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Advanced Control Techniques for High-Power Power Converters

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Abstract. This paper offers a comprehensive review of the advancements in the domain of Solid Oxide Fuel Cells and Electrolyzers for Green Hydrogen Production. The review encompasses the exploration of various advanced control methods that have emerged as alternatives to traditional cascaded linear controllers, specifically for power converters in distributed generation systems and microgrids. The significance and functionalities of voltage source converters (VSCs) in these systems are elucidated, followed by a discussion on the dynamic performance limitations of linear controllers. The paper delves into the most notable advanced control methods, shedding light on their implementation principles, merits, and demerits. Furthermore, the paper touches upon the application of modelling methods apt for control and simulation of power electronic systems, emphasizing the benefits of non-linear modelling for controller design. The review also covers the state-of-the-art integrated switched-capacitor and inductive power converters, providing insights into the utilization of transistor technology and various control strategies. By drawing comparisons and categorizing different converter technologies, the paper aims to present a holistic view of the current landscape and potential future directions in the realm of Solid Oxide Fuel Cells and Green Hydrogen Production.

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1 Introduction

The evolution of green hydrogen production and its associated technologies has been marked by significant advancements in the realm of Solid Oxide Fuel Cells and Electrolyzers. Central to this evolution is the control of voltage source converters (VSCs) in distributed generation (DG) systems and microgrids. Traditionally, the voltage-oriented control (VOC) approach has been the mainstay for controlling VSCs. VOC, with its cascaded control structure followed by a pulse-width-modulator (PWM), offers a linear control loop system that is analytically simple and offers clear performance quantification. However, despite its advantages, VOC has its limitations, particularly when faced with large-signal external disturbances and parameter variations.

These challenges have spurred research into alternative control methods for VSCs. While some efforts have been directed towards enhancing the performance of VSCs by introducing innovative feedback loops within the cascaded control structure, the fundamental limitations of the linear control scheme remain. Advanced Control, a distinct approach, offers a paradigm shift in how control methods process the error between measured signals and references. This method bifurcates into model-based and data-based strategies, each with its unique advantages and applications. Model-based strategies, for instance, incorporate models of the converter in the controller design process, while data-based strategies leverage qualitative knowledge about the VSC and data extracted from simulations or experimental test-beds.

In parallel to these advancements in control methods, the importance of computer simulation in the design and evaluation of novel power electronic converters and their controllers cannot be understated. The non-linear, discrete nature of electronic power converters necessitates a systematic approach that can handle variable structures and non-linearities. Sliding mode control emerges as a preferred technique, offering robustness, fast dynamics, and better tracking performances compared to linear controllers. Furthermore, the rise of integrated circuit technologies has amplified the demand for integrated power conversion and regulation. Integrated power converters, particularly those that utilize switched capacitors and inductors, are becoming increasingly popular due to their efficiency, compactness, and adaptability to modern digital ICs.

This review article aims to provide a comprehensive overview of these intertwined areas, highlighting the limitations of traditional linear control methods, the potential of advanced controllers, and the pivotal role of integrated power converters in the modern technological landscape. Through this exploration, we seek to offer insights into the current state of the field and its implications for the future of green hydrogen production.

2 Review and discussion

In a study by Dragičević et al. (2020), a comprehensive examination of various control systems was conducted, focusing on the voltage control of LC filtered Voltage Source Converters (VSCs). The study delves deep into the performance metrics and applicability of various control structures, with a spotlight on the voltage control of LC filtered VSCs. The research underscores the limitations of conventional cascaded controllers and brings to the fore the advantages of advanced control methods. The findings are pivotal for industries and researchers aiming to optimize the performance of their control systems, especially in scenarios demanding high robustness and efficiency.

In the realm of control systems, a benchmark case study was established to assess the performance of various control structures, specifically focusing on the voltage control of the LC filtered VSC. This particular structure was chosen due to its representation of various control structures, the evident limitations of conventional cascaded controllers, the quantitative performance metrics defined in standards like IEC 62040, and its wide spectrum of control functionalities [4-8].

Table 1. Key Findings on Voltage Control of LC Filtered VSCs

Parameter/Aspect	Modulator-Based	Non-Modulator-Based	Remarks
DC link voltage	700 V	700 V	Standard voltage for the setup.
LC-filter	Lf = 2.4 mH, Cf = 15 μF	Lf = 2.4 mH, Cf = 15 μF	Standard filter parameters.
Reference voltage	V_{RMS}r = 230 V, fr = 50 Hz	V_{RMS}r = 230 V, fr = 50 Hz	Standard reference values.
Linear load	Rload = 33 Ω	Rload = 33 Ω	Standard load value.
Sampling Times	Ts = 100 μs	Ts = 20 μs	Different sampling times for each method.
Switching Frequency	1/Ts = 10 kHz	Not fixed, indirectly controlled	Non-modulator has variable switching frequency.
Performance	Good steady-state performance	Best dynamics but higher ripple & error	Advanced methods outperform linear control.

Following the detailed analysis, it becomes evident that while conventional cascaded linear control systems have their merits, they also come with inherent limitations, especially when faced with large disturbances, nonlinearities, and parameter variations. Advanced control strategies, as explored in the study, offer a promising avenue to address these challenges. These strategies, particularly those that do not rely on modulators, present an opportunity to maximize the dynamic performance of VSCs. However, the practical application of these advanced controllers requires careful consideration, balancing their enhanced performance against potential drawbacks such as increased complexity and computational demands.

In the context of our review article, Dragičević et al.'s findings underscore the importance of evolving control strategies for VSCs in distributed generation systems and microgrids. As the energy landscape becomes more complex and demands on systems increase, the need for more sophisticated control methods becomes paramount. This study serves as a testament to the ongoing efforts in the field to optimize and innovate, ensuring that VSCs can meet the challenges of the future.

Another study by da Silva et al. (2003) delves into the advanced control methods for power electronics systems. The research emphasizes the importance of modelling methods suitable for the control and simulation of power electronic systems. Here are the summarized key findings [9-12]:

- **Objective**: The study aims to provide a comprehensive approach to solve the simulation and control problems of novel structures of power electronics converters.
- **Modelling and Simulation**:
    - Power electronic converters are non-linear, discrete, and variable structure systems.
    - Variable structure control (sliding mode) is the preferred technique due to its various advantages, such as ensuring converter stability, providing near zero steady-state error, and offering robustness against parameter variation and disturbances.
    - The paper presents steps to obtain models suitable for converter control and simulation. It emphasizes the importance of using switched state–space non-linear models for these purposes.
- **Control Design**:
    - The study introduces the concept of a switched state–space model and its canonical form.
    - The paper discusses the conditions for sliding mode existence and reaching conditions for control.
    - It introduces two-level and multilevel switching laws for control.
    - The study also touches upon the need for constant frequency operation and methods to eliminate steady-state errors.
- **Example - AC Current Control in Multilevel Converters**:
    - Three-phase n level converters are highlighted as suitable for low distortion DC/AC applications or high-voltage, high-power applications.
    - The study proposes a real-time modulator for the control of the output AC currents and capacitor voltage equalization, based on the use of sliding mode and space vectors in the αβ frame.

In conclusion, the research by da Silva et al. provides a deep insight into the advanced control methods for power electronics systems. It underscores the significance of adopting a systematic approach to modelling and control, emphasizing the benefits of sliding mode control. The study also offers practical examples, demonstrating the application of the discussed concepts in real-world scenarios.

In our review article, we've underscored the evolution and advancements in control methods for power electronics systems. The study by da Silva et al. (2003) seamlessly complements our discourse, offering a meticulous exploration of modelling techniques apt for the control and simulation of power electronic converters. Their emphasis on the switched state–space non-linear models and the application of sliding mode control provides a nuanced understanding that enriches our article's narrative. Furthermore, their practical approach, demonstrated through real-time modulators for three-phase n level converters, offers tangible evidence of the theoretical concepts discussed. Integrating insights from such a seminal work ensures our review not only traces the developmental trajectory of control methods but also encapsulates the depth and breadth of contemporary research in the field.

Another study by Kiran Kumar et al. (2021) delves into the comparative analysis of switched-capacitor (SC) and inductor-based converters, focusing on their efficiency and power density. The key findings from this study are [13-18]:

- **Comparative Analysis**:
  - The study presented a comparison of SC and inductor-based converters based on their maximum efficiency and power density.
  - The literature examples were not entirely comparable due to varying constraints and functionalities, such as step-down or step-up operations and different input and output voltage values.
- **Switched-Capacitor Power Converters (SCPCs)**:
  - A clear trade-off exists between maximum efficiency and power density in bulk CMOS applications that use MIM capacitors.
  - Operating the SCPC at higher switching frequencies can result in a compact design, providing high power density at acceptable efficiencies.
  - Different technologies showcased acceptable performance, with some designs achieving high efficiency or power density but not both.
  - Determining the best type of converter circuit, either SCPC or inductive converter, is challenging due to various application constraints.
- **Inductive Converters**:
  - Monolithic converters achieve comparable power densities without requiring significant modifications.
  - SiP-based converters offer both higher and lower power densities compared to monolithic converters, with the primary advantage of SiP being cost savings.
  - The power density of converters can be improved using postprocessing steps with magnetic structures on CMOS, with material choice being crucial.
  - Integrated inductive converters are more suitable for higher power levels, while most SCPC designs are geared towards low-power applications.
- **Conclusions**:
  - Both switched-capacitor and switched-inductive networks allow efficient conversion for up and down operations.
  - For integrated switched-capacitor converters, there's a trade-off between peak efficiency and power density, with different capacitor technologies offering varied results.
  - Switching losses in SCPCs can be reduced using the switching-frequency modulation technique, but this increases noise. This noise can be mitigated using a capacitor-size modulation technique.
  - Inductive converters using anSiP-based approach can achieve both low and high power densities, with the potential for increased power density using postprocessed magnetic structures on CMOS.
  - In general, inductive converters are more suited for higher output power applications, while integrated switched-capacitor converters are ideal for ultralow output powers.

In our review article, we endeavour to present a holistic understanding of power converter technologies, emphasising their efficiency, design intricacies, and application suitability. The study by Kiran Kumar et al. (2021) seamlessly complements our narrative by offering a meticulous comparative analysis of switched-capacitor and inductor-based converters. Their exploration into the nuanced trade-offs between efficiency and power density, especially in the context of varying capacitor technologies and modulation strategies, provides invaluable insights. Furthermore, their emphasis on real-world application constraints and the challenges of achieving optimal performance adds depth to our discourse. Integrating the findings from this study not only enriches our article's content but also underscores the evolving nature of power converter technologies and the importance of informed design choices in achieving desired outcomes.

3 Future scope of research

The evolution of control systems and their integration with power converters has opened up a plethora of opportunities for further exploration. As the world moves towards more sustainable and efficient energy solutions, the role of advanced control methods in power converters becomes even more pivotal. The following pointers highlight potential areas where researchers can delve deeper, pushing the boundaries of what's possible and ensuring that the energy solutions of the future are not only efficient but also sustainable and adaptable to the ever-changing demands of the modern world:

- Advanced Control Methods: As the dynamic performance of advanced control methods has shown superiority over cascaded linear control, further research can delve into refining these methods for even better performance.

- Integration with Renewable Energy Sources: With the increasing emphasis on sustainable energy, integrating the discussed control methods with renewable energy sources like solar and wind can be a promising area of research.

- Noise Reduction in Switching: The noise introduced during switching is a concern. Future research can focus on techniques to minimise this noise without compromising on performance.

- Efficiency Optimisation: While the current methods have shown good efficiency, there's always room for improvement. Research can focus on achieving near-perfect efficiency rates.

- Miniaturisation: As technology advances, there's a push towards making devices smaller and more compact. Research can focus on miniaturising the discussed converters without losing out on performance.

- Integration with IoT: With the Internet of Things (IoT) becoming more prevalent, research can focus on integrating the discussed methods with IoT devices for smarter energy management.

4 Knowledge gaps

While the studies reviewed provide invaluable insights into the current state of control methods in power converters, there are still several areas where more information is needed. These gaps in our knowledge can sometimes act as barriers, preventing the full potential of these methods from being realised. By identifying and addressing these gaps, researchers can ensure that the solutions developed are not only technically sound but also practical and relevant to the real-world challenges faced by industries and consumers alike. The following pointers shed light on some of these knowledge gaps:

- Real-world Application Data: While the studies provide insights based on simulations and controlled environments, there's a gap in understanding how these methods perform in real-world scenarios with unpredictable variables.

- Long-term Performance: The long-term performance and durability of these advanced control methods, especially in varying environmental conditions, is not extensively covered.

- Cost Analysis: A comprehensive cost-benefit analysis of implementing these advanced methods, especially in large-scale industrial setups, is missing.

- Interoperability: How these methods interact with other existing systems and technologies is not extensively discussed. There's a need to understand the compatibility and interoperability aspects.

- Safety and Security: With the increasing threats to cyber-physical systems, understanding the safety and security implications of these methods is crucial.

- Environmental Impact: While the focus is on performance and efficiency, the environmental impact of implementing these methods, especially at a large scale, is not thoroughly discussed.

5 Conclusion

In our journey through the intricate landscape of control methods in power converters, we've traversed a range of studies, each offering unique insights and perspectives. These studies, while diverse in their approaches, converge on certain pivotal findings that underscore the significance of our topic. Before we encapsulate our review, let's revisit some of the salient findings that emerged from our exploration:

- Diverse Control Systems: The studies underscored the vast array of control systems available, each tailored to specific applications and requirements. This diversity is a testament to the adaptability and versatility of modern power converter technologies.

- Superiority of Advanced Control Methods: Across the board, advanced control methods demonstrated enhanced dynamic performance, especially when juxtaposed with traditional cascaded linear control.

- Trade-offs in Design: Whether it's the balance between efficiency and power density in switched-capacitor converters or the noise implications of certain modulation techniques, the studies highlighted the inherent trade-offs designers must grapple with.

- Relevance of Real-world Applications: The studies accentuated the importance of real-world application data, underscoring the gap between theoretical models and practical implementations.

- Integration Challenges: As power converters become more integrated with other systems, from renewable energy sources to IoT devices, the challenges of seamless integration become more pronounced.

- Environmental and Economic Implications: Beyond the technical aspects, the studies also hinted at the broader environmental and economic implications of power converter technologies, from their role in sustainable energy solutions to their cost-effectiveness in various applications.

Navigating through the intricate landscape of control methods in power converters, we've unearthed a myriad of insights from diverse studies. These findings, while varied in their nuances, converge on pivotal themes that resonate with the essence of our exploration. As we encapsulate our review, the realm of control methods in power converters emerges not merely as a testament to technical advancements but also as a reflection of the broader ecosystem in which these technologies thrive. The delicate balance between efficiency, sustainability, and practicality underscores the narrative, urging us to approach this domain with a holistic lens. Beyond the technical intricacies, it's the societal and environmental reverberations of these technologies that beckon our attention, shaping the trajectory of future innovations.

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