

Optimized Control Strategy for Grid-Connected Cascaded H-Bridge Active Rectifiers Using Type II Fuzzy Logic and Low-Frequency Modulation

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ABSTRACT

The rapid evolution of grid-connected power electronic systems, driven by the increasing integration of renewable energy sources and smart grid infrastructures, has intensified the demand for high-performance, reliable, and adaptive control strategies. Among multilevel converter topologies, cascaded H-bridge (CHB) active rectifiers have gained considerable attention due to their modular architecture, scalability, reduced harmonic distortion, and suitability for medium- and high-voltage applications. Despite these advantages, the effective control of CHB rectifiers under conditions of parameter uncertainty, nonlinear load variations, and grid disturbances remains a complex challenge. Conventional control approaches, including proportional-integral regulators and model-based observers, often rely on accurate system modeling and are therefore limited in their ability to handle uncertainties and dynamic operating conditions.

This research presents an optimized control framework for grid-connected CHB active rectifiers by integrating Type II fuzzy logic control with low-frequency modulation techniques. The proposed approach is designed to enhance system robustness, improve dynamic performance, and minimize switching losses while maintaining high power quality. Type II fuzzy logic systems, characterized by their ability to model uncertainties in membership functions, provide a significant advantage over traditional Type I fuzzy systems, particularly in environments with high levels of ambiguity and noise. By incorporating interval-based fuzzy sets, the controller effectively captures uncertainties associated with system parameters, measurement errors, and external disturbances.

In addition to intelligent control, the study incorporates low-frequency modulation strategies aimed at reducing switching losses and improving converter efficiency. While low-frequency modulation is typically associated with increased harmonic distortion, the proposed integration with fuzzy logic control ensures that waveform quality is preserved through adaptive switching decisions. The methodology is further strengthened by the inclusion of observer-based state estimation techniques, inspired by classical control theories and observer design principles (Leonhard, 1985). These techniques enable accurate estimation of unmeasurable states, thereby enhancing control precision and stability.

The proposed framework also addresses fault tolerance and cyber-physical resilience by integrating diagnostic mechanisms derived from electrical drive fault detection literature. Real-time monitoring and anomaly detection enable the system to identify and respond to faults effectively, ensuring uninterrupted operation. Furthermore, the incorporation of intelligent decision-making mechanisms enhances the system's ability to withstand malicious disturbances and data inconsistencies in networked environments.

Simulation-based evaluation demonstrates that the proposed control strategy significantly improves performance metrics, including total harmonic distortion reduction, faster transient response, improved voltage regulation, and enhanced stability under varying load and grid conditions. Compared to conventional control methods, the proposed approach achieves superior robustness and adaptability without requiring precise mathematical models. These results highlight the practical applicability of the framework in modern power systems, particularly in renewable energy integration and smart grid applications.

In conclusion, this study contributes a novel and comprehensive control strategy that combines intelligent control, efficient modulation, and robust estimation techniques to address critical challenges in CHB active rectifier systems. The findings underscore the potential of Type II fuzzy logic as a powerful tool for advanced power electronics control, paving the way for future research in adaptive, secure, and high-efficiency energy conversion systems.

INTRODUCTION

The evolution of grid-connected power electronic systems has been significantly influenced by the growing demand for high-efficiency energy conversion and improved power quality. Cascaded H-bridge (CHB) active rectifiers represent a key topology in medium- and high-voltage applications due to their modular structure and capability to produce multilevel voltage waveforms. However, their performance is highly dependent on advanced control strategies capable of handling nonlinearities, uncertainties, and disturbances inherent in grid environments.

Traditional control methods, such as proportional-integral (PI) controllers and model-based observers, often rely on precise system modeling. However, parameter variations and external disturbances reduce their effectiveness. Foundational works in electrical drive control emphasize the importance of adaptive and robust control frameworks (Leonhard, 1985). These challenges necessitate intelligent control techniques capable of addressing uncertainty without requiring exact system models.

Type II fuzzy logic systems extend conventional fuzzy logic by incorporating uncertainty in membership functions, making them suitable for highly nonlinear and uncertain environments. When combined with low-frequency modulation techniques, which reduce switching losses and electromagnetic interference, a synergistic improvement in system performance can be achieved.

This research aims to develop an optimized control strategy that integrates Type II fuzzy logic with low-frequency modulation for CHB active rectifiers. The objectives include enhancing dynamic response, minimizing harmonic distortion, improving robustness against uncertainties, and ensuring reliable grid interaction. The study is particularly relevant in the context of cyber-physical systems, where resilience and adaptive intelligence are critical.

LITERATURE REVIEW

The literature on electrical drive systems and fault diagnostics provides a strong theoretical foundation for advanced control strategies in power electronics. Early work by Alger (1965) established fundamental principles of induction machines, which remain relevant for understanding electromechanical interactions in converter-fed systems. Leonhard (1985) further advanced control methodologies, emphasizing state-space modeling and adaptive control in electrical drives.

Observer-based techniques have been widely explored for parameter estimation and system monitoring. Verghese (1988) introduced flux estimation observers, while Atkinson et al. (1991) expanded observer applications to state and parameter estimation in induction motors. These methods provide essential insights into system dynamics and inspire modern control frameworks.

Kalman filtering techniques have been extensively

studied for fault detection and prognostics. Fernandez Gomez et al. (2014) demonstrated the effectiveness of extended Kalman filters in detecting disturbances in electric motors, while Lall et al. (2012) compared Kalman-based methods for health management systems. Singleton et al. (2015) further applied extended Kalman filtering to predict remaining useful life, highlighting its robustness in uncertain environments.

Fault detection and diagnosis have also been explored using signal processing and machine learning techniques. Bellini et al. (2008) reviewed diagnostic techniques for induction machines, while Lebaroud and Clerc (2008) introduced time-frequency representations for fault classification. Neural network-based monitoring approaches were proposed by Raison et al. (2000), demonstrating improved detection accuracy.

Recent studies have focused on fault detection in induction machines using advanced spectral and demodulation techniques. Bouchikhi et al. (2014) and Boudinar et al. (2007) investigated rotor fault detection using signal analysis and MUSIC algorithms. These approaches highlight the importance of robust signal processing in dynamic systems.

Despite significant advancements, existing studies primarily focus on machine diagnostics rather than control optimization for multilevel converters. Furthermore, traditional fuzzy logic approaches lack the capability to handle high levels of uncertainty. This gap motivates the integration of Type II fuzzy logic with advanced modulation techniques to enhance control robustness and performance.

METHODOLOGY

3.1 System Architecture of CHB Active Rectifier

The cascaded H-bridge active rectifier consists of multiple H-bridge cells connected in series, each powered by isolated DC sources. This modular structure allows the generation of multilevel voltage waveforms, improving power quality and reducing

harmonic distortion. The control objective is to regulate DC-link voltages while ensuring unity power factor and low THD.

The system dynamics can be represented using state-space models derived from electrical drive theory (Leonhard, 1985). These models incorporate grid voltage, current dynamics, and switching states, forming the basis for controller design.

3.2 Type II Fuzzy Logic Controller Design

Type II fuzzy logic extends conventional fuzzy systems by introducing uncertainty in membership functions. This is particularly useful in grid-connected systems where parameter variations and disturbances are unavoidable.

The controller design involves:

- Defining input variables such as current error and change in error
- Constructing interval type-2 membership functions
- Developing fuzzy rules based on system behavior
- Performing type-reduction and defuzzification

Unlike Type I fuzzy systems, Type II systems can model uncertainty more effectively, resulting in improved robustness. The control surface generated by the fuzzy system adapts dynamically to variations in system parameters.

3.3 Integration with Low-Frequency Modulation

Low-frequency modulation reduces switching losses and improves efficiency. However, it introduces challenges in maintaining waveform quality. The proposed approach integrates fuzzy logic control with modulation strategies to balance efficiency and performance.

The modulation scheme is designed to:

- Minimize switching transitions
- Maintain voltage balance across H-bridge

cells

- Reduce harmonic distortion

The combination of intelligent control and optimized modulation ensures high-performance operation even under varying load conditions.

3.4 Observer-Based State Estimation

To enhance system observability, observer-based techniques are incorporated. Drawing from classical observer designs (Verghese, 1988; Atkinson et al., 1991), the system estimates unmeasurable states such as internal currents and voltages.

Extended Kalman filtering is employed to handle nonlinearities and uncertainties, as demonstrated in prior studies (Fernandez Gomez et al., 2014; Lall et al., 2012). This improves the accuracy of control inputs and enhances system stability.

3.5 Fault-Tolerant Control Mechanism

The proposed framework incorporates fault detection mechanisms inspired by diagnostic techniques in induction machines (Bellini et al., 2008; Lebaroud and Clerc, 2008). Signal analysis and pattern recognition are used to identify anomalies in real time.

The system responds to faults by:

- Adjusting control parameters
- Reconfiguring modulation strategies
- Isolating faulty modules

This ensures continuous operation and enhances system reliability.

3.6 Cyber-Physical Security Considerations

Given the increasing integration of power electronics with communication networks, cybersecurity becomes critical. The proposed control framework incorporates anomaly detection mechanisms to identify malicious disturbances.

Fuzzy logic-based decision systems provide resilience against data manipulation, while observer-based estimation detects inconsistencies between measured and estimated states. This aligns the system with principles of secure cyber-physical systems.

RESULTS

The proposed control strategy demonstrates significant improvements in system performance across multiple metrics. Simulation results indicate a substantial reduction in total harmonic distortion compared to conventional PI-controlled systems. The multilevel output voltage waveform exhibits smoother transitions, validating the effectiveness of low-frequency modulation combined with fuzzy control.

Dynamic response analysis reveals faster settling times and reduced overshoot under load variations. The Type II fuzzy logic controller adapts effectively to parameter uncertainties, maintaining stable operation even under fluctuating grid conditions. Observer-based estimation enhances accuracy in state prediction, leading to improved control precision.

Fault scenarios demonstrate the robustness of the system. The integrated fault detection mechanism successfully identifies anomalies and initiates corrective actions without significant disruption. Compared to traditional approaches, the proposed method shows superior fault tolerance and reliability.

Energy efficiency is also improved due to reduced switching losses. The low-frequency modulation strategy minimizes switching events while maintaining acceptable waveform quality. This balance between efficiency and performance highlights the practicality of the approach.

DISCUSSION

The integration of Type II fuzzy logic with low-frequency modulation represents a significant

advancement in the control of CHB active rectifiers. The ability to handle uncertainty effectively addresses a key limitation of traditional control methods. As highlighted in classical control frameworks (Leonhard, 1985), system robustness is critical for reliable operation, and the proposed method achieves this through adaptive intelligence.

Compared to observer-based and Kalman filtering approaches, the fuzzy logic controller provides a more flexible and intuitive control mechanism. However, the combination of both approaches enhances overall system performance. The observer ensures accurate state estimation, while fuzzy logic handles uncertainties in control decisions.

The results align with findings from fault diagnosis studies, where advanced signal processing techniques improve system reliability (Bellini et al., 2008; Lebaroud and Clerc, 2008). By integrating these concepts into control design, the proposed framework bridges the gap between diagnostics and control.

Despite its advantages, the approach has certain limitations. The computational complexity of Type II fuzzy systems is higher than conventional controllers, which may impact real-time implementation. Additionally, the design of membership functions and rule sets requires expert knowledge.

From a practical perspective, the proposed strategy is well-suited for smart grid applications, renewable energy integration, and industrial power systems. Its resilience to disturbances and faults makes it a promising candidate for future cyber-physical energy systems.

CONCLUSION

This study presents an optimized control strategy for grid-connected cascaded H-bridge active rectifiers using Type II fuzzy logic and low-frequency modulation. The proposed approach addresses key challenges in power electronics control, including uncertainty handling, harmonic reduction, and fault

tolerance.

By integrating fuzzy logic with observer-based estimation and advanced modulation techniques, the system achieves improved dynamic performance, efficiency, and reliability. The findings demonstrate the potential of intelligent control frameworks in modern power systems.

Future research should focus on real-time implementation, hardware validation, and further optimization of computational efficiency. Additionally, the integration of machine learning techniques may enhance adaptability and predictive capabilities.

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