby suppressing its resonance and improving system stability. Based on the above description and analysis, it is known that filters have a certain impact on system stability.

Due to the relative dispersion of renewable energy in both physical and electrical aspects, there are longer transmission lines and more transformer equipment between distributed generation and the grid. From the point of common coupling (PCC) of grid connected inverters, there is an inductive impedance in the grid [6]. As distributed generation systems grow in size and capacity, multiple inverters will operate in parallel at the PCC. In this case, the interaction between inverters and between the inverter and the power grid will be more significant, which may lead to complex oscillation problems and affect the stable operation of the power grid system [7-8].

When analyzing the stability of grid connected inverters, the methods commonly used can be divided into state space methods [9] and impedance analysis methods [10]. When using state space methods to analyze stability, it is necessary to collect all state parameters of grid connected inverters and grid components to construct a unified system state space model. On this basis, the characteristic equations and eigenvectors of the state space model are further analyzed to determine the stability of the grid connected inverter system [11-12]. From this, it can be seen that the state space method relies on the integrity and determinacy of the grid connected inverter system when analyzing system stability. Once the components or parameters of the system change, it is necessary to establish a new state space model for the system. In grid connected systems containing distributed generation, the structure and parameters of the constituent units can change at any time, making the use of state space methods for system analysis cumbersome and complex [13-14].

In order to simplify and improve the model establishment and stability analysis of grid connected inverters, researchers have proposed impedance analysis methods [15]. When studying the impedance stability of the interaction system between grid connected inverters and the power grid, this method treats them as two independent subsystems and establishes impedance models based on their respective control structures and parameter characteristics. Any changes in the structure or parameters of the constituent units of either party will not interfere with the other, avoiding the need to rebuild impedance models and simplifying the process of system analysis. After constructing an impedance model, the equivalent circuit of the interacting system is represented through a linear network structure, and impedance stability standards are applied to evaluate the stability of the system.

Traditional stability analysis of grid-connected inverters often focuses on the design and optimization of control strategies [16-17], while there is less research on the interaction between the inverter and the grid and its impact on system stability. In recent years, impedance modeling methods have attracted attention due to their unique advantages in stability analysis and design of grid-connected inverters. Through in-depth analysis of the impedance characteristics of the inverter and the grid, the nature of the stability of the grid-connected inverter can be effectively revealed and theoretical support can be provided for the design of control strategies [18].

In view of this, this study aims to conduct an in-depth analysis of the stability issues of single-phase LCL grid connected inverters through an impedance model-based approach. Firstly, an output impedance model of a grid connected inverter was established, and a new large bandwidth three loop controller, namely two dead-beat controllers and one proportional-integral controller (DB-DB-PI), was introduced to improve the dynamic performance and stability of the inverter.

The stability research of grid connected inverters cannot be separated from an accurate system model, and a good model is conducive to the analysis of relevant principles and the extraction of conclusions. Reference [19] provides several commonly used methods for modeling communication systems, including harmonic linearization method, reduced order averaging method, dynamic phase method, and abc-dq transformation method. References [20] and [21] conducted small signal modeling on single/three-phase grid connected inverters and designed control parameters based on the model. Reference [22] models a three-phase grid connected inverter using an equivalent Z-source network and provides a control strategy for decoupling the d-g axis grid side current component. Reference [23] established a common mode equivalent model for grid connected inverters for leakage current analysis, and applied this model to full bridge and half bridge single-phase photovoltaic grid connected inverters. Reference [24] provides low-frequency and high-frequency models of three-phase grid connected inverters in different coordinate systems. The low-frequency model is used for control system design, and the high-frequency model is used for grid connected current harmonic analysis.

There is an increasing amount of research on the stability of grid connected inverters, but there is a lack of research on the modeling of output impedance of grid connected inverters and the interaction between impedance in grid connected interactive systems. Voltage or current resonance caused by the interaction between impedance in interactive systems is a common stability problem [25]. Therefore, based on existing research, this project studies the stability of grid connected inverters and provides an inverter output impedance model. And through MATLAB/simulation verification and spectral analysis, the output impedance at different sampling frequencies was measured. The consistency between the simulation results and theoretical analysis was visually verified through Bode plots, thus verifying the effectiveness of the method.

1.1 Research objectives and methods

The main research objective of this thesis is to establish an impedance model-based stability analysis method for grid connected inverters, conduct analysis on the stability characteristics of LCL type grid connected inverters under the DB-DB-PI large-bandwidth, triple-loop control strategy, reveal the key factors affecting their stability, and propose effective stability improvement strategies. By combining theoretical analysis and simulation verification, the aim is to improve the stability of grid connected inverters and provide support for their safe and reliable operation in the power system.

The methods used in this study mainly include two key steps: constructing an impedance model and analyzing the spectrum after small signal injection. Firstly, by analyzing the circuit characteristics of single-phase LCL grid connected inverters in detail, a comprehensive output impedance model is established, which can accurately describe the dynamic behavior of the inverter under different operating conditions. Subsequently, small signal injection technology is used to excite the system in MATLAB/Simulink environment. Spectral analysis is used to measure the output impedance at different sampling frequencies, and the analysis results are visually displayed through Bode plots to verify the accuracy of the impedance model and the effectiveness of the control strategy. It is shown that by appropriately designing controllers and optimizing the output impedance characteristics of inverters, the stability and reliability of grid connected inverter systems can be effectively improved.

The following structure of this thesis is arranged as follows: Chapter 2 will review relevant literature to provide support for the research background and theoretical foundation; Chapter 3 provides a detailed description of the research methodology and control strategy design; Chapter 4 verifies the proposed theory and method through simulation experiments and analyzes the comparison between simulation results and theory; Chapter 5 proposes effective methods to improve stability based on the analysis results. Finally, Chapter 6 summarizes the research findings and discusses future research directions. The structure of the article is arranged reasonably, starting from the research background and purpose, to the introduction of methodology, and then to the simulation experiment verification and result analysis. Finally, the research results are summarized and future research directions are pointed out, aiming to provide readers with a clear research idea and a detailed analysis process.

2 Stability analysis of grid connected inverters

This chapter derives the expressions for the output voltage of the inverter and the grid current, and analyzes the stability of the inverter grid connected system with voltage control and current control. Through these analyses, the basic criterion for judging the stability of the power grid is the output impedance. Research has shown that accurate information on output impedance is crucial for designing controllers for grid connected inverters to ensure their stable operation when connected to the grid.

2.1 Output impedance model of grid connected inverter

When analyzing the impact of grid impedance on the stability of grid connected inverters, conventional methods model the inverter and grid impedance as a whole. Although this method can reveal the basic characteristics of the system, it can lead to complex models and the conclusions obtained are difficult to adapt to the changing conditions of grid impedance [26]. To address this issue, this section proposes a stability criterion derivation method based on impedance [27]. This method conducts impedance benchmark analysis on the stability of grid connected inverters, allowing for easy extension to the operation of multiple inverters connected to the grid without the need to re model the inverter system when the grid impedance changes. This impedance-based stability criterion provides a flexible and effective tool for the design and stability analysis of grid connected inverters.

As shown in Fig. 1, the equivalent circuit of a single-phase LCL type grid connected inverter connected to a weak current grid is presented. The control method is voltage control where ideal voltage source connected $v_{os}(s)$ in series with the inverter output impedance $Z_0(s)$.

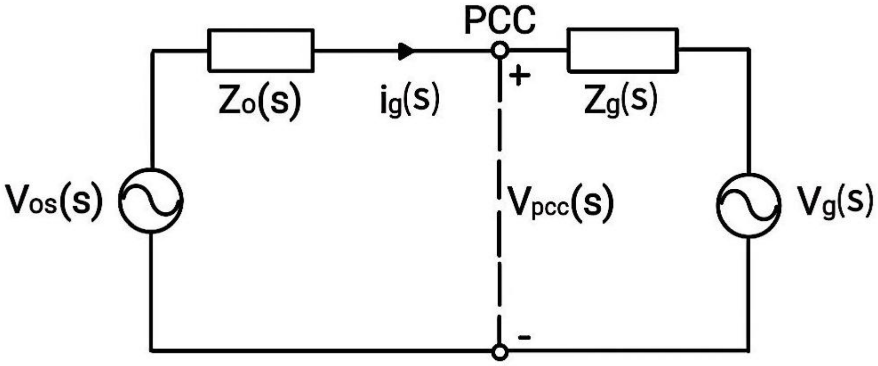

Figure 1. Grid-connected equivalent voltage circuit diagram.

The PCC in the Fig. 1 is the common coupling point of the grid connected inverter. The left end of the PCC is the equivalent circuit of the grid connected inverter, and the right end is the equivalent circuit of the power grid. The grid connected inverter is described using Norton equivalent circuit, where $V_{pcc}(s)$ is the common coupling point voltage, $i_g(s)$ is the grid connected current, $Z_0(s)$ is the output impedance of the grid connected inverter, and $Z_g(s)$ is the grid impedance. Fig. 2 shows a current controlled inverter [35], which is generally equivalent to a parallel circuit between an ideal current source $i_s(s)$ and the inverter output impedance $Z_0(s)$.

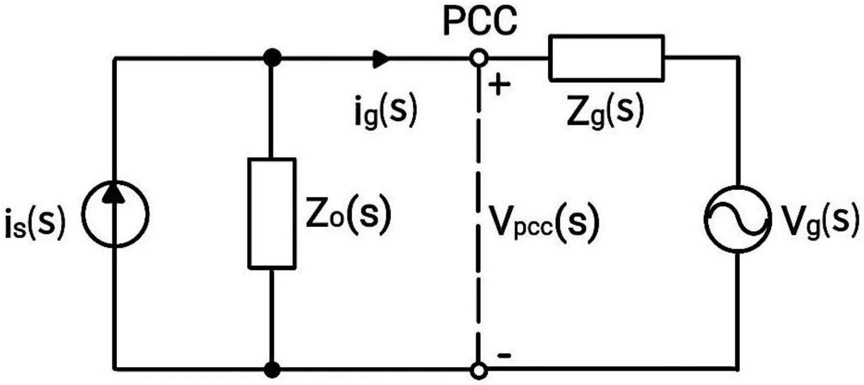

Figure 2. Grid-connected equivalent current circuit diagram.

2.2 Mathematical derivation of stability analysis

The output impedance of the grid-connected inverter plays a crucial role in the stability of the grid-connected system, and the stability criterion is derived here. First a voltage-controlled grid-connected inverter is considered. According to Fig. 1, the expression for the output voltage $v_0(s)$ or the common coupling point voltage v_{PCC} can be expressed as follows.

$$\begin{aligned} v_{PCC} &= v_0(s) = v_{os}(s) - Z_0(s)\frac{v_{os}(s) - v_g(s)}{Z_0(s) + Z_g(s)} \\ &= \frac{Z_g(s)}{Z_0(s) + Z_g(s)} v_{os}(s) + \frac{Z_0(s)}{Z_0(s) + Z_g(s)} v_g(s) \\ &= \frac{1}{1 + {Z_0(s)}/{Z_g(s)}} [v_{os}(s) + \frac{Z_0(s)}{Z_g(s)} v_g(s)] \\ &= N_1(s)[v_{os}(s) + \frac{Z_0(s)}{Z_g(s)} v_g(s)] \qquad (1) \end{aligned}$$

Where $N_1(s)$ is

$$N_1(s) = \frac{1}{1 + {Z_0(s)}/{Z_g(s)}} \qquad (2)$$

From the expression of the output voltage $v_0(s)$, it can be seen that, when the grid impedance is 0 (i.e., $Z_g(s) = 0$), the $v_0(s)$ expression does not contain the right half-plane pole, so the grid-connected system is stable. On the contrary, when the grid impedance is not 0 (i.e., $Z_g(s) \neq 0$), the stability of the grid-connected system should be judged according to the stability of $N_1(s)$. If $Z_0(s)/Z_g(s)$ satisfies the Nyquist stability criterion, then $N_1(s)$ is stable, and thus the grid-connected system is stable.

When the current-controlled grid-connected inverter example is considered similar derivation can be made. According to Fig. 2, the expression $i_g(s)$ of the grid-connected current is:

$$\begin{aligned} i_g(s) &= \frac{Z_0(s)}{Z_0(s) + Z_g(s)} i_s(s) - \frac{1}{Z_0(s) + Z_g(s)} v_g(s) \\ &= \frac{1}{1 + {Z_g(s)}/{Z_0(s)}} [i_s(s) - \frac{v_g(s)}{Z_0(s)}] \\ &= N_2(s)[i_s(s) - \frac{v_g(s)}{Z_0(s)}] \qquad (3) \end{aligned}$$

Where the $N_2(s)$ is

$$N_2(s) = \frac{1}{1 + {Z_g(s)}/{Z_0(s)}} \tag{4}$$

From the expression of grid-connected current $i_g(s)$, it can be seen that, when the grid impedance is 0 (i.e., $Z_g(s) = 0$), the $i_g(s)$ expression does not contain the right half-plane pole, so the grid-connected system is stable. On the contrary, when the grid impedance is not 0 (i.e., $Z_g(s) \neq 0$), then the grid-connected system should be judged according to the stability of $N_2(s)$. If $Z_g(s)/Z_0(s)$ satisfies the Nyquist stability criterion, then $N_2(s)$ is stable, and thus the grid-connected system is stable.

In summary, both voltage controlled and current controlled grid connected inverters meet the Nyquist stability criterion for impedance ratio.

3 DB-DB-PI control

This chapter introduces an efficient DB-DB-PI control strategy for LCL output filters of single-phase grid connected voltage source inverters. This strategy achieves fast and stable response and high-quality output voltage waveform through a triple closed-loop control system [28], where the Pulse Width Modulation (PWM) modulator emits pulse signals and synchronization signals to accurately adjust the inductor current and output voltage [29]. This strategy has high-bandwidth control capabilities and excellent robustness, can effectively cope with grid interference, achieve smooth switching between grid-connected and off-island operations, and has broad application prospects for power interface converters in nano- and microgrids.

3.1 Control circuit structure

This Fig. 3 presents a three-loop control system for a grid-connected inverter. The first loop, controlled by a Dead-Beat (DB) controller, manages the inverter output voltage V_O by adjusting the duty cycle d of the PWM. The second DB controller regulates the inverter output current i_L, using a reference current i_L^{REF} and a current measurement to ensure the output matches the desired performance. The third loop, featuring a Proportional-Integral (PI) controller, controls the grid current i_g based on a reference generated from desired active and reactive power setpoints ($P*$ and $Q*$), contributing to the stability and efficiency of power transfer to the grid. This multi-loop strategy provides precise control over different aspects of inverter operation, crucial for maintaining stability under varying grid conditions.

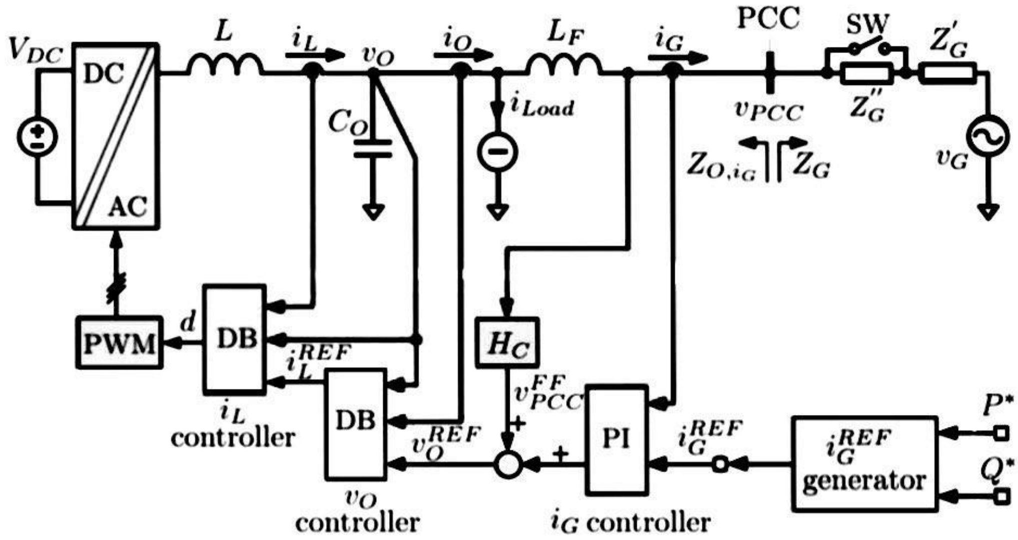

Figure 3. Large-bandwidth triple-loop control system [30].

When looking the Fig. 3, the innermost layer (inductor current controller) is composed of an inductor current i_L control circuit, which is adjusted using a deadbeat controller to achieve fast response and precise control. On the contrary the intermediate layer (output voltage controller) is used to control the output voltage v_0 using a deadbeat control strategy to maintain stable output voltage, working in conjunction with the innermost control loop. Outermost layer (grid current controller) is where the grid current i_G control loop adopts a discrete-time PI controller to regulate the injected current into the power grid, improve the adaptability and stability of the entire system to external changes [30].

Naturally the control law includes a PWM modulator which convert the duty cycle signal *d* generated by the DB-DB-PI controller into a periodic pulse signal, which is used to drive the power switch of the grid connected inverter, achieving precise adjustment of current and voltage.

Finally when considering the idea of DB-DB-PI controller its fundamental idea is to combining the advantages of DB control and PI control, aiming to optimize the performance of the entire control system, especially to improve the control bandwidth of the external power grid current circuit. The Fig. 4 introduces the main concept of DB-DB-PI controller, that is the triple control loop architecture (cascade control loops).

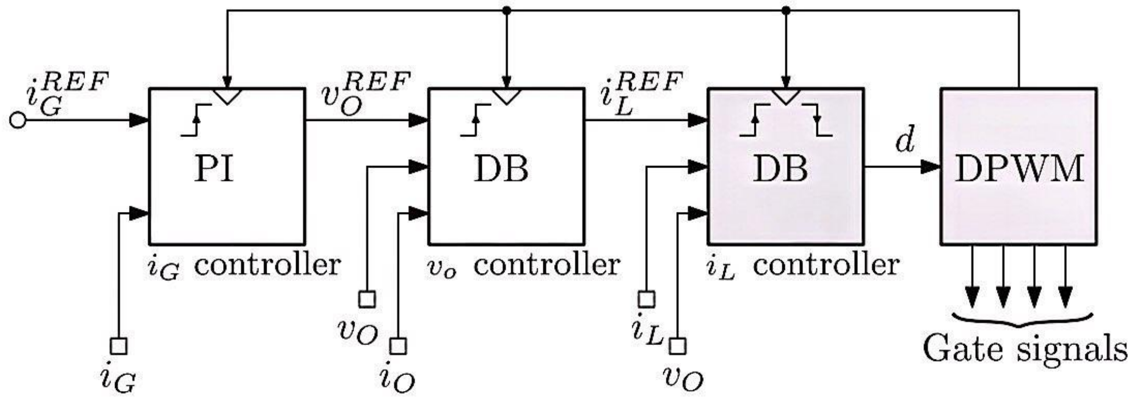

Figure 4. Triple-loop controller architecture showing the DB-DB-PI control [31].

To understand the control principle and the mathematical equations behind it, it is preferable to go through the separate functionalities. This done by starting from dead-beat inductor current controller (i_L controller) that is depicted in Fig. 5.

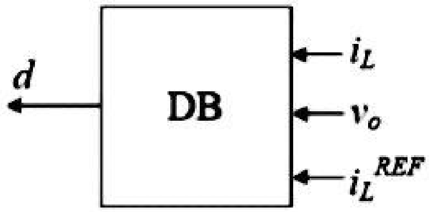

Figure 5. Inductance current controller.

When considering the deadbeat inductor current controller as shown in Fig. 5, the input signal is inductor current i_L, output voltage v_0 and the reference current i_L^{REF}. Output signal is a discrete duty cycle signal d . In each control iteration, the equation is updated using the following duty cycle.

$$d(k) = \frac{Lf_{sw}}{V_{DC}} \cdot [i_L^{REF}(k) - i_L(k)] + \frac{v_0(k)}{2V_{DC}} + \frac{1}{2} \qquad (5)$$

where V_{PC} is the DC-link voltage, L represents the modeled value of the filter inductor. The inductor current is sampled twice in each switching cycle. Therefore, the duty cycle update period is $\frac{T_{sw}}{2}$. Similar derivation can be done for the output voltage controller depicted in Fig. 6.

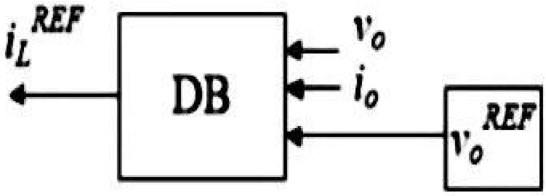

Figure 6. Output voltage controller.

For the dead-beat output voltage controller as shown in Fig. 8, the input signal is the output voltage v_0, output current i_0 and the reference voltage v_0^{REF}, Where the output voltage and the output current obtained from the analog-to-digital conversion circuit acquisition. The output signal is the reference current i_L^{REF}. The governing equations are available in the literature [16].

$$i_L^{REF}(n) = C_0 f_{sw} \cdot [v_0^{REF}(n) - v_0(n)] + i_0(n) \qquad (6)$$

where C_0 is the modeled value of the output capacitance C_0 and v_0 is sampled once in each switching cycle. The current reference update period is T_{sw}.

3.2 Performance characteristics and significance

The triple-loop controller is used for interconnecting converters and has multiple advantages, ensuring accuracy and high-quality performance. These controllers provide stable and uninterrupted power supply to local loads through the v_0 voltage control circuit, while significantly reducing harmonics on the inverter and grid sides through a simple LCL output filter. In addition, the i_G controller for grid current can achieve seamless switching i_G^{REF} between grid connected and islanded operation modes, and adapt to grid interference [30]. This series of features improves the performance and reliability of inverters in variable operating environments.

The significance of the triple-loop control strategy lies in achieving high-performance control of grid connected inverters. It significantly improves the overall performance of grid connected inverters when interacting with microgrids, especially in the implementation of large bandwidth for grid current control. For the three control loops, the internal loop uses a DB controller to adjust the converter current to achieve ideal damping and fast overcurrent protection of the system. The intermediate loop introduces a predictive DB type controller to adjust the output voltage and ensure seamless mode switching.

Compared to other solutions, the DB controller offers an almost ideal option for the inner loop, with excellent tracking capabilities and minimal response delay. Although the DB controller is sensitive to parameter mismatch, changes in system parameters are not sufficient to cause significant performance degradation in practical applications, and therefore do not constitute a serious problem. This triple-loop control strategy significantly improves the performance and reliability of grid connected inverters by combining these characteristics.

4 Impedance measurement

This chapter focuses into the impedance measurement technology of grid connected inverters using small signal injection method, and provides a detailed explanation of how to implement this method in MATLAB/Simulink environment. Meanwhile, this section also demonstrates how to construct a simulation measurement model and provides a detailed explanation of it.

4.1 Small signal injection method

Small signal injection method is a commonly used testing and measurement technique in control systems, power electronics, and power system analysis, especially in studying the dynamic response and stability of systems. This method involves injecting a small, controllable disturbance signal (voltage or current) under normal operating conditions of the system, and then measuring the system's response to this disturbance to evaluate the dynamic or impedance characteristics of the system.

Impedance sweep simulation measures the impedance model of grid connected inverters by building a circuit model in Simulink and injecting disturbance signals. The specific operation steps in this thesis are as follows:

a. Build circuit model: First, build the model of the tested circuit in Simulink and ensure that it can operate normally at the steady-state operating point. This step is the foundation for ensuring the accuracy of simulation results.

b. Design disturbance signal: Design two different voltage disturbance signals (denoted here as signal 1 and signal 2), which are used to inject into the system at specific frequencies to collect voltage and current responses at corresponding frequencies.

c. Inject disturbance signal 1 and collect data: Select a specific frequency of disturbance signal 1 to inject into the PCC point of the system, then collect the voltage and current signals at that point and perform dp-transformation (direct current to alternating current transformation) to convert them to the frequency domain for analysis.

d. Inject disturbance signal 2 and collect data: Similarly, inject disturbance signal 2 at another frequency and collect voltage and current signals at the PCC point for dq-transformation.

e. Frequency analysis: Use fast Fourier transform (FFT) to process the collected voltage and current signals, and calculate the amplitude and phase of the voltage and current components at the corresponding disturbance frequency.

f. Calculate impedance matrix: Based on the data obtained in the previous steps, use the amplitude and phase of the ratio of voltage and current components to calculate the impedance matrix value at that frequency.

g. Frequency scanning: Change the frequency of the disturbance signal, repeat steps 3 to 6 until it covers the entire frequency range of interest, and obtain impedance solutions at these frequencies.

h. Result display and analysis: Finally, plot the impedance values at all frequencies into graphs, such as Bode or Nyquist plots of impedance, which helps to intuitively understand the impedance characteristics of the system over the entire frequency range.

4.2 MATLAB/Simulink simulation model

Basic circuit of the DB-DB-PI control inverter output impedance measurement model established in MATLAB/Simulink as shown in Fig. 7. The collected inductive current i_L signal, the output voltage v_0 signal and the output current i_G signal are transmitted to the DB-DB-PI control system. The block diagram of the DB-DB-PI control system is shown in Fig. 8 where the DB and PI controllers are seen as a separate blocks.

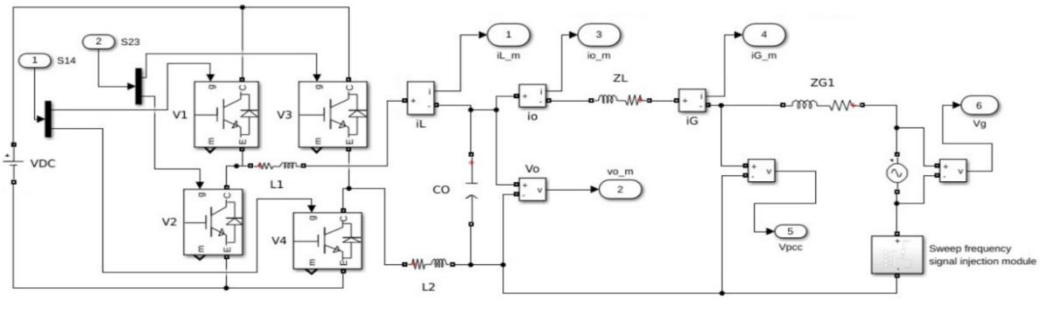

Figure 7. Output impedance measurement simulation model made with Simulink.

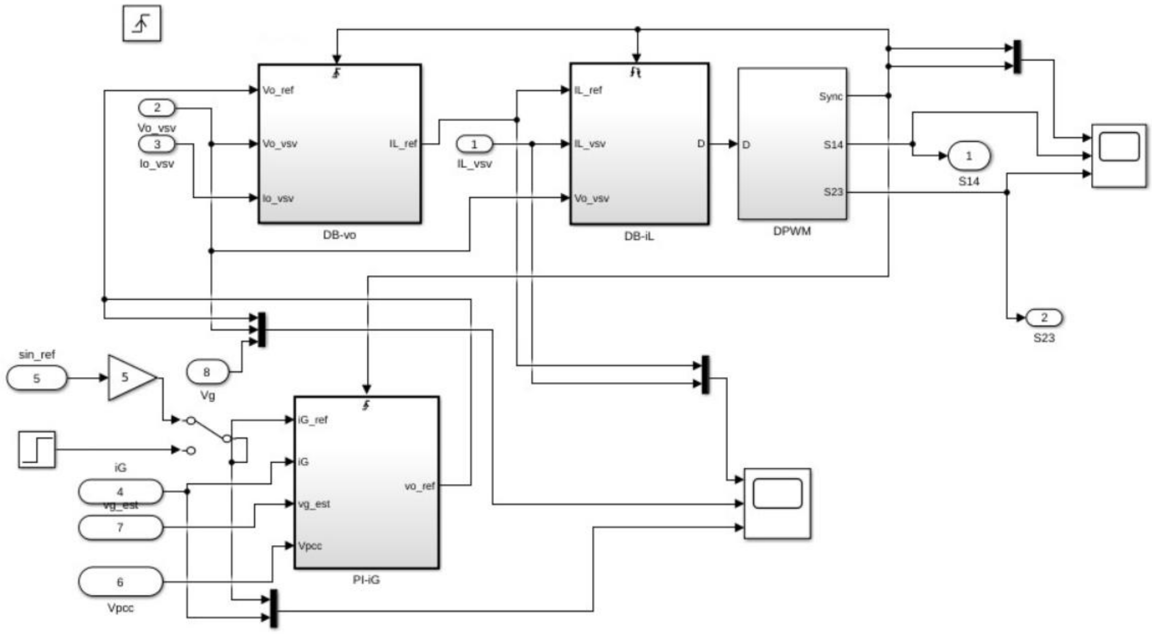

Figure 8. The DB-DB-PI control system.

The simulation model of the inductive current controller established by (5) is shown in Fig. 9.

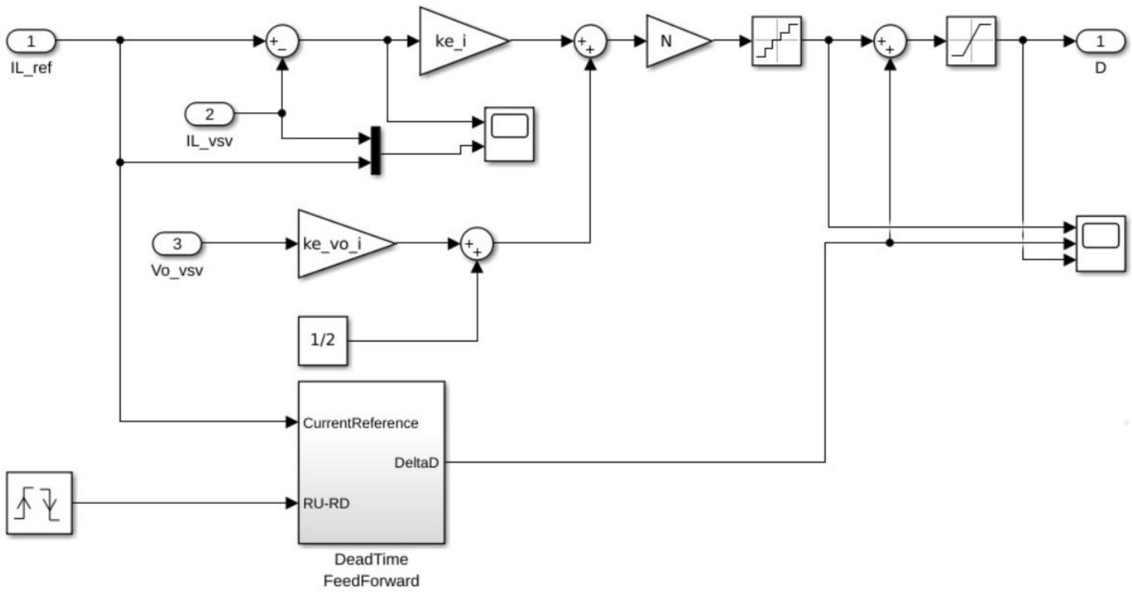

Figure 9. The simulation model of the inductive current controller.

The simulation model of the output voltage controller established by (6) is shown in Fig. 10.

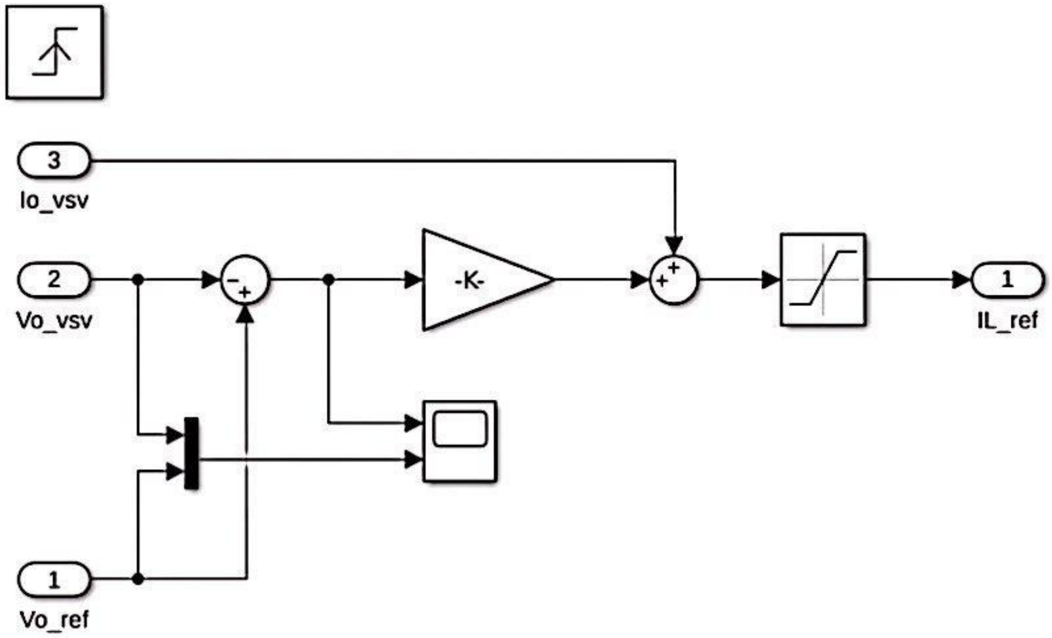

Figure 10. The simulation model of the output voltage controller.

The simulation model of the grid-connected current controller established by (7) is shown in Fig. 11.

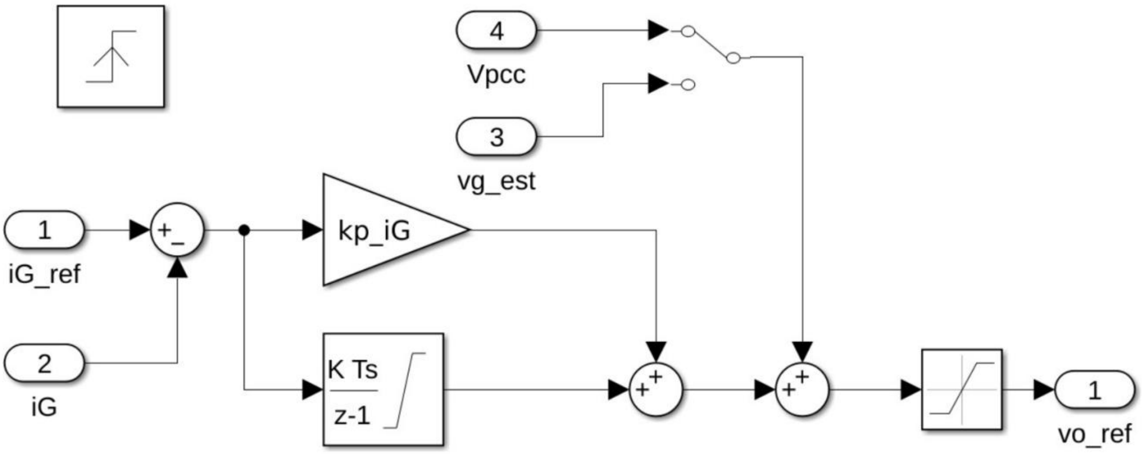

Figure 11. The simulation model of the grid-connected current controller.

Finally the PWM modulator is represented with simulation model seen in Fig. 12.

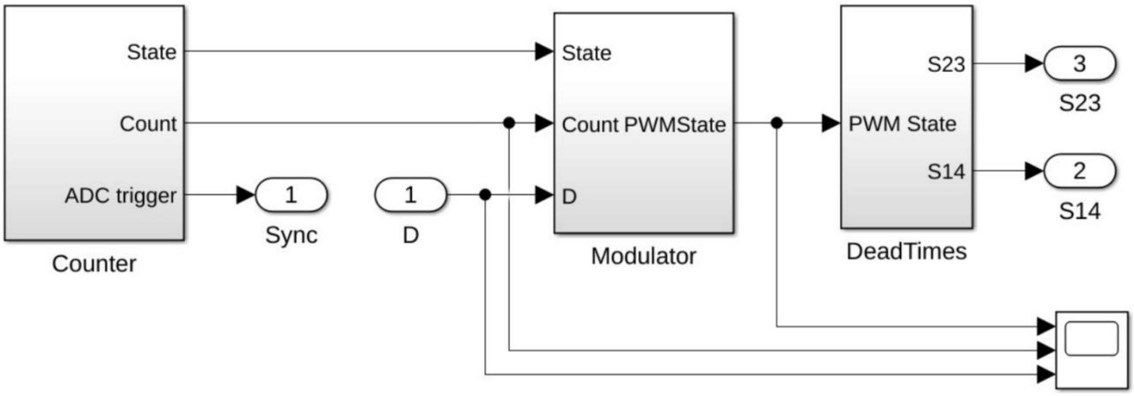

Figure 12. The simulation model of the PWM modulator.

The figures represented here shows the simulation model main functionalities and main level of the blocks. Using the derived simulation model and analysis is made to simulate the measurement of output impedance of the inverter.

4.3 Simulations

This chapter introduced a simulation model of a single-phase LCL grid connected inverter in MATLAB/Simulink environment, and adopts DB-DB-PI control strategy to successfully measure the output impedance of the inverter. By using the active small signal injection method, precise measurement of the inverter output impedance can be studied by simulations, and the obtained results can be compared and analyzed with the theoretical impedance. This process not only verifies the credibility of the measurement method, but also provides important technical support for the performance optimization and reliable operation of grid connected inverters. Through the establishment of simulation models and the implementation of control strategies, this chapter demonstrates a research approach that combines simulation technology and experimental methods in the field of power electronics, which has guiding significance for improving the accuracy and efficiency of grid connected inverter design.

From to [1], the theoretical output impedance of a grid-connected inverter with different control structures is expressed through various formulas.

The theoretical value of the equivalent output impedance of the grid connected inverter when no control is applied is:

$$Z_o(S) = \frac{1}{sC_o} \tag{7}$$

The current DB controller's output impedance $Z_{O,\,i_L}(z)$ is given as a function of the inverter output voltage $V_O(z)$ and the current $I_L(z)$, factoring in the frequency f_{sw} and the inductor L.

$$Z_{O,\,i_L}(z) = -\frac{V_O(z)}{I_L(z)} = \frac{4f_{sw}L}{1 - z^{-1}} \tag{8}$$

In the DB-DB control structure, the output impedance $Z_{O,\,v_o}(z)$ is a relation of the output voltage $V_O(z)$ over the current $I_O(z)$, described by the capacitor C_O and the frequency f_{sw}.

$$Z_{O,\,v_o}(z) = -\frac{V_O(z)}{I_O(z)} = \frac{1}{C_O f_{sw}} \cdot \frac{z - 1}{2z^2 - 2z + 1} \tag{9}$$

Lastly, for the DB-DB-PI control structure, the output impedance $Z_{O,\,i_G}(z)$ is an intricate combination that incorporates the previous DB-DB impedance expression and factors in additional PI control contributions, adjusting the impedance based on the frequency and the parameters of the PI controller.

$$\begin{aligned} Z_{O,\,i_G}(z) &= -\frac{V_O(z)}{I_G(z)} = W_{v_O}(z) \cdot H_{PI_{i_G}}(z) + Z_{O,\,v_O}(z) \\ &= \frac{1}{C_O f_{sw}} \cdot \frac{C_O f_{sw} \cdot H_{PI_{i_G}}(z) + z - 1}{2z^2 - 2z + 1} \end{aligned} \tag{10}$$

4.4 Measurement results and analysis

The frequency of the sine small signal is 10^2 Hz~10^4 Hz. Here 20 sample frequencies are considered that are logarithmically divided and injected them into the PCC end of the grid connected inverter in sequence [32]. The waveform of PCC terminal voltage and grid connected current is stored in the MATLAB workspace in the form of data through the *To Workspace* module. The data is then used for FFT spectrum analysis in MATLAB, and the ratio of voltage and current at the corresponding sampling frequency is the modulus and phase angle of the simulated measured output impedance of the grid connected inverter.

The simulation measurement results of the inverter output impedance without control are shown in Fig. 13, where the solid line represents the theoretical output impedance modulus and phase angle, and the dots represent the simulated output impedance modulus and phase angle measured at the corresponding sampling frequency.

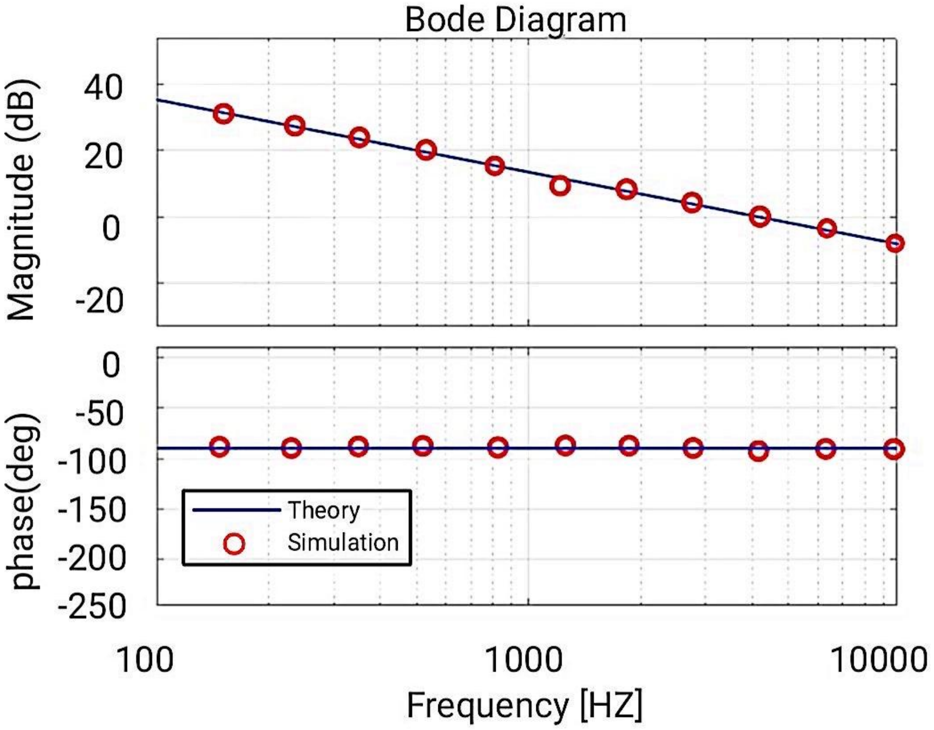

Figure 13. The output impedance without control.

The simulation results of DB-DB control grid connected inverter output impedance are shown in Fig. 14, where the solid line represents the theoretical output impedance modulus and phase angle, and the point represents the measured output impedance modulus and phase angle at the sampling frequency. The theoretical output impedance of the DB-DB controlled grid connected inverter can be determined by the small signal dynamic relationship between the output voltage and output current.

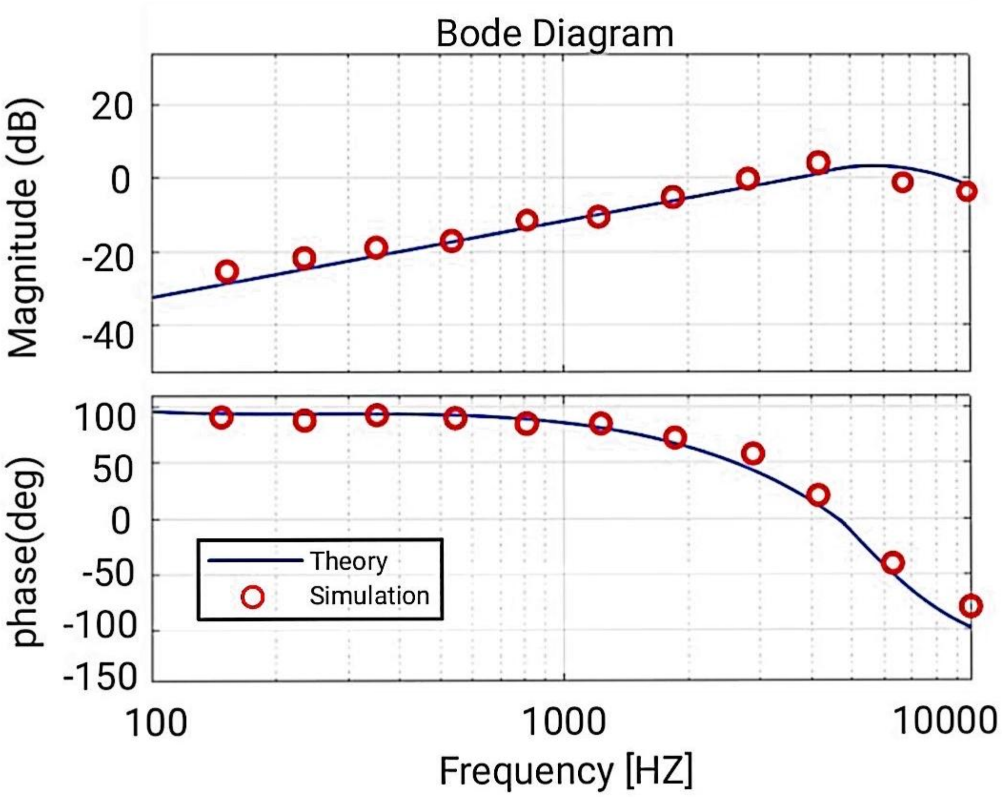

Figure 14. The output impedance results using DB-DB control.

The simulation results of DB-DB-PI control grid connected inverter output impedance are shown in Fig. 15, where the solid line represents the theoretical output impedance modulus and phase angle, and the dots represent the measured output impedance modulus and phase angle at the sampling frequency. The theoretical output impedance of the DB-DB-PI control grid connected inverter can be determined by the small signal dynamic relationship between the output voltage and output current.

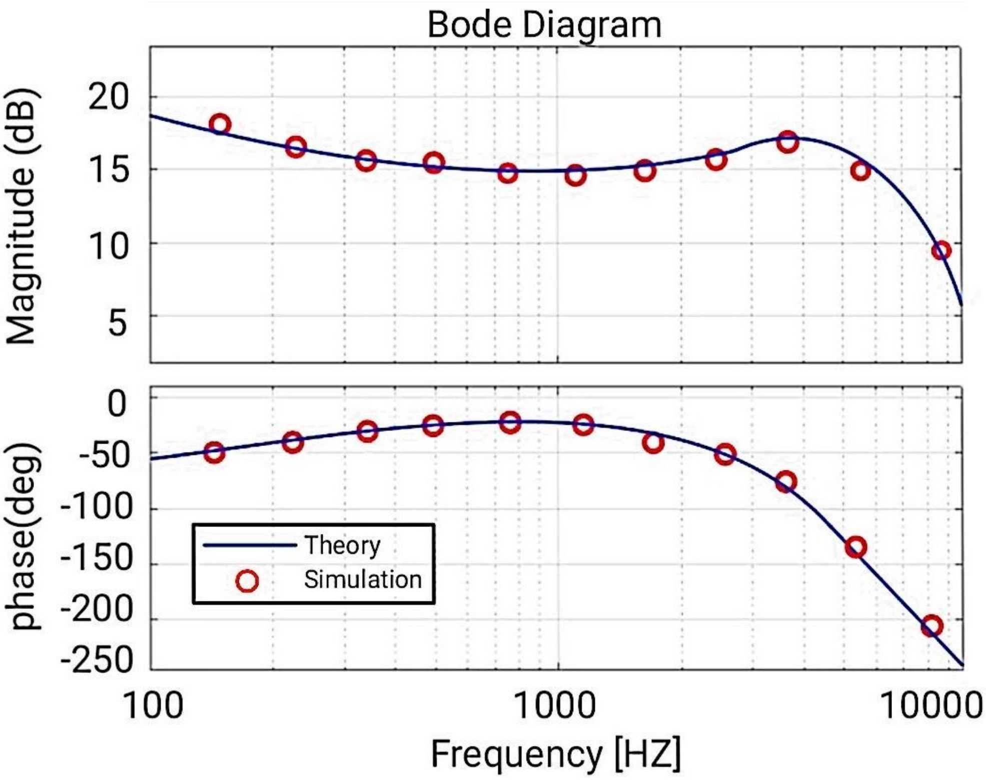

Figure 15. The output impedance results using DB-DB-PI control.

Despite the small discrepancies, as shown in the figure, the simulation measurement results also have a high degree of fit with the theoretical output impedance curve.

During the simulation process, it should be noted that after recording the waveform data of PCC terminal voltage v_{PCC} and grid connected current i_G through MATLAB/simulink simulation, stable voltage and current waveform data need to be extracted, and Fourier decomposition and measurement should be carried out through spectrum analysis to obtain the amplitude and phase angle of the corresponding injection frequency. Otherwise, significant measurement errors may exist. By adding a scope to the MATLAB/simulink simulation model to observe the output voltage and current waveforms in real time, and record the data for processing after the waveforms stabilizes. At low frequencies, the voltage at the PCC terminal and grid current waveforms stabilize quickly, while at high frequencies, more small signal periods need to be injected to stabilize the voltage at the PCC terminal and grid current waveforms.

5 Stability improvement strategy

In this bachelor's thesis, active impedance technology was adopted to improve the stability of grid connected inverters. Active impedance technology relies on power electronic converters to dynamically adjust the output impedance characteristics of the inverter, automatically optimizing impedance matching based on the real-time situation of the power grid, and providing more flexible adaptability. In addition, by optimizing the filter design at the output of the inverter, such as replacing traditional LC filters with LCL filters, and adjusting filter parameters such as inductance, capacitance, damping ratio, etc., the impedance characteristics of the inverter can be further optimized.

The resonance peak damping method of LCL filter can be divided into two types: passive damping and active damping. Passive damping adds damping to the system by adding a resistor in series or parallel to a branch of the filter capacitor or inductor. It has the advantages of simple implementation and is not affected by switching frequency. However, the introduction of resistors will cause additional losses in the system and weaken the filtering performance of LCL. The active damping rule is to feedback the state variables in the LCL filter and suppress the resonant peak through appropriate control links [34-36]. Compared with passive damping method, active damping method is more flexible and does not introduce additional losses, thus gaining widespread attention.

The active damping LCL filter is introduced to improve the dynamic response and stability of the system by measuring the phase difference between the converter output current and voltage. Specifically, active damping reduces the oscillation of the LCL filter by connecting a voltage source that controls the current to the capacitor of the filter. Fig. 16 shows a voltage source controlling current connected to the capacitor of the LC output filter.

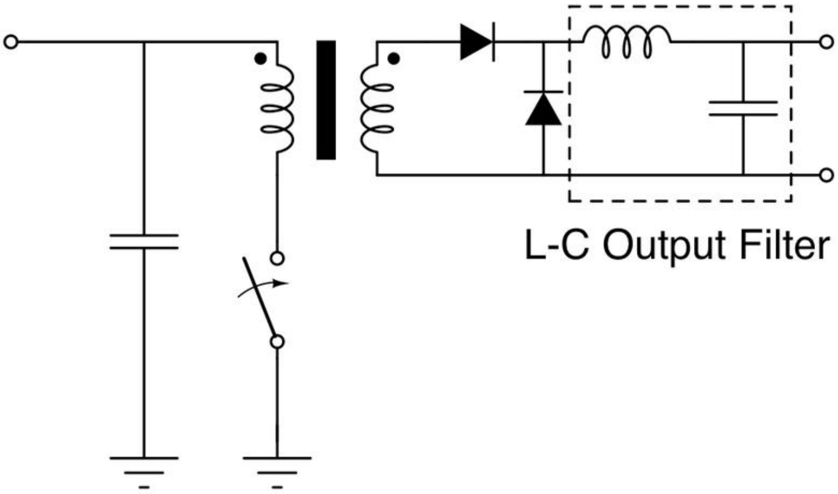

Figure 16. Active damping method for L-C output filter.

Fig. 17 shows the simulated PCC voltage and current waveforms of a single active rectifier in an unstable state, comparing the situation before and after activating the active rectifier. At 0.24 seconds, the active damper is activated. It can be seen from this that the resonance phenomenon triggered by the change in gate impedance is effectively suppressed by the active damper.

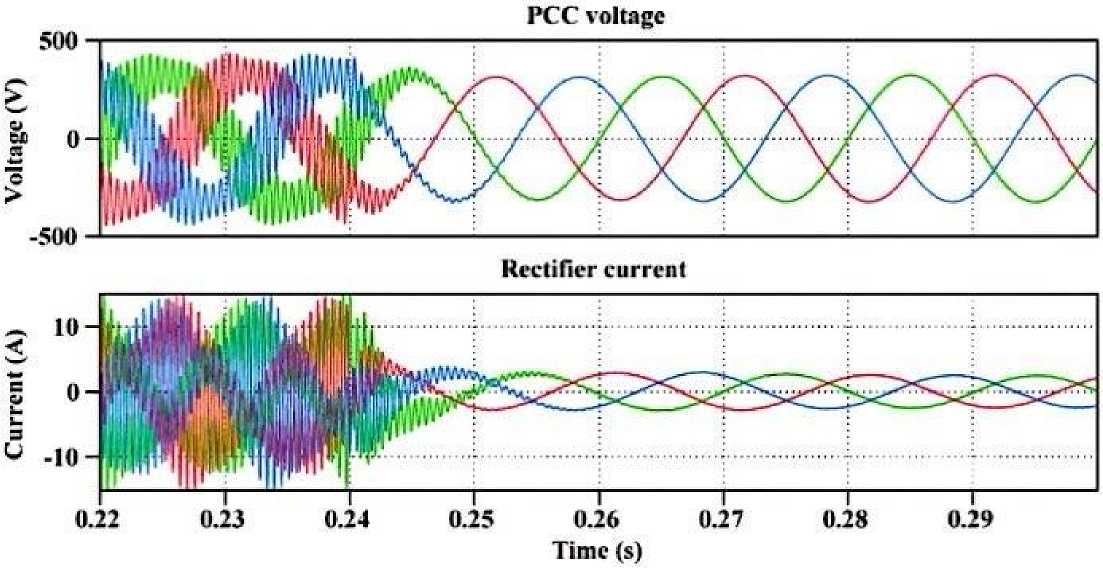

Figure 17. Simulated PCC voltage and current under unstable conditions of a single active rectifier before and after using an active damper at 0.24 seconds.

As shown in the Fig. 17, the system is unstable before using active damping method, but stable after using it. Obviously, the active damping method can effectively improve the stability of the grid-connected inverter.

In addition, impedance matching is a key method to improve the stability of grid connected inverters. By adjusting the output impedance of the inverter and the input impedance of the power grid, the interaction between the two can be improved, thereby enhancing the stability of the entire system. This process involves the application of various technological means.

Impedance adjustment technology artificially increases the output impedance of the inverter by changing its control strategy, such as introducing virtual impedance, implementing damping control, or adopting dynamic adjustment control, in order to achieve better impedance matching.

Impedance matching technology is a method of achieving optimal transmission between signal sources, loads, and transmission lines by adjusting the impedance values of components [33]. This technology has a wide range of applications in sensor design, as it can improve the efficiency and quality of signal transmission. Through impedance matching, signal loss during transmission can be reduced, noise interference can be reduced, and the signal-to-noise ratio of the signal can be improved. In addition, impedance matching can also optimize the dynamic range and linearity of the system, thereby improving the measurement accuracy of the sensor.

However, impedance matching technology also has some limitations. Firstly, it is sensitive to environmental factors such as temperature, humidity, etc., which may cause changes in impedance values, thereby affecting the effectiveness of signal transmission. Secondly, impedance matching often requires precise adjustment and calibration, which increases the complexity and cost of sensor design. In addition, for some complex application scenarios, such as biomedical sensors, impedance matching may be difficult to achieve.

Finally, the small signal stability analysis method allows for analyzing the dynamic interaction between the inverter and the power grid through a small signal model, identifying potential unstable modes, and addressing these issues by adjusting control strategies.

Small signal stability, also known as small disturbance stability, involves the ability of a system to maintain synchronization when encountering minor signal disturbances, especially in the case of small disturbances. The slight disturbance mentioned here occurs in the initial stage of system interconnection, when the connections between systems are still weak. The impact of these disturbances is minimal and sufficient to introduce necessary damping into the system model without compromising the accuracy of the analysis [37], often leading to linearization of low-frequency transmission lines.

By using these methods alone or in combination, stable operation of grid connected inverters can be ensured under various working conditions and grid environments.

6 Conclusions

This thesis analyzes the stability of single-phase LCL grid connected inverters using impedance model-based methods. The core is to construct an output impedance model for grid connected inverters and implement an innovative DB-DB-PI large bandwidth three loop control strategy. This control strategy significantly improves the stability and performance of grid connected inverters by internally adjusting the output current of the inverter, the voltage of the filter capacitor, and externally adjusting the injected grid current.

Through MATLAB/Simulink simulation experiments, combined with small signal injection method and spectrum analysis, this study successfully measured the output impedance of the inverter at different frequencies, and visually displayed the simulation results through Bode diagrams. These results are consistent with theoretical analysis, effectively proving the important role of impedance in determining the stability of grid connected inverters, and also verifying the effectiveness of the DB-DB-PI large bandwidth three loop control strategy.

Firstly, this study emphasizes the indispensable role of impedance models and demonstrates their effectiveness as a method for analyzing stability. This model has been proven to be the cornerstone for understanding and ensuring the normal operation of grid connected inverters. Secondly, the effectiveness of the DB-DB-PI control strategy was thoroughly studied, which is a large bandwidth three loop control method. Simulation verification has shown that this strategy significantly enhances the stability of grid connected inverters. This discovery highlights the potential of this strategy in effectively regulating the output of grid connected inverters, marking a significant advancement in control methods.

In addition, a key aspect of this study is the consistency between the observed simulation experiments and theoretical analysis. This consistency not only affirms the effectiveness and accuracy of the proposed method, but also provides a solid theoretical basis and experimental verification for the design and optimization of grid connected inverters. The consistency between theoretical and practical experimental results is crucial for advancing the field and cultivating confidence in these methods.

Finally, the significance of this study goes far beyond theoretical contributions, providing substantial guidance for the practical design and optimization of grid connected inverters. For example, impedance adjustment technology improves impedance matching by modifying the control strategy to increase the output impedance of the inverter. Active impedance technology utilizes power electronic converters to dynamically adjust the output impedance of the inverter, automatically optimizing it based on real-time conditions of the power grid, and enhancing the adaptability of the system. The individual or combined application of these technologies ensures that grid connected inverters can operate stably under various working conditions and grid environments. Through these insights, this study paves the way for innovative design methods to ensure that grid connected inverters can meet the constantly changing needs of power electronic systems.

In summary, the research results of this article are of great significance for promoting the development of grid connected inverter technology and improving the stability and efficiency of power systems. Future work will further explore other types of grid connected inverters and control strategies to expand the application scope and depth of this study.

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