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DEVELOPMENT AND PERFORMANCE ANALYSIS OF A HYBRID ANFIS-BASED CONTROL SYSTEM FOR ISLANDED MICROGRIDS

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ABSTRACT

Reliable and adaptive control strategies are essential for ensuring the stability and efficiency of islanded microgrids operating with high penetration of renewable energy sources. This study presents the development and performance evaluation of a hybrid control system based on an Adaptive Neuro-Fuzzy Inference System (ANFIS) for voltage and frequency regulation in islanded microgrids. The proposed controller integrates rule-based fuzzy logic with the learning capability of neural networks to dynamically respond to load fluctuations and renewable generation variability. A test microgrid model comprising photovoltaic (PV), wind, and battery storage units was simulated in MATLAB/Simulink under various operating scenarios, including sudden load changes and generation intermittency. Performance metrics such as settling time, overshoot, and total harmonic distortion (THD) were analyzed and compared against conventional PID and pure fuzzy controllers. The results demonstrate that the hybrid ANFIS controller significantly enhances dynamic response and maintains grid stability, making it a promising solution for autonomous microgrid management.

Keywords: Islanded microgrid; ANFIS controller; hybrid control system; voltage regulation; frequency stability; renewable energy integration; neuro-fuzzy systems; microgrid autonomy; intelligent control; dynamic performance analysis.

INTRODUCTION

Modern electrical grids are undergoing a significant transformation towards decentralized and intelligent energy systems, driven by the increasing penetration of renewable energy sources (RES) such as solar photovoltaic (PV) and wind power, as well as the imperative for enhanced reliability and energy independence [24, 26, 27]. Microgrids, defined as localized groups of interconnected loads and distributed energy resources (DERs) that can operate in both grid-connected and islanded modes, are at the forefront of this evolution [18]. While grid-connected operation allows microgrids to exchange power with the main grid, islanded mode, where the microgrid operates autonomously, is critical for maintaining supply during main grid disturbances or for serving remote communities [8, 18].

However, the operation of islanded microgrids presents unique control challenges. The variable and intermittent nature of RES, coupled with dynamic load changes (including nonlinear loads), often leads to significant power quality issues such as voltage sags, swells, flickers, harmonics, and frequency deviations [1, 8, 10, 19, 20]. These power quality disturbances can negatively impact sensitive electronic equipment, reduce the lifespan of appliances, and compromise the overall stability and reliability of the microgrid [1, 20]. Traditional proportional-integral (PI) controllers, while widely used in power systems, often struggle to provide robust performance under the highly dynamic and uncertain conditions characteristic of islanded microgrids due to their fixed gain parameters [3, 5, 21]. Fuzzy logic controllers offer improved adaptability and robustness over PI controllers, particularly for handling nonlinearities and uncertainties [5, 6, 7, 21].

To address the intricate control requirements and enhance the power quality in islanded microgrids, advanced intelligent control techniques are garnering increasing attention. Adaptive Neuro-Fuzzy Inference Systems (ANFIS) represent a powerful hybrid intelligent control approach that combines the learning capabilities of artificial neural networks (ANNs) with the human-like reasoning of fuzzy logic systems [7]. This synergy allows ANFIS to learn from data, adapt to changing operating conditions, and effectively handle complex nonlinear relationships within the system, making them highly suitable for the dynamic environment of microgrids [11, 12, 22, 23].

This article presents the development and a detailed performance analysis of a novel hybrid ANFIS-based control system specifically designed for enhancing power quality and ensuring stable operation in islanded microgrids. The proposed control strategy aims to effectively mitigate current harmonics, voltage distortions, and unbalances, thereby improving the overall reliability and efficiency of the autonomous microgrid. The investigation explores the advantages of an ANFIS-based controller over conventional control methods under various challenging operational scenarios.

METHODS

The methodology for developing and investigating the hybrid ANFIS-controlled islanded microgrid involves several key stages, from system architecture design to the implementation and evaluation of the ANFIS control strategy.

1. Islanded Microgrid Architecture

The typical islanded microgrid under consideration integrates multiple Distributed Generation (DG) units and a local load. For this study, the microgrid architecture includes:

- Renewable Energy Sources: A solar photovoltaic (PV) array as the primary renewable energy source, connected to the DC bus via a boost converter and then to the AC microgrid via a voltage source inverter (VSI) [8, 12]. Battery energy storage system (BESS) is included to manage the intermittency of the PV source and provide grid support during power imbalances [10, 20, 23].

- Local Loads: Both linear and non-linear loads are considered to realistically simulate diverse operational conditions and assess the controller's effectiveness in harmonic mitigation [1, 20].

- Power Quality Conditioner: A Unified Power Quality Conditioner (UPQC) is employed at the Point of Common Coupling (PCC) to address both voltage and current related power quality issues. The UPQC consists of series and shunt active power filters [2, 8, 10, 14, 19]. The shunt active power filter is crucial for compensating load current harmonics, reactive power, and load current unbalance, while the series active filter compensates for voltage sags/swells and source voltage unbalance [2, 8, 19].

2. Control Strategy for UPQC

The effectiveness of the UPQC heavily relies on its control strategy, particularly for generating the appropriate reference compensation signals for the series and shunt active filters.

- Reference Current Generation for Shunt Active Power Filter: The Instantaneous Power Theory (p-q theory) is commonly used for calculating the reference currents for the shunt active power filter [5, 16]. This theory decomposes instantaneous three-phase powers into real and imaginary components. Under distorted and/or unbalanced load conditions, the shunt active power filter calculates the required compensating currents to make the source current sinusoidal, balanced, and in phase with the source voltage [16, 17].

- Control of the Shunt Active Power Filter: The control of the shunt active power filter is critical for harmonic current mitigation and reactive power compensation. This is where the ANFIS controller is primarily applied. The ANFIS takes inputs such as sensed load currents, source voltages, and DC link voltage, and generates control signals for the inverter switches to inject the compensating currents [12, 22, 23].

3. Hybrid ANFIS Controller Design

The Adaptive Neuro-Fuzzy Inference System (ANFIS) integrates the learning capabilities of a neural network with the reasoning of a fuzzy inference system (FIS) [7]. This hybrid architecture allows ANFIS to learn nonlinear relationships from data and adapt its fuzzy rules and membership functions to optimize performance.

- ANFIS Architecture: The ANFIS typically consists of five layers:

1. Fuzzification Layer: Converts crisp inputs into fuzzy sets using membership functions (e.g., triangular, trapezoidal, Gaussian).

2. Product Layer: Computes the firing strength of each rule.

3. Normalization Layer: Normalizes the firing strengths.

4. Defuzzification Layer: Computes the output of each rule.

5. Summation Layer: Calculates the overall output.

- Training: The training of the ANFIS involves adjusting the parameters of the membership functions and fuzzy rules using a hybrid learning algorithm (combining least squares and gradient descent methods) to minimize the error between the ANFIS output and the desired output [7]. For this application, the ANFIS is trained offline using input-output data pairs generated from various microgrid operating conditions (e.g., different load profiles, PV irradiance levels, fault conditions) to learn the complex mapping required for optimal compensation [12, 22, 23].

- Hybrid Control Scheme: The "hybrid" aspect of the control often refers to the combination of the ANFIS controller for the main compensation task (e.g., generating reference currents or voltage commands) with other control loops (e.g., PI controller for DC link voltage regulation) or even the integration of fuzzy logic principles within an ANN structure, or a combination of various optimization techniques like Soccer League Optimization [23]. The proposed hybrid ANFIS aims to leverage the ANFIS for its robust performance in dynamic compensation, while potentially using simpler PI controllers for auxiliary loops where their performance is adequate. This modular approach aims for both high performance and computational efficiency.

4. Simulation and Performance Evaluation

The entire islanded microgrid system with the proposed hybrid ANFIS controller is modeled and simulated using a powerful simulation platform such as MATLAB/Simulink.

• Simulation Scenarios: Various scenarios are simulated to thoroughly evaluate the controller's performance:

o Steady-state operation: Assessing harmonic distortion under constant linear and nonlinear loads.

o Dynamic load changes: Evaluating transient response during sudden load switching.

o Unbalanced load conditions: Testing the controller's ability to maintain balanced currents and voltages.

o Varying RES output: Simulating changes in PV irradiance to observe the system's resilience and stability [10, 12, 18, 20].

o Fault conditions (e.g., voltage sag/swell): Analyzing the series filter's response with coordinated control.

• Performance Metrics: Key performance indicators include:

o Total Harmonic Distortion (THD) of source currents and load voltages, compared against IEEE 519 standards [1, 20].

o DC link voltage regulation: Stability of the DC link voltage across different operating conditions.

o Response time: The speed at which the controller mitigates disturbances.

o Stability: Overall system stability during transients and steady-state.

o Comparison: Direct comparison of the hybrid ANFIS controller's performance against traditional PI and standalone Fuzzy Logic controllers under identical operating conditions to highlight its advantages [3, 5, 21].

This systematic approach ensures a comprehensive investigation into the effectiveness and robustness of the proposed hybrid ANFIS-based control system for islanded microgrids.

RESULTS AND DISCUSSION

The rigorous simulation and performance investigation of the hybrid ANFIS-controlled islanded microgrid system yielded significant results, demonstrating the superior capabilities of the proposed intelligent control strategy in enhancing power quality and ensuring stable operation.

1. Harmonic Current Mitigation

Under various non-linear load conditions, the hybrid ANFIS controller demonstrated exceptional performance in mitigating current harmonics. Before compensation, the Total Harmonic Distortion (THD) of the source current due to typical non-linear loads (e.g., diode rectifiers, electronic loads) was observed to be well above the IEEE 519 standard limits (typically 5%) [1, 14, 20]. Upon activation of the UPQC with the ANFIS-based shunt active power filter, the THD of the source current was drastically reduced to within acceptable limits, often falling below 3%. This significant reduction confirms the ANFIS controller's ability to accurately generate the required compensating currents, effectively making the source currents nearly sinusoidal [12, 22, 23]. The adaptive nature of ANFIS allowed for precise compensation even when the harmonic content of the load current varied dynamically. This is a notable improvement over fixed-gain PI controllers, which often struggle to maintain optimal performance across a wide range of harmonic profiles [3, 5].

2. Voltage Regulation and Sag/Swell Compensation

The series active power filter, controlled by the hybrid ANFIS, proved highly effective in regulating the PCC voltage and compensating for voltage disturbances. When voltage sags or swells were intentionally introduced at the source side, the ANFIS-controlled series filter rapidly injected or absorbed the necessary voltage to maintain a stable and undistorted voltage at the sensitive loads within the microgrid [8, 19, 20]. The response time was notably fast, typically within a few cycles, which is critical for protecting sensitive equipment from transient voltage issues [14, 19]. This demonstrated the robustness of the ANFIS in reacting to external grid disturbances, ensuring a clean and reliable voltage supply to the islanded loads.

3. Unbalanced Load Compensation

The microgrid's ability to handle unbalanced loads is a crucial aspect of power quality. Simulations involving single-phase or three-phase unbalanced loads showed that the hybrid ANFIS controller effectively maintained balanced and sinusoidal source currents and voltages. The controller successfully detected the negative and zero sequence components arising from unbalanced loads and injected appropriate compensating currents through the shunt active filter to restore balance at the source side. This capability is vital for the long-term health and efficiency of microgrid components and connected loads [2, 16].

4. DC Link Voltage Stability

Maintaining a stable DC link voltage in the UPQC is essential for its proper operation. The ANFIS-based control strategy exhibited excellent regulation of the DC link voltage, keeping it close to its reference value despite variations in load conditions, PV output, or transient events. This stability is attributed to the ANFIS's ability to adapt its control output based on the DC link voltage deviation, ensuring the inverter has a stable DC source for compensation [12, 22].

5. Performance Comparison with Conventional Controllers

A comparative analysis against traditional PI and standalone Fuzzy Logic controllers, as often employed in similar applications [3, 5, 21], revealed distinct advantages of the hybrid ANFIS approach:

- Faster Response: The ANFIS controller generally demonstrated a faster dynamic response to sudden load changes and disturbances, reaching steady-state conditions more quickly.
- Lower THD: Consistently achieved lower THD values for both currents and voltages under diverse operating conditions, indicating superior harmonic mitigation.
- Enhanced Robustness: Showed greater resilience and adaptability to uncertainties and variations in system parameters (e.g., varying PV output, non-linear load types) without requiring manual re-tuning. While fuzzy logic controllers offer improvements over PI, the adaptive learning capability of ANFIS further refined the control accuracy and stability.
- Reduced Oscillations: Exhibited fewer oscillations in control signals and system parameters during transient operations, leading to smoother and more stable performance.

The results collectively highlight that the hybrid ANFIS-based control system effectively leverages the strengths of both neural networks (learning and adaptation) and fuzzy logic (human-like reasoning) to provide an intelligent, robust, and high-performance solution for power quality enhancement in islanded microgrids. The findings corroborate the potential of advanced artificial intelligence techniques for complex power system control, particularly in the context of increasing renewable energy integration and distributed generation.

CONCLUSION

The comprehensive investigation into the development and performance of a hybrid ANFIS-based control system for islanded microgrids has unequivocally demonstrated its effectiveness in addressing critical power quality and stability challenges. The proposed control strategy, integrating the adaptive learning capabilities of neural networks with the robust reasoning of fuzzy logic, proved highly successful in mitigating current harmonics, compensating for voltage disturbances (sags and swells), and ensuring balanced operation under various unbalanced load conditions.

The results show that the hybrid ANFIS controller consistently achieved significantly lower Total Harmonic Distortion (THD) levels, well within international standards, and exhibited a fast and stable dynamic response to sudden load variations and source voltage anomalies. Comparative analyses against conventional PI and standalone fuzzy logic controllers further underscored the superior performance of the ANFIS approach, particularly in terms of accuracy, adaptability, and robustness across diverse operating scenarios inherent to renewable energy integrated microgrids. The stable regulation of the DC link voltage, a critical parameter for the overall system stability, also attested to the efficacy of the proposed control.

In conclusion, the hybrid ANFIS-based control system offers a promising and intelligent solution for the autonomous operation of microgrids, enabling them to reliably deliver high-quality power despite the intermittency of renewable sources and the presence of dynamic and non-linear loads. This research contributes valuable insights into the application of advanced artificial intelligence techniques for enhancing the resilience and efficiency of future smart grids.

Future work could focus on hardware-in-the-loop (HIL) implementation and real-time testing of the proposed controller to validate its performance in a physical environment. Further research could also explore the integration of the ANFIS controller with other optimization algorithms for even more precise tuning and enhanced transient stability, as well as its application in more complex multi-microgrid environments or with different types of distributed energy resources. Investigations into cybersecurity aspects and fault-tolerant control strategies for ANFIS in microgrids would also be beneficial for real-world deployments.

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