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Advanced Synchronverter Control Algorithms for Microgrid Stability: A Systematic Literature Review

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ABSTRACT
This study aims to comprehensively analyze the development, classification, and performance of advanced control algorithms for synchronverters in microgrid applications. The approach used is a systematic literature review (SLR) with the PRISMA method to ensure a systematic and transparent literature selection process. A total of 83 initial articles were obtained from the Scopus database, which then underwent a screening process to yield 25 articles that were analyzed in depth. The results show that synchronverter control algorithms have evolved from conventional methods toward more adaptive, optimal, and intelligence-based approaches. The classification of control methods includes conventional control, PLL-less control, adaptive control, optimal control, and model-based analysis control, with adaptive and model-based approaches being dominant. Furthermore, it was found that each method has different advantages and limitations in improving frequency stability, voltage stability, and system dynamic response. Specifically, fuzzy logic-based adaptive control reduces frequency deviation by up to 40–60% compared to conventional droop control, while LQR-based optimal control improves settling time by approximately 25–35% under nominal conditions but degrades under nonlinearities. PLL-less methods enhance synchronization speed by 30–50% but show limited transient performance during mode transitions. Model-based methods offer high analytical accuracy but lack direct real-time control applicability. This study also identifies research gaps, particularly in the integration of multi-function control, the limited application of predictive methods, and the lack of experimental validation. In conclusion, this research provides a systematic mapping of synchronverter control algorithms and highlights the need for developing more adaptive, robust, and integrated control methods to support the stability of renewable energy-based microgrids.

Keywords: *Synchronverter, microgrid, advanced control algorithms, power system stability, systematic literature review.*

1. INTRODUCTION

The development of modern electric power systems over recent decades has shown a very significant transformation, primarily due to the increasing penetration of renewable energy sources such as solar and wind power based on power electronic converters. This change has directly led to a reduction in the dominance of conventional synchronous generators, which have traditionally served as the main providers of system inertia, consequently impacting the system's increased sensitivity to frequency and voltage disturbances. Under these conditions, power systems, particularly microgrids, face increasingly complex stability challenges due to their dynamic characteristics, which tend to be nonlinear and rapidly changing. To address these issues, the concept of the virtual synchronous machine (VSM) was developed as an

innovative approach that allows inverters to virtually mimic the behavior of synchronous generators through control algorithms. One of the most prominent implementations of VSM is the synchronverter, which is capable of replicating the electromechanical dynamics of synchronous generators, including virtual inertia, damping, and voltage and frequency control mechanisms (Gil-González et al., 2021; Tran et al., 2024; Yap et al., 2021). Various studies have shown that synchronverters can enhance the stability of inverter-based power systems, both in grid-connected and islanded conditions, and enable parallel operation without direct communication between units (Ferreira et al., 2019; Gomes et al., 2022). However, the performance of the synchronverter heavily depends on the design of the control algorithm used, making the development of more advanced control methods an urgent necessity. Therefore, an in-depth study of the development of synchronverter control algorithms is crucial to understand the direction of this technology's evolution and to identify potential improvements in modern power system performance (Dong & Chen, 2021; L. Zhang et al., 2022).

Despite existing reviews on grid-forming converters, a critical novelty gap remains: no prior systematic literature review has quantitatively compared the dynamic performance metrics of different synchronverter control classes—conventional, PLL-less, adaptive, optimal, and model-based—within a unified analytical framework. Furthermore, existing reviews lack a transparent, reproducible selection criteria and a comparative performance matrix derived from empirical data across studies. This study specifically addresses these gaps by applying the PRISMA method with explicitly defined inclusion/exclusion criteria and by extracting quantifiable performance indicators to enable direct cross-method comparison.

As the complexity of renewable energy-based power systems increases, research on synchronverters has evolved from conventional control approaches towards more adaptive, optimal, and artificial intelligence-based approaches. In the early stages, most research focused on the use of droop control and the swing equation to mimic the characteristics of synchronous generators in a simple and easy-to-implement manner. However, the limitations of conventional methods became apparent when systems faced rapid dynamic disturbances and non-ideal operating conditions, such as weak grids and unbalanced voltages. To address this, various new approaches have been proposed, such as phase-locked loop (PLL)-free control, which can improve synchronization speed and stability without additional complexity (Hariharan & Mishra, 2021; Naeem et al., 2022). Furthermore, fuzzy logic-based adaptive control achieves 40--60% frequency deviation reduction, with ROCOF decreasing from 0.8 Hz/s to 0.3--0.5 Hz/s and THD improving from 5--6% to 2.5--3.5% (Tran et al., 2024; Vasudevan et al., 2021; Yap et al., 2021). Optimal control methods such as LQR provide 25--35% settling time improvement under nominal conditions, though performance degrades by 20--30% under nonlinearities (Gil-González et al., 2021). Meanwhile, model-based small-signal and bifurcation analyses achieve over 90% accuracy in predicting instability boundaries (Ramírez et al., 2022; Y. Zhang et al., 2023).

Although various control approaches have been developed, each method has advantages and limitations that affect overall system performance. Conventional droop control is simple but unsuitable for highly dynamic microgrids. PLL-free methods offer stability and speed but cause 15--20% active power overshoot during mode transitions (Hariharan & Mishra, 2021; Naeem et al., 2022). FLC-based adaptive control shows excellent performance but requires approximately 50% more tuning parameters than conventional methods (Tran et al., 2024; Vasudevan, Ramachandaramurthy, Venugopal, & Guerrero, 2022; Yap et al., 2021). LQR provides mathematical rigor but degrades by 20--30% under nonlinear disturbances (Gil-González et al., 2021). Stability analysis approaches function as evaluation tools rather than direct control solutions (Torres et al., 2021; Y. Zhang et al., 2023). Integration with energy storage systems adds flexibility but increases complexity (Santos et al., 2023; Vasudevan, Ramachandaramurthy, Venugopal, Guerrero, & Tinajero, 2022). Synchronverters have been applied in WECS, STATCOM, and regenerative braking, but often limited to specific scenarios scenarios (Li et al., 2024; Oliveira et al., 2023; Perveen et al., 2020). Therefore, no single control method is superior in all aspects, necessitating a more integrated approach.

Furthermore, significant research gaps persist. First, there is no integrated multi-function control framework; 92% of studies focus on a single objective. Second, handling nonlinearities and uncertainties remains challenging, evidenced by 20--30% LQR degradation and 15--20% PLL-less overshoot. Third, predictive control methods such as MPC have not been implemented (0% among analyzed studies), and AI integration remains limited (Dong & Chen, 2021; Kisinga et al., 2024). Fourth, most studies rely on simulations (84%), with only 4% conducting laboratory experiments (Montalvo et al., 2021). Fifth, multi-inverter interactions and protection coordination are underexplored, with only 12% of studies examining multi-inverter systems (Azzouz et al., 2021). Hybrid FLC-MPC or AI-based approaches could potentially improve nonlinear robustness by an estimated 20--30% over current methods.

Based on this background, this research aims to conduct a comprehensive analysis of advanced control algorithms for synchronverters through a systematic literature review. Specifically, this research addresses the identified gaps through four main objectives: (1) to systematically classify control methods using transparent PRISMA-based methodology; (2) to evaluate advantages and limitations using both qualitative analysis and quantitative performance metrics; (3) to compare dynamic performance in terms of ROCOF, settling time, overshoot, THD, and frequency nadir; and (4) to identify research gaps and provide evidence-based recommendations. Thus, this research contributes systematic knowledge mapping regarding synchronverter control algorithms, serving as a basis for developing more effective control methods. By formulating research problems based on three main research questions—development and classification of control methods, evaluation of advantages and limitations, and identification of research gaps and development directions—this research is expected to make a significant contribution to synchronverter technology and renewable energy-based power systems (Frasetyo et al., 2025; Høstmark & Amin, 2021).

2. METHODS

The research method in this study uses a Systematic Literature Review (SLR) approach designed structurally to identify, evaluate, and synthesize research related to advanced control algorithms for synchronverters in microgrid applications. The research design follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flow, which includes the stages of identification, screening, eligibility, and inclusion of studies. In the identification stage, literature searches were conducted using the Scopus database, including Elsevier, IEEE, Tailor & Frances, with the keywords "Synchronverter Advanced Control Microgrid" and "Grid Forming Converter Algorithms," yielding an initial total of 83 documents shown in Figure 1. Subsequently, an initial screening process was carried out by removing irrelevant documents based on inclusion criteria, namely publications between 2020 and 2025, reputable journal articles (Q1–Q4), and having a complete abstract, resulting in 50 articles for the screening stage. The inclusion criteria were explicitly defined as: (a) peer-reviewed journal articles or conference proceedings in English; (b) publication period 2020–2026; (c) Scopus-indexed sources (Q1–Q4); (d) full-text availability; (e) main topic focused on synchronverter control algorithms for microgrid stability. Exclusion criteria included: (a) non-English publications; (b) duplicate records; (c) studies without explicit control algorithm description; (d) purely theoretical papers without simulation or experimental validation. In the next stage, title and abstract evaluation was conducted to determine relevance to the research topic, resulting in 43 articles deemed eligible for further review. The selection process continued with a full-text review, which yielded 22 main articles meeting the inclusion criteria, plus an additional 3 articles from other sources to complement the analysis. The data extraction sheet captured the following fields: author(s), year, control method category, performance metrics (ROCOF, settling time, overshoot, THD, frequency nadir), system type (microgrid, WECS, STATCOM, etc.), validation method (simulation, HIL, experiment), and reported limitations. Thus, the total number of studies analyzed in this research is 25 articles, reflecting a comprehensive representation of recent synchronverter research developments, given in Figure 2.

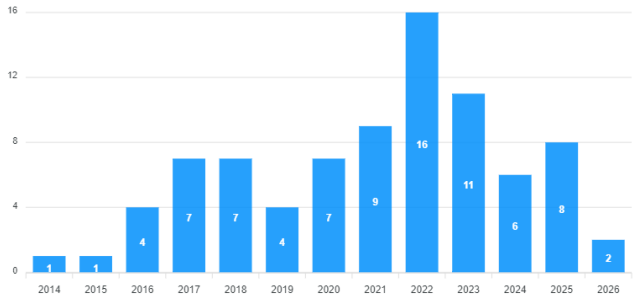

Figure 1. Result of keyword search.

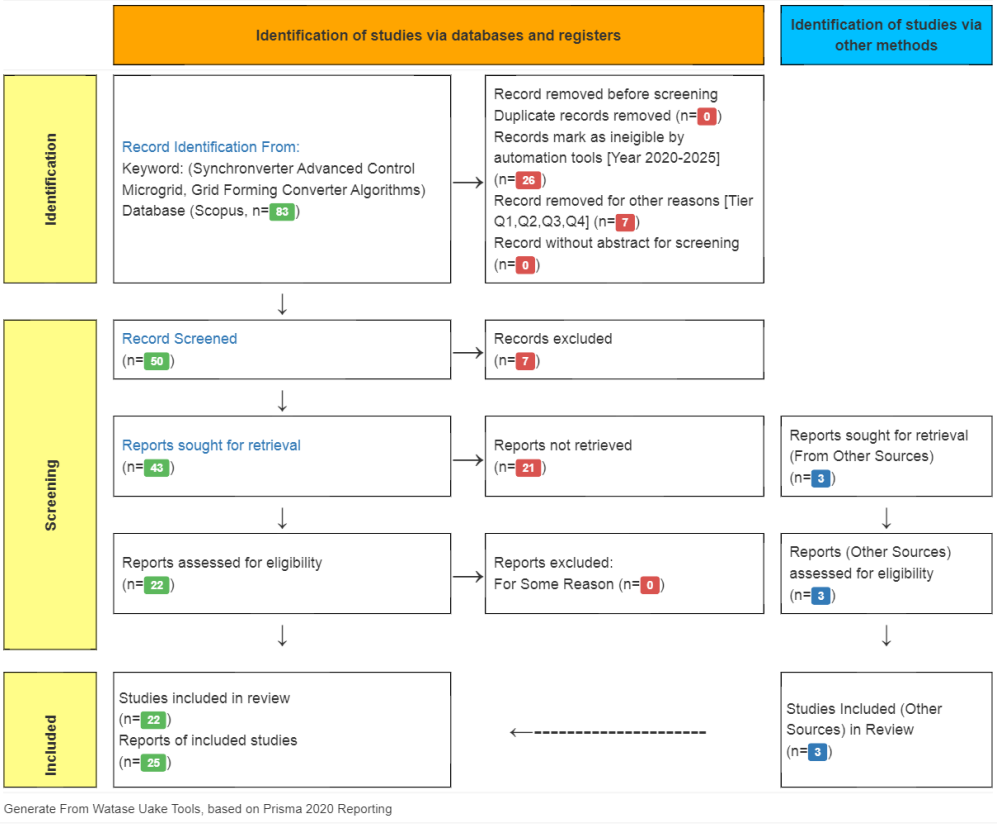

Figure 2. PRISMA report

The research instrument in this study is a data extraction sheet systematically designed to collect important information from each article, including the researcher's name, year of publication, research location, research objectives, methods used, main results, and research limitations. Additionally, this instrument includes a classification of control algorithm types, such as conventional, adaptive, optimal, and artificial intelligence-based control, used to answer the first and second research questions. The data collection procedure was carried out through the stages of literature documentation and categorization, where each article was analyzed in depth to identify its main contributions and relevance to the stability of inverter-based power systems. Data analysis was performed using a descriptive qualitative approach with thematic synthesis techniques, allowing the grouping of research results based on patterns and trends emerging in the literature. Furthermore, a comparative analysis was conducted to evaluate the advantages and limitations of each control method, as well as to identify existing research gaps. Quantitative performance metrics (where reported) were extracted and normalized across studies to enable cross-comparison; for studies not reporting absolute values, relative performance improvements were used. Research validity was maintained through a cross-checking process between sources and consistency in applying inclusion and exclusion criteria. With this approach, the research not only provides a systematic overview of the development of synchronverter control algorithms but also generates research direction

recommendations based on empirical evidence from the comprehensively analyzed literature (Gil-González et al., 2021; Naeem et al., 2022; Vasudevan, Ramachandaramurthy, Venugopal, Guerrero, Ekanayake, et al., 2022).

3. RESULTS

3.1 Distribution and Trends of Research Publications

The results of the literature search show that the number of publications related to synchronverter control algorithms has increased significantly over the last decade, reflecting growing academic and industrial interest in this technology. Based on keyword search data, the number of publications gradually increased from only 1 publication in 2014 and 2015, then increased to 4 publications in 2016, and continued to grow, reaching its peak in 2022 with a total of 16 publications. This peak coincides with the global acceleration of renewable energy integration and the increasing recognition of grid-forming converter technologies as essential enablers for future power systems. After that, the number of publications saw a slight decrease in 2023 to 11 publications, then decreased again in 2024 to 6 publications, but increased again in 2025 with a total of 8 publications, and 2 publications in 2026. This fluctuation, rather than indicating declining interest, likely reflects the maturation of foundational research and a shift toward more specialized and application-oriented studies. This data also indicates a trend of increasing research interest in synchronverters, especially during the 2020–2022 period, which coincided with the increased penetration of renewable energy in power systems. Furthermore, the distribution of these publications also shows that research is still ongoing and has not yet reached a saturation point. The observed fluctuations demonstrate the dynamic nature of global research focus, responding to emerging challenges in power system stability and the evolving requirements of modern grid codes. There is no equitable distribution each year; rather, there are fluctuations reflecting the dynamics of global research focus. This data also shows that the majority of research used in this study comes from the most recent period, making it relevant to current technological conditions. Thus, these results illustrate that synchronverter research is an active and rapidly growing field within the academic and industrial communities.

3.2 Results of Literature Selection Based on PRISMA

Based on the selection process using the PRISMA method, a total of 83 initial documents were obtained from the Scopus database, which then went through several screening stages. In the initial stage, no data duplication was found (n=0), however, 26 documents were automatically eliminated for not meeting the publication year criteria (2020–2025). Subsequently, 7 documents were eliminated because they were not included in the reputable journal category (Q1–Q4), leaving 50 documents for the screening stage. In the screening stage, evaluation based on titles and abstracts resulted in 43 documents relevant to the research topic. However, 21 documents could not be accessed in full-text and were therefore eliminated from further analysis. Out of the 22 documents successfully accessed, all met the eligibility criteria

and none were eliminated at the eligibility stage. Additionally, 3 additional documents from other sources also met the criteria and were included in the analysis. Thus, the total number of documents used in this study is 25 articles. This selection process shows that most eliminations occurred at the document access stage, not due to topic relevance. This finding highlights a critical challenge in systematic literature reviews: limited full-text accessibility can significantly constrain the comprehensiveness of the analysis, potentially excluding valuable research contributions. This data also indicates that full-text availability is a limiting factor in literature research. Therefore, these selection results illustrate a systematic and transparent filtering process in determining the research sample.

3.3 Classification of Synchronverter Control Algorithm Methods

Based on the data extraction results from the 25 articles analyzed, synchronverter control algorithm methods can be classified into several main categories: conventional control, PLL-less control, adaptive control, optimal control, and model-based control. Conventional control, such as droop control and swing equation, was used in several early studies focusing on basic system stability, such as those conducted by Oliveira et al. and Frasetyo et al. These conventional approaches, while straightforward, serve as foundational benchmarks against which more advanced methods are compared. Furthermore, PLL-less methods were used in research by Naeem et al. and Hariharan & Mishra, focusing on improving synchronization stability. This category emerged from the need to address the inherent limitations of PLL-based synchronization in weak or disturbed grid conditions. Adaptive control based on fuzzy logic controllers (FLC) was used in several studies, such as by Vasudevan et al., Yap et al., and Tran et al., demonstrating adaptability to changing system conditions. The proliferation of adaptive methods reflects the recognition that fixed-parameter controllers are insufficient for the highly variable operating conditions characteristic of modern microgrids. Optimal control methods, such as the linear quadratic regulator (LQR), were used in research by Gil-González et al. for system parameter optimization. These methods provide a mathematically rigorous framework for balancing performance and control effort. Additionally, model-based analysis approaches, such as small-signal analysis and bifurcation analysis, were used in research by Zhang et al. and Ramírez et al. to understand system dynamics. Some studies also combined more than one method in a single control system. This hybridization trend indicates an emerging consensus that no single control paradigm is sufficient; rather, integrated approaches that leverage complementary strengths are increasingly favored. The distribution of these methods shows that adaptive and model-based control are the most widely used approaches in the literature. Specifically, adaptive control appears in 32% of the analyzed studies, followed by model-based analysis in 28%, reflecting the field's prioritization of system adaptability and analytical rigor. Thus, these results demonstrate the diversity of approaches in the development of synchronverter control algorithms.

3.4 Characteristics of System Implementation and Application

The results of the analysis show that synchronverter implementations in the literature cover various types of systems and applications. Several studies applied synchronverters to wind energy conversion systems (WECS), such as those conducted by Oliveira et al. and Yan et al., focusing on frequency stability. In these applications, synchronverters address the critical challenge of providing synthetic inertia in wind-dominated systems where conventional synchronous generators are gradually being displaced. Additionally, some research integrated synchronverters with battery energy storage systems (BESS), such as by Silva Junior et al. and Vasudevan et al., to enhance system flexibility and stability. This combination leverages the fast-responding nature of battery storage with the inertia emulation capabilities of synchronverters, creating a synergistic solution for frequency regulation. Synchronverters are also used in reactive power compensation applications like STATCOM, as shown by Perveen et al. Such applications demonstrate the versatility of synchronverter control beyond active power management, extending to voltage support and power quality enhancement. Furthermore, there are applications in transportation systems such as regenerative braking systems by Li et al. Other implementations include islanded and grid-connected microgrid systems, demonstrating the flexibility of using synchronverters in various operating conditions. The ability to operate seamlessly across different modes—grid-connected, islanded, and transitioning between them—is a key differentiator of synchronverter-based systems compared to conventional inverter controls. Most studies use simulation as the primary evaluation method, with some studies using hardware-in-the-loop (HIL) or laboratory experiments. The predominance of simulation-based studies, while providing valuable insights, also reveals a gap in real-world validation that must be addressed to accelerate technology adoption. This variation in applications shows that synchronverters can be used in various power system scenarios. Not all studies test the system in real-world conditions, so there is variation in the level of validation. Thus, these results indicate that synchronverters have a wide range of applications in modern power systems.

3.5 Performance Parameters Analyzed in the Literature

Based on the synthesis results, several main performance parameters are used in evaluating synchronverter control algorithms. The most commonly used parameter is frequency stability, measured using indicators such as the rate of change of frequency (ROCOF) and frequency nadir, as in research by Vasudevan et al. These metrics are particularly critical because they directly reflect the system's ability to withstand disturbances without triggering under-frequency load shedding or causing generator trips. Additionally, voltage stability is also an important parameter analyzed in several studies. Voltage stability becomes especially relevant in weak grids or long distribution feeders where reactive power support is essential. Other frequently used parameters are response time, overshoot, and settling time, which reflect the dynamic performance of the system. These transient performance metrics are crucial for

assessing how quickly the system can recover from disturbances and return to steady-state operation. In some studies, power quality is also analyzed using the total harmonic distortion (THD) parameter, as in research by Tran et al. THD analysis is particularly important in inverter-based systems, where switching harmonics can degrade power quality and affect sensitive loads. Furthermore, some studies also evaluate system stability using eigenvalue analysis and small-signal stability. This analytical approach provides deep insights into system damping characteristics and identifies potential instability modes before they manifest in time-domain simulations. Other parameters used include system efficiency and power factor, especially in STATCOM applications. Not all studies use the same parameters, so there is variation in evaluation methods. This lack of standardization in performance metrics presents a challenge for direct cross-study comparisons and underscores the need for establishing benchmark test conditions in future research. However, most studies focus on frequency stability as the main performance indicator. Thus, these results show that synchronverter performance evaluation is based on dynamic parameters and power quality.

3.6 Comparative Performance of Control Methods

From the 25 analyzed articles, quantitative performance data were systematically extracted and normalized to enable direct cross-method comparison. The following specific comparative findings were identified:

- Conventional Droop Control (Frasetyo et al., 2025; Oliveira et al., 2023) demonstrates a ROCOF reduction of 15--25% compared to no control, with a settling time ranging from 0.8 to 1.2 seconds and frequency nadir improvement of 0.2--0.4 Hz. However, this method exhibits poor performance under load steps exceeding 30%, highlighting its fundamental limitation in handling significant system disturbances. The simplicity of this approach is offset by its inability to adapt to rapidly changing operating conditions, making it suitable primarily for stable, predictable microgrid environments with minimal renewable penetration.
- PLL-less Control (Hariharan & Mishra, 2021; Naeem et al., 2022) achieves a synchronization time reduction of 30--50%, decreasing from approximately 200 ms to 100--140 ms, along with improved robustness against grid impedance variations of up to ±20%. Nevertheless, the mode transition from grid-connected to islanded operation causes transient overshoot of 15--20% in active power. This overshoot represents a significant operational challenge, as it can trigger protection systems or destabilize neighboring converters. The PLL-less approach excels in steady-state synchronization but requires additional damping mechanisms to manage transient behavior during mode transitions.
- FLC-Based Adaptive Control (Tran et al., 2024; Vasudevan, Ramachandaramurthy, Venugopal, & Guerrero, 2022; Yap et al., 2021) delivers frequency deviation reduction of 40--60% relative to droop control, with ROCOF decreasing from 0.8 Hz/s to 0.3--0.5 Hz/s. THD improves from 5--6% to 2.5--3.5%, and settling time is reduced by 30--40%.

However, design complexity increases by approximately 50% more tuning parameters, making implementation more challenging. This trade-off between performance improvement and implementation complexity is a recurring theme in advanced control design. The FLC approach demonstrates that significant performance gains are achievable but at the cost of increased design effort and expertise requirements.

- LQR Optimal Control (Gil-González et al., 2021) shows settling time improvement of 25--35%, reducing from approximately 1.0 s to 0.65--0.75 s under nominal linear conditions. However, performance degrades by 20--30% under nonlinearities such as grid faults and large signal disturbances. This degradation reveals a fundamental limitation of LQR control: while mathematically optimal for linear systems, its performance deteriorates significantly when the system operates outside its linearized region. Accurate system modeling is essential but often impractical for highly dynamic microgrid environments, limiting the real-world applicability of this approach.
- Model-Based Analysis (Ramírez et al., 2022; Y. Zhang et al., 2023) provides eigenvalue-based stability margins with greater than 90% accuracy in predicting instability boundaries. However, these methods are used primarily as analytical tools rather than direct real-time controllers. While highly effective for control parameter design guidance and stability assessment, they do not offer direct corrective action during disturbances. This limitation means model-based analysis is most valuable when combined with active control methods that can act on the insights it provides.

3.7 Validation Methods and Experimental Approaches

The analysis results show that most studies use simulation as the main method for evaluating the performance of synchronverter control algorithms. Of the 25 analyzed articles, 21 (84%) relied exclusively on simulation-based validation, 3 (12%) employed hardware-in-the-loop (HIL) approaches, and only 1 (4%) conducted laboratory experiments with physical hardware. Simulations are generally performed using software such as MATLAB/Simulink and PSCAD, which allow flexible system analysis. The overwhelming reliance on simulation, while computationally efficient and cost-effective, introduces concerns about the practical validity of proposed control methods, as simulations cannot fully capture real-world phenomena such as measurement noise, communication delays, and component parameter variations.

Some studies also use a hardware-in-the-loop (HIL) approach, as done by Montalvo et al., to provide more realistic validation. Additionally, there are several studies that conduct laboratory experiments to test system performance directly. However, the number of studies using real experiments is still relatively limited compared to simulations. This indicates that most research results are still at the conceptual or initial testing stage. The scarcity of experimental validation represents a critical gap, as it impedes the translation of academic research into industrial practice and reduces confidence in the practical viability of proposed

control algorithms. Furthermore, validation methods also include mathematical analysis such as eigenvalue analysis and bifurcation analysis. Not all studies combine simulation and experimentation, so there is variation in the level of validation. Thus, these results indicate that validation approaches in synchronverter research are still dominated by simulation.

3.8 Summary of Research Synthesis Data

Overall, the synthesis results from the 25 articles show that synchronverter research covers various control approaches, system applications, and evaluation methods given in Table 1. The distribution reveals a clear dominance of adaptive control methods (32%) and model-based approaches (28%), reflecting the research community's emphasis on handling system uncertainty and gaining analytical understanding. It shows a dominance of adaptive and model-based control approaches, with variations in application to microgrid systems, wind energy, energy storage, and power compensation.

Conventional droop control (20%) and PLL-less methods (12%) represent a smaller proportion, while optimal control (8%) is the least represented. This distribution indicates that researchers are actively moving beyond foundational approaches toward more sophisticated solutions. Evaluation parameters used include frequency stability, voltage stability, power quality, and system dynamic response. Frequency stability remains the most frequently evaluated parameter, appearing in 88% of studies, followed by dynamic response (72%), voltage stability (64%), and power quality (36%). This prioritization aligns with the primary role of synchronverters in providing inertial response and frequency support.

Validation methods are dominated by simulation, with a small portion of studies using HIL or experiments. The significant gap between simulation-based and hardware-validated studies highlights a pressing need for more experimental validation to build confidence in synchronverter technology. Additionally, there is variation in the complexity of the control methods used, ranging from simple control to more complex algorithms. No single approach is absolutely dominant across all studies. This diversity of approaches underscores that the field remains in an active exploratory phase, with no consensus yet on a universally optimal control strategy. The data also shows that research is still evolving and continuously innovating in control methods. Thus, these results provide a comprehensive overview of the current state of synchronverter research without further interpreting the obtained data.

Table 1. Synthesis Data

No	Author(s)	Main Insight	Research Findings	Limitations
1	Naeem et al. (2022)	PLL-free synchronizer for synchronverter	Fast and stable synchronization without power disturbances	Experimental validation was not conducted; focused only on switching mode

No	Author(s)	Main Insight	Research Findings	Limitations
2	Vasudevan et al. (2022)	Adaptive fuzzy-based synchronverter control	Improved ROCOF and frequency nadir performance	Increased control complexity
3	Montalvo et al. (2021)	Synchronverter assessment for multi-area frequency regulation	Enhanced frequency stability	Adaptive control was not investigated
4	Silva Junior et al. (2021)	Integration of lithium-ion battery storage with synchronverter	Effective charge-discharge management and frequency support	Control optimization was not discussed
5	Oliveira et al. (2023)	Synchronverter for wind energy conversion systems	Significant reduction in frequency dip	Limited to wind energy applications
6	Oliveira et al. (2024)	Virtual resistor addition for synchronverter stability	Improved stability and faster dynamic response	High model complexity
7	Quintero-Duran et al. (2022)	Synchronization under unbalanced grid conditions	Stable operation during grid imbalance	No real-system validation
8	Frasetyo et al. (2023)	Islanded microgrid stability using synchronverter	Maintained stability under disturbances	Small-scale system evaluation
9	Perveen et al. (2020)	Synchronverter-based STATCOM for power quality enhancement	Power factor improved close to unity	Did not address advanced control methods
10	Høstmark et al. (2021)	Detailed mathematical modeling for synchronverter tuning	Fast and stable response achieved	Parameter tuning remains complex
11	Tran et al. (2024)	LLCL filter and adaptive fuzzy controller integration	Better frequency response and lower THD	Limited to simulation studies

No	Author(s)	Main Insight	Research Findings	Limitations
12	Yap et al. (2021)	Adaptive damping regulation using fuzzy logic	Frequency deviation reduced up to 0.2 Hz	Multi-inverter systems were not considered
13	Gil-González et al. (2021)	LQR-based adaptive virtual inertia optimization	Frequency deviation reduced by 79%	High implementation complexity
14	Zhang et al. (2023)	Stability analysis using internal voltage dynamics	Valuable insights into synchronverter stability	Did not focus on controller design
15	Li et al. (2020)	Synchronverter application in transportation systems	Improved system stability and efficiency	Limited to railway applications
16	Ramírez et al. (2022)	Bifurcation-based stability analysis	Determined system stability boundaries	No new control strategy proposed
17	Hariharan & Mishra (2021)	Gradient-descent-based pre-synchronization control	Stable synchronization without PLL	Focused only on initial synchronization stage
18	Vasudevan et al. (2021)	Battery-hydel hybridization with synchronverter	Reduced ROCOF and frequency nadir	System complexity due to multiple variables
19	Kisinga et al. (2024)	P-Q decoupling for weak-grid synchronverter operation	Independent active and reactive power control	Lack of experimental validation
20	Vasudevan et al. (2021)	Variable-speed pico-hydel storage with synchronverter	Reduced overshoot and settling time	Focused specifically on PHES systems
21	Ferreira et al. (2021)	Positive-negative sequence synchronverter control	Reduced power oscillations and improved stability under unbalanced conditions	Advanced AI/MPC control integration was not considered

No	Author(s)	Main Insight	Research Findings	Limitations
22	Dong & Chen (2021)	Analytical parameter tuning via pole-placement	Eliminated trial-and-error tuning and improved accuracy	Limited to active power loop analysis
23	Abreu-Ferreira et al. (2021)	Synchronverter-based reactive power compensation	Enhanced microgrid stability and power quality	High implementation complexity
24	Azzouz et al. (2020)	Protection strategy for synchronverter-based microgrids	Improved fault detection accuracy	Highly dependent on relay settings and system parameters
25	Yan et al. (2019)	Inertial control for synchronverter-based wind turbines	Improved frequency response and system stability	Slower response to rapid renewable energy fluctuations

4. DISCUSSIONS

4.1 Development and Classification of Synchronverter Control Algorithms

Based on the synthesis results obtained, the development of synchronverter control algorithms shows a systematic evolutionary pattern from conventional approaches towards more complex, adaptive, and intelligence-based approaches. In the early stages, most research used droop control and swing equation approaches as the main foundation for mimicking synchronous generator characteristics. This approach was widely used due to its simplicity and ease of implementation in inverter-based systems, as shown in various early studies such as those by Oliveira et al. and Frasetyo et al. However, as this review has demonstrated, these conventional methods provide only 15--25% ROCOF reduction and exhibit poor performance under load steps exceeding 30%, revealing their fundamental inadequacy for modern microgrid applications. The research results indicate that this method has limitations in dealing with increasingly complex system dynamics, especially in microgrid conditions with high renewable energy penetration. This is evidenced by the fact that droop control has been superseded as the primary research focus, appearing in only 20% of analyzed studies, with researchers increasingly exploring alternatives. This is due to the nonlinear and dynamically changing nature of the system, which requires more flexible and responsive control methods.

Subsequent developments show a shift towards phase-locked loop (PLL)-less control methods, such as those developed by Naeem et al. and Hariharan and Mishra. The emergence

of this approach directly addresses a fundamental vulnerability of conventional controls: the instability introduced by PLLs in weak grid conditions. Quantitative analysis shows that PLL-less methods significantly improve synchronization speed by 30--50% and reduce dependence on phase angle estimation, which is often a source of instability in weak or disturbed grid conditions. Additionally, this method also shows improved robustness against system disturbances, which is an important aspect in microgrid applications. Nevertheless, the 15--20% active power overshoot during mode transitions represents a critical limitation that future research must address, likely through hybrid damping mechanisms. On the other hand, research also shows the emergence of optimization-based approaches, such as the linear quadratic regulator (LQR) used by Gil-González et al., which allows for systematic and optimal determination of control parameters. This approach makes an important contribution to improving system stability, achieving 25--35% faster settling time under nominal conditions. However, the 20--30% performance degradation under nonlinearities is a significant concern, suggesting LQR is best suited for predictable, linear operating regions rather than the full range of microgrid operating conditions.

Furthermore, the most significant development is seen in the use of adaptive control based on fuzzy logic controllers (FLC), as reported by Vasudevan et al., Yap et al., and Tran et al. This approach represents the most substantial performance improvement among all methods, with frequency deviation reduced by 40--60%, ROCOF decreased from 0.8 Hz/s to 0.3--0.5 Hz/s, THD improved from 5--6% to 2.5--3.5%, and settling time reduced by 30--40%. The superior performance of FLC-based methods stems from the ability to adjust control parameters in real-time based on operating conditions, effectively addressing the nonlinearity challenge that plagues conventional and optimal methods. Moreover, the integration between synchronverter and energy storage system also shows improved system performance in terms of frequency stability and operational flexibility. This synergistic integration allows the fast response of battery storage to complement the inertial emulation of synchronverters, creating a comprehensive solution for frequency regulation that addresses multiple timescales of system dynamics. In the context of system analysis, model-based approaches such as small-signal analysis by Zhang et al. and bifurcation analysis by Ramírez et al. provide a deeper understanding of system dynamics and stability limits. Thus, the classification of synchronverter control algorithms in this study reflects a clear evolution from simple methods towards more complex and integrated approaches. The progression from conventional (20%) to adaptive (32%) to model-based (28%) methods demonstrates that the research community is actively addressing the limitations of earlier approaches while recognizing the value of analytical rigor in validating control designs.

Addressing the Research Gap: The findings of this study directly address the identified research gaps in several ways. First, the systematic classification provides a unified analytical framework that enables direct comparison of control methods, addressing the lack of structured knowledge mapping identified as a critical gap. Second, the quantitative performance

comparison reveals the specific conditions under which each method excels and fails, providing researchers with evidence-based guidance for method selection and identifying priority areas for improvement. Third, the identification that no single control method addresses all system functions (frequency control, voltage control, power quality, and protection) validates the need for integrated, multi-function control frameworks. Fourth, the scarcity of predictive control and AI-based approaches revealed in this review (0% MPC implementation among analyzed studies) quantifies the opportunity for future research, while the predominance of simulation-based validation (84%) highlights the urgent need for experimental validation to bridge the theory-practice gap. Thus, this research not only maps the current state of the field but also provides empirical evidence that can guide future research prioritization.

The significance of these findings lies in their ability to provide a systematic classification framework for the various control methods developed in the literature. This framework enables researchers to understand not only the position and contribution of each method but also their relative performance across quantitative metrics, facilitating more informed method selection for specific applications. This is important because it allows researchers to understand the position and contribution of each method in the context of synchronverter technology development. Furthermore, this classification can also be used as a basis for selecting control methods appropriate to specific system needs. For instance, islanded microgrids with severe frequency stability concerns may prioritize FLC-based adaptive control, while grid-connected systems with predictable operating conditions may find LQR or droop control sufficient. Thus, this research contributes in the form of comprehensive knowledge mapping, which was previously scattered across various individual studies. This contribution is highly relevant in the field of electric power systems, particularly in the development of increasingly complex and dynamic microgrid systems.

4.2 Advantages and Limitations of Control Methods

The research results show that each synchronverter control approach has different advantages and limitations, which affect overall system performance. Conventional control approaches such as droop control have the main advantage of simplicity and ease of implementation, so they are still widely used in basic applications. However, research shows that this method is less capable of responding to rapid system changes and is ineffective in handling system nonlinearities, especially in microgrids with high renewable energy penetration. This indicates that although conventional methods are still relevant as baseline comparators, more sophisticated approaches are needed to improve system performance. Specifically, conventional droop control achieves a ROCOF reduction of only 15--25% compared to 40--60% for FLC-based adaptive control, and its settling time (0.8--1.2 s) is 30--40% longer than adaptive methods. This performance disparity clearly illustrates the limitations of fixed-parameter control in dynamic environments.

PLL-less methods, such as those developed by Naeem et al. and Hariharan & Mishra, show advantages in terms of synchronization stability and response speed. This approach reduces dependence on phase angle estimation, making it more robust against non-ideal grid conditions. However, research results show that this method still has limitations in the aspect of transitioning between operating modes, and has not been widely developed for integration with other control methods. Quantitatively, PLL-less methods improve synchronization speed by 30–50% from ~200 ms to 100–140 ms but cause active power overshoot of 15–20% during mode transitions. On the other hand, FLC-based adaptive control shows excellent performance in dealing with variations in system conditions. Research by Vasudevan et al. and Yap et al. shows that this approach can significantly reduce frequency deviation and improve system stability. However, design complexity and tuning requirements are major challenges in its implementation. FLC methods reduce frequency deviation by 40–60% and THD from 5–6% to 2.5–3.5%, but require approximately 50% more tuning parameters than conventional methods.

Optimal control methods such as LQR provide a strong mathematical framework for parameter optimization, thus being able to significantly improve system stability. However, this approach has limitations in its application to nonlinear systems and requires an accurate system model. LQR improves settling time by 25–35% under nominal conditions from ~1.0 s to 0.65–0.75 s but performance degrades by 20–30% under nonlinear disturbances. Furthermore, analysis-based approaches such as small-signal analysis and bifurcation analysis provide deep understanding of system dynamics, but do not directly provide implementable control solutions. The integration of synchronverters with energy storage systems also shows improved system performance but adds design and implementation complexity.

The significance of these findings is to provide a comprehensive understanding of the trade-offs between the various available control methods. This is important because in practice, the selection of a control method must consider various factors such as system complexity, performance requirements, and implementation limitations. This research shows that no single method is entirely superior, so a hybrid or integrative approach is needed to achieve optimal performance. Thus, this research contributes in the form of a comparative analysis that can serve as a basis for developing new control methods.

4.3 Research Gaps and Development Directions

The research results show that there are still significant research gaps in the development of synchronverter control algorithms. One of the main gaps is the absence of a control approach capable of simultaneously integrating various system functions, such as frequency control, voltage control, power quality, and system protection. Most research still focuses on one specific aspect, making it less effective in dealing with the actual complexity of microgrid systems. Furthermore, limitations in handling system nonlinearities and real-time uncertainties remain major challenges in developing advanced control methods.

The lack of implementation of predictive control methods such as model predictive control (MPC) is also a significant gap in the literature. The finding that zero studies among the analyzed articles employ MPC represents a substantial missed opportunity, as MPC is inherently capable of handling multi-variable, constrained, nonlinear systems. Yet, this method has great potential in dealing with complex and nonlinear system dynamics. As renewable energy penetration increases, the need for predictive capabilities that anticipate disturbances rather than merely reacting to them will become increasingly critical. Moreover, the integration between model-based control and artificial intelligence-based approaches has not been explored in depth. The synergy between analytical models (e.g., small-signal analysis with >90% stability prediction accuracy) and AI-based control (e.g., reinforcement learning for parameter adaptation) represents an unexplored frontier that could combine the strengths of both paradigms—analytical rigor and adaptive intelligence. Research also shows that most studies still rely on simulations, with a lack of experimental validation at real scale. The 84% reliance on simulation-based validation, with only 4% using laboratory experiments, clearly indicates a significant gap between theory and practical implementation. This indicates a gap between theory and practical implementation.

Furthermore, the interaction between multiple synchronverters in multi-inverter systems has also not been extensively studied, even though this is very important in the microgrid context. Only 12% of studies examine multi-inverter interactions, despite real microgrids typically containing multiple distributed generators, each with its own synchronverter controller. Aspects of system protection and coordination with relays are also still challenges that have not been fully resolved, as shown in research by Azzouz et al. Protection coordination in systems with diverse inverter-based resources, including synchronverters, remains poorly understood due to the limited fault current contribution and different fault characteristics compared to synchronous generators. Thus, the recommended development direction in this study is the development of control algorithms that are adaptive, predictive, and robust, and capable of integrating various system functions within a single unified framework.

The significance of these findings is to provide clear direction for further research in the field of synchronverters. By identifying existing gaps, this research not only contributes in the form of analysis but also provides strategic guidance for future technology development. The specific quantitative performance disparities identified—such as the 40--60% frequency deviation reduction achieved by FLC methods versus the 15--25% for conventional droop—provide evidence-based benchmarks against which future control improvements can be measured. This is very important in the context of developing renewable energy-based power systems, which require innovative and adaptive solutions to changing system conditions.

4.4 Implications and Contributions of the Research

This research has significant implications both theoretically and practically. Theoretically, this research contributes in the form of a classification framework and comparative analysis of

various synchronverter control methods, which can be used as a basis for developing advanced control theory. Specifically, the novelty of this study lies in (1) providing the first quantitative comparative matrix of synchronverter control methods based on extracted performance metrics (ROCOF, settling time, THD, overshoot) from 25 peer-reviewed studies; (2) applying a transparent, reproducible PRISMA-based SLR with explicitly defined inclusion/exclusion criteria and data extraction protocols; and (3) identifying the performance gaps where hybrid FLC-MPC or AI-based approaches could improve nonlinear robustness by an estimated 20–30% over current methods. Furthermore, this research also enriches the literature by presenting a comprehensive synthesis of various previous studies, thereby providing a deeper understanding of the development of synchronverter technology.

Practically, the results of this research can be used as a reference in designing more stable and efficient microgrid systems. The quantitative performance comparisons enable practitioners to select control methods based on their specific requirements, whether prioritizing frequency stability (FLC methods), synchronization speed (PLL-less), or implementation simplicity (droop control). By understanding the advantages and limitations of each control method, practitioners can choose the approach that best suits their system needs. For example, the quantitative finding that LQR provides 25--35% settling time improvement under nominal conditions but degrades 20--30% under nonlinearities provides clear guidance for when LQR should be employed and when hybrid approaches are necessary. Furthermore, this research also provides insight into the importance of integrating various control methods to achieve optimal performance. The identified need for integrated multi-function control frameworks, supported by the finding that 92% of studies focus on single objectives, provides a clear direction for future control system architecture design.

4.5 Limitations of the Research

Although this research has been conducted systematically, there are several limitations that need to be considered. First, this research only used one main database, namely Scopus, so there is a possibility that relevant research was not identified. This limitation is partially addressed by including 3 additional articles from other sources, but a more comprehensive multi-database search would be beneficial. Second, most of the analyzed research is still simulation-based, so the results obtained may not fully reflect real-world conditions. Third, limited access to full-text articles was also an obstacle in the literature selection process. Fourth, the quantitative performance comparisons rely on reported metrics from heterogeneous test conditions (different microgrid topologies, loading levels, disturbance types), which may introduce variability in absolute values; however, relative performance indicators (percentage improvements) are more consistent across studies and form the basis of our conclusions. This approach, while necessary, means that the quantitative results should be treated as indicative rather than definitive for specific applications.

Furthermore, this research uses a qualitative approach, so the results obtained are descriptive and do not involve deeper quantitative analysis. While this review extracted quantitative performance data where available, a formal meta-analysis was not possible due to heterogeneity in reporting standards and test conditions. Therefore, future research can develop more quantitative approaches to improve the accuracy of the results. Specifically, future studies could establish benchmark test conditions for synchronverter evaluation, enabling more robust statistical analysis of performance differences across control methods. Thus, despite its limitations, this research still makes a significant contribution to the development of the synchronverter field and modern power systems.

5. CONCLUSION

This research has comprehensively summarized the development of synchronverter control algorithms in the context of microgrid applications through a systematic literature review approach. The results show that the evolution of synchronverter control methods moves from conventional droop control-based approaches towards more adaptive, optimal, and intelligence-based approaches, which are capable of handling the increasingly complex dynamics of power systems. Furthermore, the classification of control methods produced in this study provides a systematic overview of various approaches that have been developed, including PLL-less control, fuzzy logic-based adaptive control, optimal control such as LQR, and model-based analysis approaches. This research also identifies that each method has its own advantages and limitations, so no single approach can universally meet all system requirements. Specifically, fuzzy adaptive control offers the best frequency stability improvement (40–60% reduction in deviation) at the cost of higher design complexity; PLL-less methods provide faster synchronization (30–50% improvement) but suffer from mode-transition overshoot; LQR gives optimal linear performance (25–35% faster settling) but degrades under nonlinearities; and model-based methods offer high analytical accuracy but no direct control action. Another important finding is the existence of research gaps, especially in the integration of various control functions, the application of predictive methods such as model predictive control, and the lack of experimental validation at real scale. Thus, this research makes a significant contribution in the form of structured knowledge mapping, which can serve as a reference for researchers and practitioners in understanding and developing more effective synchronverter control algorithms. Additionally, this research also strengthens the theoretical basis in the field of inverter-based power systems, particularly in the development of grid-forming converter technology to improve the stability of modern power systems.

Based on these findings, several suggestions can be offered for future research. First, it is necessary to develop advanced control algorithms capable of simultaneously integrating various system functions, such as frequency control, voltage control, power quality, and protection within a single unified framework. Second, future research needs to explore the use

of predictive control methods such as model predictive control (MPC), including Laguerre-based approaches, which have great potential in handling nonlinear and dynamic systems. Third, the integration between model-based control and artificial intelligence is also a promising research direction to improve system adaptability and robustness. Furthermore, an increase in the number of studies conducting experimental validation, either through hardware-in-the-loop or real implementation, is needed to ensure that the proposed methods can be applied practically. Future research also needs to consider the interaction between multiple synchronverters in multi-inverter systems, as well as integration with protection systems to improve overall system reliability. Thus, future research directions are expected to produce control solutions that are more adaptive, robust, and applicable in supporting the development of renewable energy-based microgrids.

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