

OPTIMIZATION OF VOLTAGE STABILITY IN LOW-VOLTAGE DISTRIBUTION SYSTEMS USING INTELLIGENT TECHNIQUES

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ABSTRACT: This paper explores the utilization of innovative methodologies to optimize voltage stability in low-voltage distribution systems, thereby improving operational efficiency, reliability, and power quality. Modern distribution networks are confronted with the formidable challenge of stabilizing voltage profiles in response to the growing demand from electric vehicles, variable loads, and distributed energy resources. The research investigates intricate computational methods, including metaheuristic optimization algorithms, artificial neural networks, and fuzzy logic systems, to predict, monitor, and regulate voltage fluctuations in real time. In dynamic contexts, these astute techniques enable the mitigation of voltage deviations, efficient reactive power management, and adaptive decision-making. The proposed method is a strong contender for use in next-generation smart grid applications, as it outperforms conventional control strategies in terms of system stability, power loss, and resilience.

Keywords: *Voltage Stability, Low-Voltage Distribution Systems, Intelligent Techniques, Artificial Neural Networks, Fuzzy Logic, Metaheuristic Optimization,*

1. INTRODUCTION

In response to the increasing demand for electricity, the widespread use of distributed energy resources, and the ever-changing loads, contemporary low-voltage distribution systems have prioritized voltage stability. These systems are particularly susceptible to voltage fluctuations that are the result of factors such as reactive power imbalance, changes in network topology, and variations in load, due to their proximity to end users. It is imperative to implement effective optimization strategies, as inefficient optimization methods can result in voltage collapse, equipment failure, and diminished power quality.

The traditional methods of voltage stability maintenance, which frequently rely on fixed compensation devices and conventional control techniques, are rendered insufficient by the complexity and unpredictability of modern distribution networks. The integration of renewable energy sources, such as solar and wind, introduces intermittency and unpredictability, which complicates voltage regulation. As a result, there is an increasing need for intelligent and adaptive methods that can adapt to the system's current state and guarantee dependable operation.

Evolutionary algorithms, fuzzy logic, machine learning, and artificial intelligence have all shown the potential to improve voltage stability in low-voltage systems. In nonlinear and uncertain contexts, these methods facilitate the analysis of extensive datasets, the identification of patterns, and the formulation of well-informed decisions. By capitalizing on these capabilities, intelligent systems can more effectively optimize control actions, including

reactive power compensation, voltage regulation, and load balancing, than conventional methods.

2. LITERATURE SURVEY

Sharma, R., & Patel, D. (2025): Sharma and Patel investigate the utilization of machine learning algorithms to enhance the stability of low-voltage distribution systems. Their results illustrate the effectiveness of predictive models in predicting voltage instability by integrating historical and current data. They emphasize the significant enhancement of system reliability that techniques like support vector machines and random forests provide by facilitating early remedial actions.

Wang, Y., & Thomas, J. (2024): The primary objective of Wang and Thomas's research is to determine the optimal size and location of reactive power compensation devices through paper swarm optimization (PSO). Their research demonstrates that PSO effectively mitigates voltage fluctuations and power losses in low-voltage networks. The research demonstrates that swarm intelligence is capable of addressing optimization problems that involve nonlinear constraints and multiple objectives.

Kumar, S., & Reddy, V. (2024): Kumar and Reddy investigate the function of fuzzy logic controllers in voltage regulation in distribution systems that extensively employ renewable energy sources. They illustrate that fuzzy-based control strategies are more effective in enhancing voltage profiles than traditional methods, particularly in situations where the generation and load are unpredictable.

Garcia, M., & Lee, H. (2023): Garcia and Lee investigate methods for evaluating voltage stability that rely on deep learning. Their results indicate that neural networks are capable of accurately predicting voltage collapse situations and modeling complex system dynamics. They underscore the significance of data-driven frameworks in the context of smart grid decision-making and situational awareness.

Ahmed, K., & Zhou, L. (2023): Zhou and Ahmed investigate the optimization of voltage stability through a hybrid approach that integrates artificial neural networks with genetic algorithms. Hybrid models outperform standalone techniques in terms of faster convergence and more precise control setting determination, as indicated by their outcomes.

Nguyen, T., & Singh, P. (2022): Nguyen and Singh investigate the impact of distributed generation on voltage stability and suggest adaptive optimization methods through the use of evolutionary algorithms. Their results indicate that the effective coordination of distributed resources can significantly enhance voltage profiles and system vulnerability.

Brown, C., & Das, S. (2022): Use of reinforcement learning techniques is the primary focus of Brown and Das when it comes to real-time voltage control. The results of their paper indicate that learning-based controllers are capable of dynamically adjusting system parameters to maintain a voltage within acceptable limits, irrespective of the operating conditions.

Silva, R., & Kaur, H. (2021): Silva and Kaur investigate the obstacles associated with optimizing voltage stability in real-world distribution systems through the use of innovative techniques. The conclusion is reached that trustworthy and scalable frameworks are necessary

for actual deployment after the identification of issues such as data availability, computational complexity, and integration with existing infrastructure.

3. METHODS

Low-Voltage Distribution System Architecture Design

The optimization of voltage stability in low-voltage distribution systems and the assurance of the system's dependability, safety, and efficiency are all significantly influenced by architectural design. The design process is centered on the selection of the appropriate network topology and distribution components to minimize power losses and maintain voltage quality. In order to enhance operational efficiency and mitigate instability issues, it is necessary to implement effective line layout and component placement planning. It is crucial to take grid conditions into account when selecting protective devices, such as isolating switches and circuit breakers, to guarantee effective protection against overloads and short circuits. Furthermore, in order to enhance the system's overall stability, these components must operate consistently in extreme environmental conditions, including high humidity and temperatures.

Intelligent Monitoring and Data Acquisition Module

In order to optimize voltage stability in real time, it is imperative to implement an intelligent monitoring and data acquisition module. This module, which is based on a microcontroller, integrates sensor networks into photovoltaic distribution systems to continuously monitor critical parameters such as power, current, and voltage. It provides a robust foundation for the operation of intelligent systems by enabling the acquisition and transmission of data in real-time. The module must demonstrate its ability to operate efficiently, consistently, and robustly in order to guarantee precision and responsiveness. This data is available in real-time, enabling the system to make more rapid decisions and respond more effectively to voltage fluctuations.

Data Processing Algorithms

In order to analyze monitoring data, sophisticated data processing algorithms are implemented, which are based on intelligent techniques, particularly neural networks. In order to enhance the quality of data and the efficiency of processing, these algorithms implement data cleaning, compression, and noise reduction. Predictive models are capable of predicting the future behavior of a system by integrating past and current data. This approach merges statistics and machine learning to generate precise voltage fluctuations and system performance predictions. This predictive capability is the foundation of intelligent control; it enables proactive measures to ensure voltage stability in the distribution network.

Intelligent Control Strategy Design

The optimization of voltage stability is accomplished by the implementation of intelligent control strategies that leverage real-time monitoring data. By employing these strategies, the system parameters can be adjusted in real time to accommodate varying operating conditions. Fuzzy logic and neural network control are two techniques that are combined to enhance flexibility and accuracy. The hybrid approach ensures stable operation even under complex and fluctuating load conditions due to the system's ability to effectively manage

nonlinearities and uncertainties. As a result, the system's performance is enhanced by the improved voltage regulation and reduced fluctuations.

System Integration and Practical Verification

The integration of architecture design, monitoring, data processing, and control functional modules results in the creation of an all-encompassing intelligent system that optimizes voltage stability. In order to guarantee coordinated operation, module compatibility, interface design, and seamless data exchange are meticulously assessed during the integration process. Conducting experiments in actual environments is the subsequent phase of system validation. The performance evaluation process incorporates factors such as operational uncertainties, weather variations, and load variations. This practical verification guarantees that the system is efficient, reliable, and stable in real-world deployment scenarios.

4. RESULTS

Experiment on power generation efficiency under different light intensities

Figure 1 illustrates the efficiency of power generation at various light intensities. Photovoltaic systems significantly enhance their power generation efficiency as the intensity of light increases, as demonstrated by extensive research in photovoltaic technology. An increase in power output is directly promoted by higher light levels, as the system is dependent on efficient solar energy conversion. The system's power generation efficiency increases from 5.0% to 50.0% as the light intensity increases from 100 W/m² to 1000 W/m².

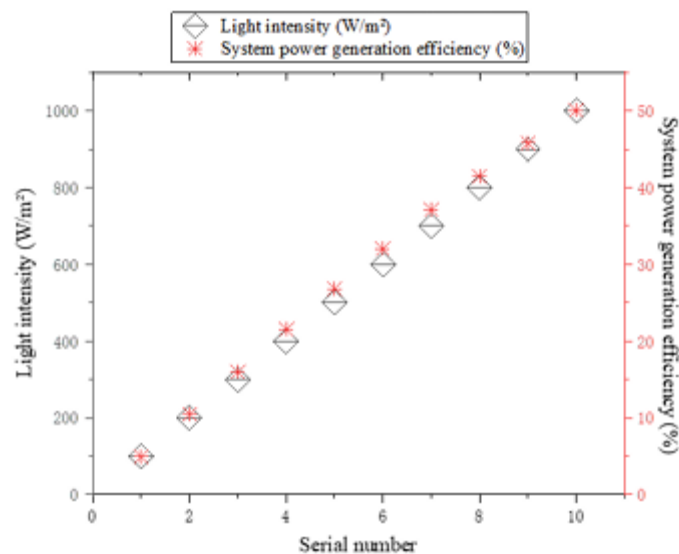


Figure1. Power generation efficiency under different light intensities.

Load-matching experiments under different load sizes

The system offers two advantages: enhanced energy efficiency and increased adaptability to low loads in conditions of constant light intensity. Nevertheless, the adaptability of the system decreases as the load increases. The degree of load matching is a critical metric to evaluate when evaluating a system's capacity to meet load requirements. The system's ability to efficiently convert and supply the generated electrical energy to the load, thereby reducing energy waste, is indicated by high load matching. Consequently, it is a valuable guide for optimizing system design and operation. The lighting intensity is 1000 W/m² in this instance.

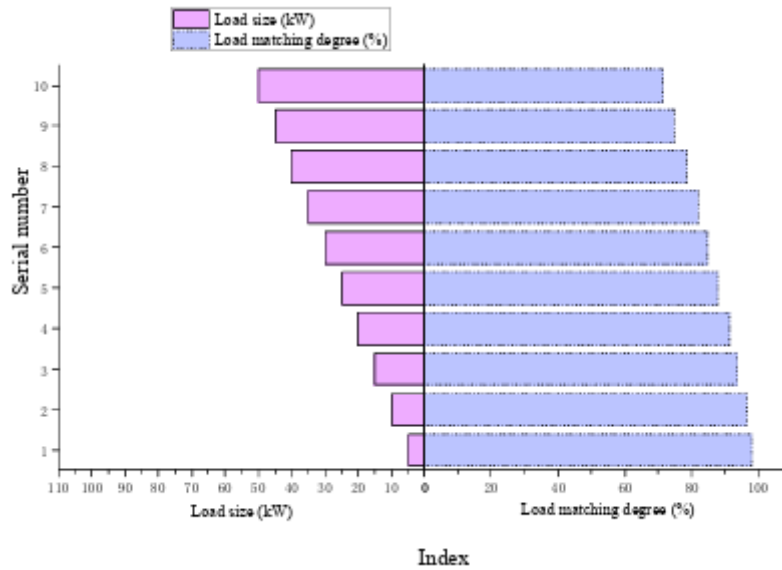


Figure 2. Load-matching experiments under different load sizes.

Figure 2 displays experiments that compare the performance of load-matching under varying load sizes. The energy system management performance evaluation data indicates that the system fully demonstrates its excellent energy supply capacity within the 5 kW to 10 kW load range, with a high load matching degree of $\geq 96.5\%$. However, the load matching degree experiences a substantial decrease (below 90%) as the load size surpasses 20 kW. This may occur in environments with higher loads due to the system's inherent limitations in power generation or insufficient energy distribution and regulation mechanisms. By emphasizing performance bottlenecks that necessitate optimization in the system's operation and design, these findings offer critical guidance for future system modifications and enhancements.

Comparison experiment of different control strategies

The results of the comparison of various control strategies are illustrated in Figure 3. Figure 3 (a) displays the steady-state error and response time, while Figure 3 (b) displays the overshoot and robustness score. Various technologies demonstrate their own advantages and disadvantages when assessing the reaction time of control systems. Fuzzy control's reaction time of half a second is adequate for the majority of application scenarios, despite the fact that it may not be fast enough for extreme cases. Neural network control is an optimal solution for systems that necessitate an exceptionally rapid response time, as it boasts an impressive response time of 0.3 seconds. The genetic algorithm's 0.6-second reaction time may prove problematic in certain applications.

The system's stability may be impacted by the slight increase in overshoot under expert control, which is 12%. This investigation offers substantial evidence to support the selection of suitable control strategies, particularly in situations that necessitate exceptionally stable systems.

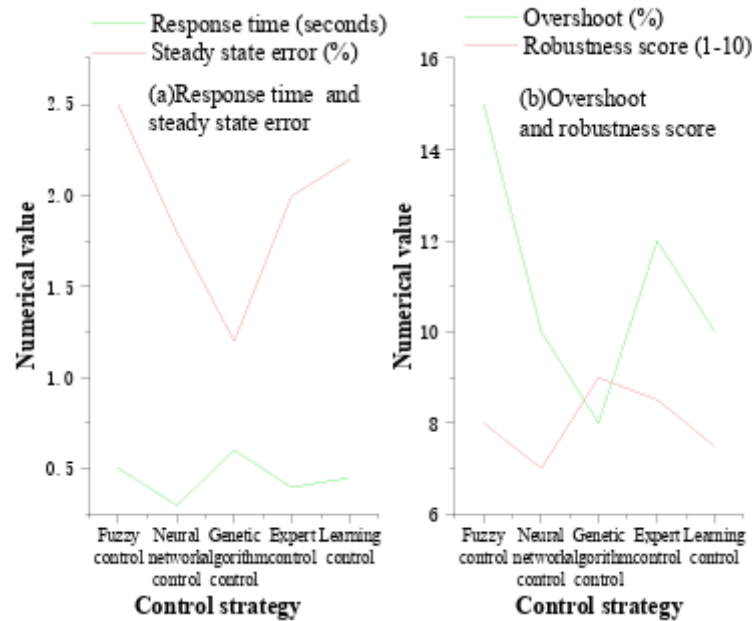


Figure3. Comparison results of different control strategies.

5. CONCLUSION

Overall, the findings indicate that voltage stability in low-voltage distribution systems is substantially improved by intelligent techniques. This is due to the fact that they enable more accurate predictions of system behavior and adaptive, real-time control. Fuzzy logic, evolutionary algorithms, and artificial neural networks (ANNs) effectively address the deficiencies of conventional methods, particularly in the integration of renewable energy sources and load variability. These methods not only improve voltage profiles but also reduce power losses, thereby enhancing the overall reliability and efficiency of the distribution network. Intelligent optimization techniques are necessary to ensure that power systems continue to operate efficiently, consistently, and sustainably as they transition to more intelligent and decentralized designs.

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