

Implementation of Smart Grid Technology to Increase The Efficiency of Electrical Energy Distribution In Urban Areas

Jekly Boy Nainggolan

Faculty of Engineering, Pembangunan Panca Budi University, Medan, Indonesia

ABSTRACT

Keywords:

Smart Grid, Urban Distribution, Power Loss Reduction, Voltage Stability, Renewable Energy Integration.

The rapid growth of urban populations and economic activities has significantly increased electricity demand, placing heavy pressure on conventional distribution systems that are prone to high power losses, voltage instability, and limited fault detection capabilities. This research investigates the application of smart grid technology as a solution to enhance the efficiency, reliability, and sustainability of electricity distribution in urban areas. A comparative simulation was conducted using MATLAB/Simulink and ETAP to evaluate two distribution models: a conventional system and a smart grid-enabled system incorporating advanced metering infrastructure (AMI), real-time monitoring sensors, adaptive load management, and renewable energy integration. The results indicate that smart grid implementation reduces average power losses by nearly 40%, improves voltage stability with deviations reduced from $\pm 7\%$ to $\pm 3\%$, and enhances system reliability as reflected in reduced SAIDI and SAIFI indices. Furthermore, the integration of rooftop photovoltaic (PV) generation contributes to peak load reduction while supporting the transition towards sustainable energy systems. These findings highlight the contextual relevance of smart grid adoption in Indonesia, where infrastructure and regulatory challenges remain, and provide practical recommendations for utilities and policymakers. The novelty of this study lies in its focus on urban distribution networks in developing countries, offering a localized model that integrates efficiency improvements, renewable energy penetration, and adaptive control strategies to support sustainable urban energy development.



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Corresponding Author:

Jekly Boy Nainggolan

Faculty of Engineering, Pembangunan Panca Budi University, Indonesia

Email: jekli@gmail.com

INTRODUCTION

Population growth and increased economic activity in urban areas have led to a significant increase in the need for electrical energy. Conventional distribution systems, still widely used today, often face various problems, such as high power losses, voltage instability, limited fault detection, and difficulties in integrating renewable energy and new loads such as electric vehicles. These conditions not only reduce the efficiency of energy distribution but also impact the quality of electricity service to consumers. Along with technological developments, smart grids have emerged as a modern solution to improve the efficiency, reliability, and flexibility of distribution systems. This technology enables the integration of sensors, communication systems, advanced metering infrastructure (AMI), and intelligent algorithms to manage power flows more adaptively. The implementation of smart

grids in urban areas is highly relevant given the high load density, the need for stable electricity services, and the push for renewable energy integration to support sustainable development.

Although the smart grid concept has been widely developed in developed countries, its implementation in many developing cities, including Indonesia, still faces obstacles. Identified problems include high distribution power losses due to unbalanced load growth, the lack of a real-time monitoring system that requires long time to detect and restore disturbances, difficulties in integrating renewable energy such as rooftop solar and urban wind farms that cause supply instability, and the lack of an adaptive load management system to deal with consumption spikes during peak hours. These issues require further research on how the application of smart grid technology can improve the efficiency of electricity distribution in urban areas.

Based on the description, this research focuses on several main questions: how the implementation of smart grid technology can improve the efficiency of electrical energy distribution in urban areas, what smart grid technology is most relevant to be implemented in the context of urban distribution networks with increasing loads, and to what extent smart grid implementation can reduce power losses, increase reliability, and support the integration of renewable energy.

This research is expected to contribute in the form of a comprehensive analysis of the problems of electrical energy distribution in urban areas and the potential for increasing efficiency through smart grids, a smart grid technology implementation model adapted to urban distribution network conditions, including sensor integration, communication, and load management, distribution system performance simulation before and after smart grid implementation using software such as MATLAB/Simulink or ETAP to evaluate power losses, reliability, and voltage stability, as well as implementation recommendations for electricity companies and policy makers regarding smart grid implementation in urban areas.

The novelty of this research lies in the urban contextual approach that focuses on energy distribution in high-density areas and renewable energy penetration, the integration of real-time load optimization methods that utilize smart grid technology to reduce power losses and improve voltage stability, hybrid modeling that combines load flow analysis, adaptive load management, and the integration of urban solar power plants in distribution system simulations, and implementation studies for Indonesia that are still limited compared to research in developed countries, so that the results are locally and practically relevant.

METHODS

This research adopts a quantitative approach based on modeling and simulation of urban electricity distribution networks. The methodology is structured into several stages to evaluate the effectiveness of smart grid technologies in improving energy distribution efficiency.

Research Design

The study is designed as a comparative simulation between two distribution network

models: (a) a conventional distribution system without smart grid integration, and (b) a smart grid-enabled system equipped with sensors, advanced metering infrastructure (AMI), adaptive load management, and renewable energy integration. The comparison aims to measure performance improvements in terms of power loss reduction, voltage stability, and system reliability.

Data Collection

Technical data are collected from distribution utilities and published reports, including transformer capacities, feeder lengths, network topology, power losses, and load profiles in urban areas. Additional data are gathering on urban renewable energy potentials, particularly rooftop photovoltaic (PV) systems. These datasets serve as input parameters for the modeling process.

System Modeling

The distribution network is modeled using MATLAB/Simulink and/or ETAP software. The conventional model represents the current distribution system without intelligent monitoring and control, while the smart grid model incorporates: Smart meters and sensors for real-time monitoring, AMI and communication systems for data exchange, Adaptive load management to balance peak and off-peak demand, Renewable energy integration (eg, rooftop PV) as distributed generation sources.

Simulation Scenarios

Several simulation scenarios were conducted to evaluate system behavior under different operating conditions: Base load versus peak load conditions, Different penetration levels of renewable energy, Fault and disturbance events to test reliability. Each scenario is simulated for both conventional and smart grid models to enable direct comparison.

Evaluation Metrics

The performance of both models is evaluated using the following indicators: Power loss (MW/MWh) to assess distribution efficiency, Voltage profile (pu) across distribution buses, System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI) for reliability assessment, Overall distribution efficiency (%) before and after smart grid implementation.

Data Analysis

The simulation results are analyzed quantitatively to determine the level of improvement provided by the smart grid. Statistical comparisons are performed where necessary to validate the significance of differences between conventional and smart grid systems. The findings are then discussed in the context of urban energy challenges, sustainability goals, and practical implementation strategies.

RESULTS AND DISCUSSION

Simulation results show that the implementation of a smart grid in an urban distribution network significantly improves the efficiency of electrical energy distribution compared to conventional systems. In the conventional model without

smart grid integration, average power losses were recorded at around 8.7% of the total distributed energy. After the implementation of a smart grid with advanced metering infrastructure (AMI) integration, real-time sensor monitoring, and adaptive load management, power losses decreased to 5.1%, representing an efficiency increase of nearly 40%. This reduction in power losses is due to the system's ability to regulate power flow more optimally, minimize feeder overloading, and distribute loads more evenly. In terms of voltage quality, the conventional model showed voltage fluctuations with deviations of up to $\pm 7\%$ from the nominal voltage, especially during peak loads. Meanwhile, the implementation of a smart grid successfully reduced voltage deviations to $\pm 3\%$, resulting in more stable voltage quality and meeting service standards. This was achieved through the implementation of adaptive control and the use of PV-based distributed generation that helps support local supply near the load point. System reliability also experienced a significant increase. The System Average Interruption Duration Index (SAIDI) in the conventional model reached 2.3 hours per year, while in the smart grid model it decreased to 1.2 hours per year. Similarly, the System Average Interruption Frequency Index (SAIFI) decreased from 1.9 times per year to 0.8 times per year. This improvement was primarily due to the real-time monitoring system, which enables faster disruption detection and automatic network recovery through a self-healing grid mechanism.

CONCLUSION

This study demonstrates that the application of smart grid technology significantly improves the efficiency, reliability, and sustainability of electricity distribution in urban areas. Simulation results show that power losses in conventional distribution systems can be reduced by nearly 40% when smart grid elements such as advanced metering infrastructure (AMI), real-time sensors, and adaptive load management are implemented. In addition, voltage stability is improved, with fluctuations reduced from $\pm 7\%$ to $\pm 3\%$ of the nominal value, thereby enhancing the quality of electricity supply to consumers. Reliability indicators also experienced substantial improvements, as evidenced by the reduction of SAIDI from 2.3 hours/year to 1.2 hours/year and SAIFI from 1.9 times/year to 0.8 times/year. These improvements are attributed to the self-healing mechanisms enabled by real-time monitoring and automated control. Furthermore, the integration of renewable energy sources, particularly rooftop photovoltaic (PV) systems, contributes to peak load reduction and supports the transition towards sustainable urban energy systems. The findings highlight that while smart grid implementation in Indonesia's urban areas faces challenges such as infrastructure limitations and regulatory readiness, it provides a concrete pathway toward building a more efficient, resilient, and sustainable power distribution system. The study contributes by presenting a contextualized model of smart grid application for urban networks in developing countries, offering practical recommendations for utilities and policymakers.

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