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LCL Filter Design Optimization

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THESIS ACCEPTANCE

This Thesis by: Ayna Aslanova
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Abstract

Active damping, as implemented in the fourth method, dynamically suppresses resonance and adapts to varying grid conditions, resulting in the lowest THD and highly effective ripple attenuation. Unlike passive damping methods, which rely on fixed resistive elements and incur significant power losses, active damping leverages real-time feedback to enhance efficiency and stability. This makes the fourth method particularly well-suited for addressing the demands of GaN and SiC-based inverter systems, where adaptability and precision are essential. The study demonstrates that this method effectively balances harmonic suppression, energy efficiency, and ease of implementation, making it the most practical solution for next-generation power systems. As renewable energy sources continue to be incorporated into power grids, the role of grid-connected inverter systems becomes ever more critical to maintaining power quality, stability, and adherence to regulatory standards. However, behind the scenes and within these systems itself, LCL filters are vital to suppress harmonics, facilitate efficient energy transfer, and meet demanding performance specifications. On the contrary, the advent of new inverter technologies like gallium nitride (GaN) and silicon carbide (SiC), offers challenges of their own. LCL filter optimization for these converters is in urgent need of creative solutions that deliver reliable performance in the face of changing grid conditions due to the unique switching frequencies and thermal stresses they experience.

The thesis investigates for four different approaches on the best optimization stability, low THD and high utilization in LCL filters in three-phase inverter systems. Using a consistent methodology, the study compares harmonic damping, ripple mitigation, component selection, and implementation complexity for each method. The first method is easier but challenges to match up performance with compact component design. The second solves best ripple but does not handle lower-order harmonics well. The third approach finds a sweet spot of performance versus system complexity by making inductance ratios optimal, but mandating elaborate parameter tuning to ensure stability. The fourth method—utilizing active damping through capacitor voltage feedback—demonstrates the highest performance, with great harmonics suppression, dynamic resonance control, and excellent adaptability to the variable grids system.

Active damping, as implemented in the fourth method, dynamically suppresses resonance and adapts to varying grid conditions, resulting in the lowest THD and highly effective ripple attenuation. Unlike passive damping methods, which rely on fixed resistive elements and incur significant power losses, active damping leverages real-time feedback to enhance efficiency and stability. This makes the fourth method particularly well-suited for addressing the demands of GaN and SiC-based inverter systems, where adaptability and precision are essential. The study demonstrates that this method effectively balances harmonic suppression, energy efficiency, and ease of implementation, making it the most practical solution for next-generation power systems.

This study's results underline the complex, multi-layered nature of designing LCL filters. It is not sufficient just to size the inductor right; the placement of resonance frequencies and the choice of damping strategies are equally crucial and must also be optimized. This research establishes a clear and comprehensive framework for LCL filter design that is suited to the needs of modern inverter systems, especially next-generation inverters built with GaN and SiC technologies. Combining serious computational with real-world applications, this study strengthens the power electronics field and offers a basis for designing the kind of resilient LCL filters

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
PWM	Pulse Width Modulation
EMI	Electromagnetic Interference
GCFAD	Generalized Constant Frequency Active Damping
FMLF	Frequency Multi Layer Foil
NPC	Neutral Point Clamped
CVF	Capacitor Voltage Feedback
CCF	Capacitor Current Feedback
RMS	Root Mean Square
PI	Proportional-Integral
PR	Proportional-Resonant

1 Introduction

A filter is a device used to sort signals in electrical engineering. When it comes to Grid-Connected Inverters, the signals that need to be sorted are the harmonics generated by the inverter itself. The first type of filter used was the L filter. L filter is larger in size and can handle only a certain amount of power, and it is not very efficient. The possibility of arc that would happen when using an L filter, is also another reason why they are not used anymore. Moving to the LCL filter, which is the same as the L filter, only better. The LCL filter has two more components. One is an inductor, and the other is a capacitor. The LCL filter is much more efficient than the L filter, and even though it has the same number of power handling components, it has a larger voltage drop across the filter itself. [6, 38]. Earlier L filters were being used commonly. LCL filters are extremely important in modern power electronic systems, especially those that control grid-connected inverters. These filters have to deal with the electromagnetic interference (EMI) generated by the inverter itself plus its harmonics, which are much more numerous and spread over a much wider frequency range than those of a typical linear power supply or any of its power factor correction variants. This is a problem with any kind of inverter, but it is especially pronounced with the new GaN-based devices because they switch much faster and are capable of much higher peak voltages. As a result, the LCL filter has to be designed to provide the necessary amount of inductance and has to do so in a way that allows not only for the very wide frequency range of generated harmonics to pass through it (to keep the inverter from being a complete EMC failure), but also to ensure that it is not unnecessarily heating up or radiating more EMI than is acceptable. [15].

Another aspect that must be considered when using GaN devices is the heat concentration they generate. Unlike silicon, which is a relatively poor thermal conductor, GaN has an energy band gap of 3.4 eV, and at least two inverters use it to make good, high-quality designs of power semiconductors. Consequently, GaN devices lead to a concentrated heat load in the filter inductors. The key elements of the LCL filter (the inductors and capacitors) must have performance and reliability that can handle the temperature rise. This situation is further aggravated because GaN inverters tend to operate at higher voltages. The inductors and capacitors in the LCL filter have to handle a reliable operation at elevated temperatures and under voltage. [40]. GaN devices also result in concentrated heat loads due to their high-power density and compact size. For maintaining performance and durability, LCL filters must be made to withstand these higher temperatures [13]. [33]. To keep the system reliable, these parts have to be strong enough to withstand these kinds of strains for an extended length of time. Moreover, developing a reliable damping mechanism for the LCL filter is quite difficult. This is due in part to the nature of the LCL filter's resonance behavior; even a damping system that performs well at one fixed frequency can behave quite differently when the system is under load. And the system behavior becomes even more variable if you consider that the load can, and does, change significantly in a power electronics application. [31].

To maintain the economy of the system and the efficiency of the damper in the LCL filter, the inverter design must be done for a reason and very thoroughly. In conclusion, GaN technology has many advantages, such as efficiency and compactness; however, LCL filter design remains a significant challenge that calls for using GaN for an inverter to multilevel instead of for a single-level inverter. [23]. This literature review examines the significant advancements in the design, and structure of LCL filters and challenges in recent years. The typical procedures for determining the elements of these filters are also described.

2 Literature Review

2.1 Overview of LCL filter design procedures

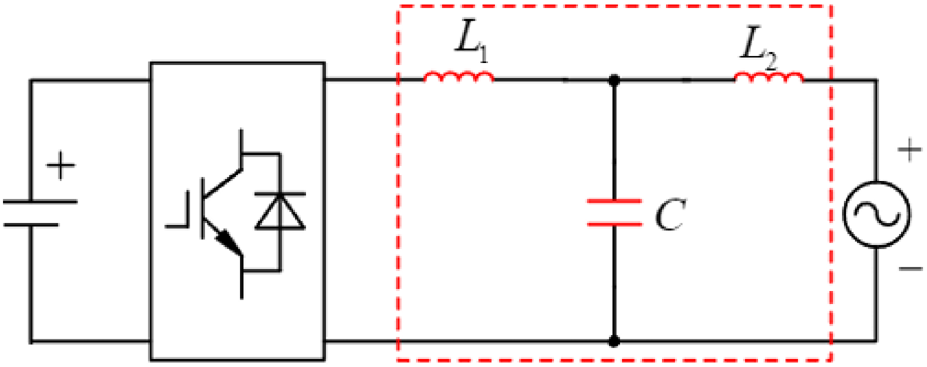

Figure 1: LCL filter overall design

According to their design parameters and application requirements, LCL filters can be grouped into a few different categories. In power electronics, where these filters are employed to control power quality and reduce inverter and converter noise, each design can be tuned to achieve optimal performance in a given application. The typical categories are summarized as follows:

2.2 L filters, LC filters and LCL filters

L filters were initial simple design filters. Due to their limited filtering capacity, bulk design, no harmonic attenuation, and high cost their usage reduced over time. L filters afterwards replaced with more advanced LCL filters which are usually used in grid-connected power inverters [26]. It is possible to design LCL filters for grid-connected power inverters in different ways [32]. Many LCL filter optimisation techniques were put forth by different researchers [35].

In 2005, researchers came up with a way of building and managing a three-phase active rectifier, the basic structure of which is an LCL filter. But this is not simply a passive filter; it has active parts—inductors and capacitors—that have been designed to meet certain attenuation and dynamic performance needs. The rectifier is efficient and dependable because the filter components have been optimally sized and specified in such a way that, even in low-energy, low-dynamics situations—like when the current is zero—it fulfills the power quality requirements of the system. During grid disruptions, the energy conversion system moves very rapidly to the next best condition. This is managed both by hardware optimization and what are now believed to be very high-performance control algorithms. [20].

Another research group proposed a systematic design method for the LCL filters in grid-connected converters. They took into consideration both active and passive damping techniques to come up with a set of strong active damping solutions. Their set of solutions aims to provide LCL filter performance that is robust in various grid scenarios and, more generally, is adequate for LCL filters in converter applications. [16].

Active damping employs additional control mechanisms that modify the damping in response to feedback from the system, while passive damping typically uses resistors that absorb energy and dampen resonances. Active damping was made possible when sophisticated control algorithms that can react quickly to changes in system behavior were created. These algorithms