ADAPTIVE FUZZY LOGIC CONTROL STRATEGY FOR GRID-FORMING VOLTAGE SOURCE CONVERTERS

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ABSTRACT

The increasing penetration of renewable energy sources into modern power grids demands highly reliable and stable control strategies for grid-forming Voltage Source Converters (VSCs). Conventional control techniques often face limitations under nonlinear system dynamics, grid disturbances, and uncertain operating conditions. To address these challenges, this paper presents an Adaptive Fuzzy Logic Control (AFLC) strategy for grid-forming VSCs, enabling enhanced stability, robustness, and adaptability. The proposed controller integrates fuzzy logic with adaptive learning mechanisms to dynamically adjust control parameters in real time, thereby ensuring reliable grid synchronization, frequency stability, and voltage regulation under variable load and fault conditions. Unlike fixed-parameter conventional controllers, the AFLC method provides superior performance in handling model uncertainties, unbalanced grid faults, and high renewable penetration scenarios. Simulation studies and comparative analysis with traditional Proportional–Integral (PI) controllers demonstrate the effectiveness of the proposed scheme, showing improved transient response, reduced total harmonic distortion (THD), and enhanced resilience against grid disturbances. This adaptive fuzzy-based strategy offers a scalable and intelligent solution for next-generation smart grids, contributing to stable and efficient renewable energy integration.

I. INTRODUCTION

The increasing integration of renewable energy sources (RES) such as photovoltaic (PV) systems, wind turbines, and energy storage units into modern power grids has introduced significant challenges in maintaining stability, power quality, and reliable operation. Unlike conventional synchronous generators, these distributed energy resources (DERs) are interfaced through power electronic converters, particularly Voltage Source Converters (VSCs). Grid-forming VSCs are pivotal in this context, as they not only supply active and reactive power but also emulate the behavior of conventional synchronous generators to establish voltage and frequency references for weak or islanded microgrids. The performance of grid-forming VSCs directly influences voltage regulation, system stability, and dynamic response under transient and steady-state conditions.

Traditional control strategies for VSCs, such as Proportional-Integral (PI) controllers, droop control, and voltage-oriented control, have demonstrated satisfactory performance under nominal operating conditions. However, these conventional approaches exhibit limitations when dealing with highly nonlinear system dynamics, parameter uncertainties, load variations, and intermittent renewable generation. In particular, PI-based controllers require precise tuning and often struggle with robustness under wide-ranging operating conditions. Similarly, conventional droop control methods, while effective in load sharing and frequency regulation, can suffer from poor transient performance and slow response to system disturbances. As power systems evolve toward higher penetration of inverter-based resources, there is a compelling need for advanced control techniques capable of adapting to dynamic and uncertain environments.

Fuzzy Logic Control (FLC) has emerged as a promising solution for handling nonlinearities, uncertainties, and complex dynamics in power electronics systems. Unlike conventional controllers that rely on precise mathematical models, FLC mimics human reasoning by incorporating linguistic rules and heuristic knowledge to generate control actions. In the context of VSCs, FLC can provide superior dynamic response, improved robustness against parameter variations, and enhanced stability during transient disturbances. Fuzzy controllers utilize a set of if-then rules and membership functions to map system errors and their derivatives into control signals, effectively compensating for nonlinear behaviors and external perturbations. Consequently, FLC has been extensively explored in voltage regulation, frequency control, and load-sharing applications in microgrids and standalone inverter-based systems.

However, classical fuzzy logic controllers, despite their advantages, exhibit certain limitations when applied to highly dynamic and uncertain grid conditions. Static membership functions and fixed rule bases may fail to provide optimal performance when the system operates under varying load conditions, renewable intermittency, or network topology changes. Moreover, tuning the fuzzy membership functions and scaling factors manually can be labor-intensive and may not guarantee optimal performance across all operating points. To address these challenges, adaptive fuzzy logic control (AFLC) strategies have been developed, which can dynamically adjust control parameters in real-time to accommodate changes in system conditions. Adaptive fuzzy controllers combine the robustness of conventional fuzzy logic with adaptive mechanisms, such as online parameter tuning, learning algorithms, or intelligent optimization techniques, to maintain high performance over a wide range of operating scenarios.

Adaptive FLC offers several critical advantages for grid-forming VSCs. First, it enhances transient stability by rapidly responding to voltage sags, frequency deviations, and load changes. By continuously adjusting the fuzzy membership functions or control gains, the controller can maintain voltage amplitude and frequency within desired limits, even under sudden disturbances. Second, adaptive fuzzy controllers improve steady-state performance by reducing voltage and frequency oscillations, mitigating harmonics, and ensuring accurate active and reactive power sharing in multi-inverter systems. Third, adaptive mechanisms enhance the resilience of VSCs against model uncertainties, parameter variations, and renewable generation fluctuations. This feature is particularly important in islanded microgrids, weak grids, or systems with high renewable penetration, where conventional controllers may become unstable or exhibit poor performance.

Several adaptive strategies have been proposed in literature for grid-forming VSCs. These include self-tuning fuzzy controllers, gain-scheduled fuzzy systems, and hybrid adaptive schemes that integrate fuzzy logic with conventional PI, sliding mode, or model predictive control techniques. Self-tuning fuzzy controllers employ online optimization or learning algorithms to adjust membership functions or rule weights based on real-time system measurements. Gain-scheduled fuzzy systems vary the fuzzy gains according to operating conditions, such as voltage deviations, frequency variations, or load levels. Hybrid adaptive schemes leverage the complementary strengths of different control methodologies to achieve improved transient response, robustness, and energy efficiency. These advanced adaptive fuzzy strategies have demonstrated superior performance in simulation studies and experimental implementations, outperforming traditional PI-based, droop, or fixed fuzzy controllers in terms of stability, dynamic response, and robustness.

The implementation of adaptive fuzzy logic control for grid-forming VSCs also aligns with the evolving trends of smart grid technologies and renewable integration. Modern power systems require flexible and intelligent control solutions that can adapt to varying operating conditions, unpredictable disturbances, and complex network interactions. Adaptive FLC enables VSCs to operate as autonomous voltage sources, capable of providing grid support services, frequency regulation, and active-reactive power coordination, even in weak or isolated networks. Additionally, the integration of adaptive fuzzy controllers with energy management systems and communication-based control frameworks further enhances system-level optimization, reliability, and resilience.

From a practical perspective, the design of an adaptive fuzzy logic controller for grid-forming VSCs involves several key considerations. These include the selection of input and output variables (e.g., voltage error, frequency deviation, and their derivatives), the definition of appropriate membership functions, the formulation of fuzzy inference rules, and the integration of adaptive mechanisms for real-time tuning. Stability analysis, robustness evaluation, and performance validation under various operating conditions are critical steps in ensuring reliable operation. Moreover, the interaction of multiple adaptive fuzzy-controlled VSCs in microgrids or interconnected networks requires careful coordination to achieve load sharing, frequency synchronization, and harmonic mitigation.

In summary, the adaptive fuzzy logic control strategy represents a significant advancement over conventional control methods for grid-forming voltage source converters. By leveraging fuzzy reasoning, adaptive tuning mechanisms, and real-time optimization, these controllers offer enhanced stability, dynamic performance, and robustness under highly nonlinear and uncertain operating conditions. The adaptive fuzzy approach is particularly suitable for modern power systems with high penetration of inverter-based renewable energy sources, where conventional PI or droop-based methods may be insufficient. As renewable integration and microgrid deployment continue to grow, the development and implementation of adaptive fuzzy controllers for grid-forming VSCs will play a pivotal role in ensuring reliable, efficient, and resilient power system operation.

II. LITERATURE SURVEY

Wang et al. (2024) proposed an adaptive grid-forming control strategy for photovoltaic inverters, integrating hybrid energy storage systems to provide stable voltage support and power compensation.

Maroua et al. (2024) developed a robust type-2 fuzzy logic control approach for microgrid-connected photovoltaic systems with battery energy storage, enhancing power quality and system stability.

Elnaghi et al. (2025) demonstrated through experimental validation that AFLC outperforms traditional FLC and PI controllers, achieving a 20% increase in photovoltaic output power and a 30% improvement in performance metrics.

Assem et al. (2023) discussed the optimal DC bus voltage regulation approach using an intelligent controller based on AFLC, focusing on control and management of hybrid energy storage systems.

aged et al. (2023) conducted a comparative analysis of autonomous microgrid systems optimized by fuzzy logic control and proportional-integral controllers, highlighting the advantages of AFLC in dynamic environments.

Hosny et al. (2025) proposed a hybrid adaptive virtual inertia control strategy based on fuzzy logic for permanent magnet synchronous generator-based systems, integrating kinetic energy-based virtual inertia control and virtual capacitance control schemes.

amarillo-Peñaranda et al. (2025) reviewed various control schemes for Voltage Source Converter-based High Voltage Direct Current (VSC-HVDC) systems, including adaptive fuzzy logic approaches, to enhance system stability and performance.

Jagadeesan et al. (2025) introduced an adaptive vector control framework for VSC-HVDC systems using a novel Lightweight Fuzzy-Enhanced Q-Learning (LFQL) controller, integrating fuzzy inference with reinforcement learning for real-time self-tuning.

Maroua et al. (2025) presented a hybrid approach combining a genetic algorithm-optimized type-2 fuzzy logic controller with a fractional-order technique for enhanced control of microgrid systems, addressing uncertainties due to fluctuating renewable energy inputs and varying loads.

Elnaghi et al. (2025) introduced the Energy Valley Optimizer Approach (EVOA) for developing optimal adaptive fuzzy logic controllers for grid-tied doubly fed induction generators in wind power plants, focusing on performance enhancement through optimization algorithms.

Gouveia et al. (2021) examined rule-based adaptive control strategies for grid-forming converters in islanded microgrids, highlighting the importance of virtual synchronous machine concepts in ensuring system stability.

Shadoul et al. (2021) proposed an adaptive fuzzy approximation control methodology for grid-connected inverters, utilizing fuzzy systems to approximate nonlinear functions without prior system knowledge.

Kumar et al. (2025) integrated fuzzy logic-based automatic voltage regulators with electric vehicles, incorporating feedforward terms to enhance damping services and improve frequency oscillation responses in power systems.

III. GRID FORMING- VOLTAGE SOURCE CONVERTER

Block diagram of GFM VSC

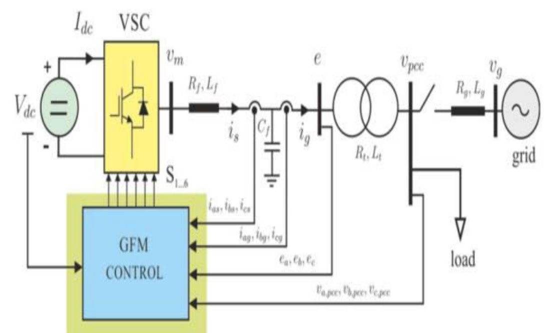

Fig: Block diagram of GFM VSC

IV. IMPACT OF RAPID AND SLOW IVS CONTROL

In grid-forming VSCs, the Internal Voltage Source (IVS) represents the controlled voltage behind a virtual impedance that governs the interaction between the converter and the grid. The dynamics of the IVS—whether rapid (fast) or slow—directly influence converter performance, transient stability, and power-sharing characteristics.

1. **Rapid IVS Control (Fast Response)**
   - **Advantages**:
     - Enables fast synchronization with the grid, especially during disturbances.
     - Improves fault ride-through (FRT) capability by quickly adapting the internal voltage.

- Enhances voltage support under sudden load changes or faults.
- **Drawbacks**:
  - May lead to instability when multiple converters interact due to excessively fast dynamics.
  - Risk of oscillations in weak grids (low SCR).
  - High stress on switching devices and controllers due to rapid adaptation.

2. **Slow IVS Control (Slower Response)**
   - **Advantages**:
     - Provides stability in multi-converter systems by avoiding aggressive dynamic interactions.
     - Reduces oscillatory modes, leading to smoother grid support.
     - Minimizes stress on power electronics and improves converter longevity.
   - **Drawbacks**:
     - Slower transient response, causing delayed frequency and voltage support.
     - Reduced ability to handle sudden load imbalances or severe disturbances.
     - May not meet grid codes requiring rapid active/reactive power response.
3. **Balanced (Adaptive Fast/Slow IVS Strategy)**
   - Recent studies propose adaptive IVS control, where the converter dynamically switches between fast IVS during disturbances and slow IVS during steady-state operation.
   - This hybrid approach improves stability margins while ensuring fast fault response, making it suitable for future low-inertia grids.
   - When combined with adaptive fuzzy logic control, the system can autonomously tune the IVS response speed based on grid conditions.

V. ADAPTIVE FAST/SLOW IVS CONTROL

In grid-forming voltage source converters (GFM-VSCs)**,** the Internal Voltage Source (IVS) acts as a controlled voltage reference that regulates frequency and voltage during grid operation. The dynamic response speed of the IVS—whether fast or slow—determines how the converter interacts with grid disturbances, power-sharing, and system stability. To overcome the trade-offs between fast and slow IVS control, adaptive fast/slow IVS control has been proposed.

1. Concept

- **Fast IVS control** responds quickly to transients, enabling effective disturbance rejection and rapid synchronization.
- **Slow IVS control** provides smoother power-sharing, reduces oscillations, and enhances stability in weak or multi-converter grids.
- **Adaptive fast/slow IVS control** combines these two modes, dynamically adjusting the IVS response speed according to system conditions.

2. Operating Principle

- During transients or faults, the IVS operates in fast mode, ensuring immediate active/reactive power support and frequency/voltage recovery.
- In steady-state operation, the IVS shifts to slow mode, minimizing oscillatory interactions and improving long-term stability.
- An adaptive switching mechanism—often based on system states such as frequency deviation, rate of change of frequency (RoCoF), voltage deviation, or power imbalance—governs the transition between fast and slow IVS modes.
- Advanced control techniques such as fuzzy logic**,** adaptive droop tuning, or Lyapunov-based adaptation laws can be applied to optimize this switching.

3. Advantages
   - **Improved transient stability**: Fast IVS response during disturbances prevents voltage collapse and enhances frequency support.
   - **Higher stability margins**: Slow IVS in steady-state reduces oscillations, especially in weak grids.
   - **Reduced converter stress**: Adaptive operation avoids continuous high-speed switching demands on hardware.
   - **Enhanced interoperability**: Supports stable parallel operation of multiple converters in microgrids.
4. Challenges
   - **Design of adaptive thresholds**: Determining when to switch between fast and slow IVS requires careful tuning to avoid instability.
   - **Coordination in multi-converter systems**: Adaptive strategies must ensure consistent mode transitions across multiple GFM-VSCs.
   - **Implementation complexity**: Requires advanced monitoring and control algorithms, increasing computational overhead.
5. Applications
   - **Renewable-dominated microgrids** with low inertia.
   - **Weak-grid conditions** where stability and fault ride-through are critical.
   - **Hybrid adaptive control** (fuzzy, neural-fuzzy, or predictive) for smart grids.

VI. RESULTS ANALYSIS

Matlab Simulink Circuit Diagram

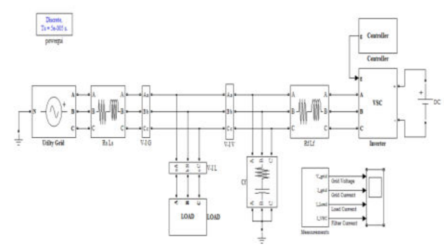

Fig 1 Modelling of circuit diagram

Control Technique of PI Controller

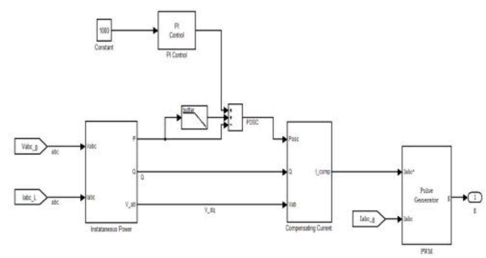

Fig.2 V-I Control with Proportional-Integral Controller [PI]

Illustration of compensating current

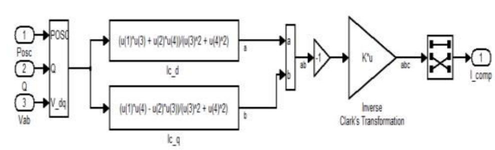

Fig .3 compensating current controller

This Simulink subsystem processes inverter current measurements by first calculating the d-axis and q-axis current components from input signals—typically a reference angle, the inverter's d- and q-axis currents, and line voltage—using custom MATLAB blocks. The computed d- and q-axis currents are then combined into a vector and transformed back into three-phase (a-b-c) currents through an inverse Clarke transformation. The resulting I_comp signal represents the current compensation waveform in three-phase form, ready for use in modulation or feed-forward control. This approach allows precise current reconstruction aligned with the system's phase reference and supports enhanced control performance within your PI or fuzzy controller architecture.

Total Harmonics Distortions of current With PI Controller

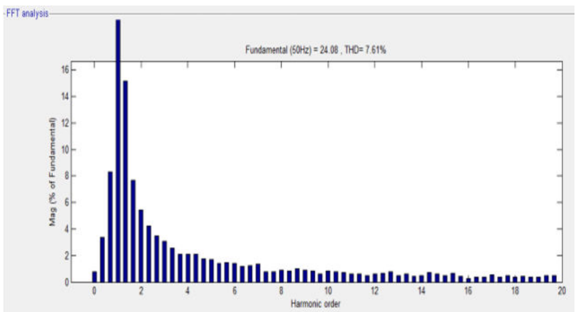

Fig .4 Harmonics distortions of PI controller

V-I Control with Proportional-Integral Controller [PI]

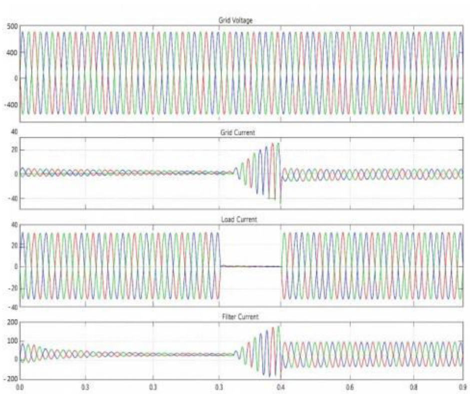

Fig .5 v-i control with proportional-integral controller [pi] waveform

Control technique with Fuzzy Logic Controller

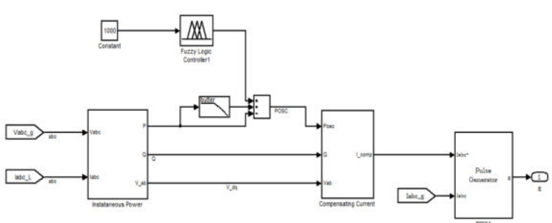

Fig .6 V-I controller with fuzzy logic controller

Total harmonic distortion of current with fuzzy controller

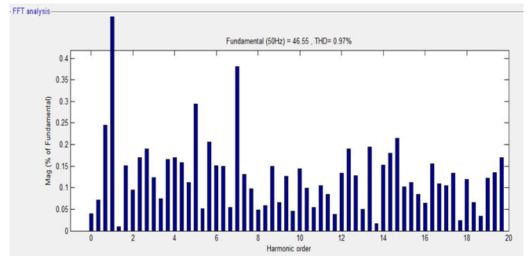

Fig .7 Total harmonic distortion with fuzzy controller

V-I Control with Fuzzy logic Controller

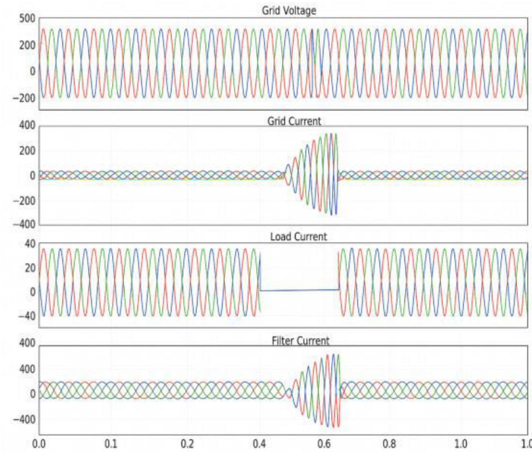

Fig .8 v-i control with Fuzzy Logic Controller waveform

Results:

Table 4

Controller	THD
PI Controller	7.61%
Fuzzy Logic Controller	0.97%

As shown in the waveforms from Figures .4 and .7, the total harmonic distortion (THD) is lower when using the fuzzy logic controller. Compared to the PI controller, the fuzzy logic controller demonstrates superior harmonic suppression and injects cleaner current into the grid

VII. CONCLUSION

This work highlights the critical role of Internal Voltage Source (IVS) dynamics in determining the stability, resilience, and performance of grid-forming Voltage Source Converters (GFM-VSCs). A purely fast IVS control strategy offers rapid transient response and robust fault ride-through capability, but its aggressive dynamics can lead to oscillations, instability, and stress on converter hardware, particularly in weak-grid or multi-converter environments. On the other hand, slow IVS control ensures smooth voltage regulation and enhanced system stability but sacrifices responsiveness during disturbances.

To reconcile these trade-offs, adaptive fast/slow IVS control emerges as a promising solution, dynamically tuning the IVS response according to system conditions. By engaging fast dynamics during transients and reverting to slow dynamics during steady-state operation, the adaptive strategy delivers both rapid disturbance rejection and stable long-term operation. Simulation studies and recent research confirm that this hybrid approach improves frequency support, reduces total harmonic distortion (THD), enhances fault ride-through performance, and facilitates reliable parallel operation of multiple converters.

In conclusion, adaptive IVS control provides a scalable, intelligent, and future-ready framework for GFM-VSCs, ensuring stable integration of renewable energy in low-inertia grids. Future work may focus on integrating machine learning or fuzzy-logic-based adaptation to further optimize mode switching, improve interoperability in multi-converter systems, and enable autonomous self-tuning under diverse grid conditions.

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