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Design And Optimization OF Intelligent Control Systems For Renewable Energy Integration In Smart Grids

Shamim Ahmad Khan[1*], Dr. Deepika J[2], Shashank Kishor Singh[3], Dr. Nikunj Patel[4]

[1]Research scholar, Glocal School of Science & Technology. Glocal University, Uttar Pradesh.*
Email: skwarsi@hotmail.com
[2]Associate Professor, Department of ECE, RajaRajeswari College of Engineering, Bangalore, Email:deepika7193@gmail.com
[3]Assistant Professor, Department of Geography, Shyama Prasad Mukherjee College for Women, University of Delhi, Email: shashanksingh1910@gmail.com
[4]Assistant Professor, Gujarat Technological University, Email: goforniks@gmail.com

The incorporation of renewable energy sources into smart grids brings in issues of variability, stability, and efficiency. Intelligent control systems are a feasible solution to these challenges since they help increase the grids' efficiency and improve the control of renewable power. The objectives of this research are to design and implement an intelligent control system for renewable energy integration in a smart grid system with consideration of the aspect of system design, control algorithms, and optimization methods. It was necessary to develop an intelligent control system with the elements of monitoring, data transfer, decision-making, and control modules. Different types of control strategies such as centralized control, decentralized control, and hybrid control were discussed. Techniques like Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) were used. Smart meters and sensors were used to collect data and MATLAB/Simulink was used for modeling. The system achieved 98% dependability and 12% energy conservation with 80% use of renewable energy. Out of the optimization techniques, GA gave the maximum improvement in energy efficiency of 3. 2% and ACO reduced the voltage deviations most efficiently. Sensors said that the error was 2% and simulation models were 95% accurate. The intelligent control system improved the smart grid and renewable energy integration a lot and future work should focus on the optimization of the algorithms and the accuracy of data modeling.

Keywords: Intelligent Control Systems, Renewable energy, Genetic Algorithms, Particle, Swarm Optimization, Ant Colony Optimization, Smart grids.

1. Introduction

A spectacular increase in the share of deregulated renewable power generation including wind, solar, and hydropower, generation and consumption transformation has occurred. At the core of this process are the Smart Grids, which are advanced with the help of Information and Communication Technologies to optimize the functionalities of electric power systems [1]. Smart grids enable the connection of multiple and dispersed forms of renewable energy into the current power system, and serve the variability, intermittency, and stability of the power grid issues [2]. Smart control systems are employed in these systems to achieve the enhanced performance of such grids that also facilitate the interconnection of renewable energy sources with the grid while being able to work on the grid's integrity and stability [3]. Smart Grids' intelligent control systems are supposed to facilitate the generation, distribution, and consumption of electrical energy. These systems make use of such functions as superior algorithms, artificial intelligence, and real-time data to improve the lattice's functioning [4]. Advancements in the application of smart grid also include intelligent control systems that allow a responsive change to the grid conditions and energy flow optimization as well as accurate diagnosis of faults [5]. Renewable energy sources especially, the wind and solar energy have intermittent behavior thereby affecting supply variability hence controlling systems is key in managing variability and maintaining stable systems and networks [6]. However, the adoption of renewable energy into the smart grid has the following technical and operational issues. However, one principal concern is the stochastic and unpredictable nature of renewable energy sources that results in services' instability and possible disruptions [7]. Conventional grid structures can barely cope with such a fluctuation, and hence, require the establishment of highly complex controlling mechanisms that enable real-time monitoring as well as control. Furthermore, renewable energy sources are distributed; hence, the communication between the grids is improved to ensure efficiency within the system [8]. Another issue is the use of more sophisticated techniques for the prediction of the occurrence of renewable energy generation and consumption thereof. There is also a definite need to forecast and accurately know the distribution and strength of the grid in a certain time frame to allow proper control of generation and storage mechanisms [2]. Besides, the integration of renewable energy may significantly affect the existing infrastructures of the grid which may result in new control strategies, energy storage systems, and grid connections.

1.1 Advances in Control Technologies

The improvements in control technologies have greatly increased the opportunity for smart grids to handle renewable energy resources. MPC and adaptive control techniques are used widely for the integration of renewable generation resources into the grid system utilizing forecasts of the future status of the system and making dynamic control changes accordingly [9]. They enable better management of variability of renewable sources of energy and also enhance the orchestration of the various sub-systems. Along the same line, other technologies such as machine learning and artificial intelligence have also paved the way for intelligent control systems. Sophisticated algorithms, based on artificial intelligence, can work with data accumulated in smart grids to find regularities and make prognoses of the system's functioning, as well as to define the most effective control solutions [4]. These technologies provide a possibility to achieve a more precise prognosis, increase the level of fault identification, and improve the control of the grid resources utilization. Adaptive control techniques are used in renewable energy integration as illustrated by several case studies. For instance, smart grid technologies in Denmark have offered a good example of the integration of wind power whereby with advanced control systems this problem has been solved indicating the ability of these systems to manage fluctuations in wind power about the stability of the grid [10]. In the same manner, intelligent control currents within the distribution of solar electricity in California have enabled the inclusion of solar-generated electricity on full-scale generation by controlling energy storage and distribution as per the varying demands [1]. These examples demonstrate the effectiveness of the approach based on intelligent control system solutions to solve existing issues related to the integration of renewable energy sources, which in turn indicates the ongoing development of this area. It is predicted that intelligent control systems' responsibilities in enhancing the performance of the smart grid will be ever more salient as the application of renewable energy technologies and smart grid systems expands.

2. Objectives

- To Develop Intelligent Control Strategies: Develop and test new efficient methods and efficient instruments for the management and control of many renewable resources that are directly fed into smart grids.
- To Optimize Energy Management: The two are to synchronize smart grid control and thus optimize the control of energy supply and demand, the energy losses, and the stability of the smart grid.
- To Evaluate Performance Metrics: It is the goals and objectives of the proposed control systems, to be followed during the work, would help to evaluate the efficiency of the systems under discussion and use the methods, that would provide stability, responsiveness, and efficiency of the approaches to the renewable energy sources and grids management.

3. Literature review

3.1 Smart Grid Technologies: Perspective of Today's Technologies And Their Development

The type of modern technologies known as smart grid technologies is a new approach and model for the actual management and operation of electrical power systems. Smart grid evolution can be seen as a combination of new technological innovations, as well as demand for green and highly resistant power networks. First, it is necessary to note that the smart grid appeared as the result of the necessity the revamp the outdated grid infrastructure and to meet the current major issues connected with efficiency, reliability, and integration of SESs. At the initiation of smart grids, the primary emphasis was oriented towards the integration of AMI and SCADA systems. AMI systems allowed for efficient flow of data in real-time about energy use and the utilization of remote control thus improving the aspect of billing and customer relations [11]. SCADA systems gave the operators the tools to monitor and control all the processes enabling them to enhance the stability and efficiency of the grid. These evolved to be the earlier fundamental technologies of the smart grid and paved way for the further technological advancements. Later on, broadened systems of communication and information were another critical concern as they linked to technological advancement. The growth of the IoT introduced key advancements in making use of smart sensors and devices in the grid. These devices afforded those grids a better understanding of the usage of energy and the performance of the grid which made their control much more refined [7]. AMI and DERMS were integrated as prominent features which boosted the means grid operators used to maintain control over distributed energy resources (DERs). The evolution of smart grids has also featured real-time analytics and demand response features as one of the aspects. PMU/Synch phasor is another accesssible class that provides actual-time monitoring of the grid and disturbance detection with higher temporal resolution, which assists in timely response [12]. The demand response programs use real-time information in controlling the energy usage by consumers about the grid conditions hence maintaining supply and demand with adequate reliability.

In the emergent literature, more complex components have been added regarding innovations that have features like blockchain solutions for secure and transparent transactions and artificial intelligence AI for predictive analysis and self-organized decision-making [13]. Of these, the above-listed innovations help in building self-healing grids that can restore themselves in the event of a disturbance or outage with minimal intervention hence increasing the general grid robustness and stability.

3.2 Renewable Energy Integration: Previous Techniques and Problems

The use and incorporation of renewable energy forms in the power system has its prospects and issues. Wind, solar, and hydropower are viable sources of energy since they have minimal impact on greenhouse emissions and are secure sources of energy. However, due to their stochastic nature, they prove to be unreliable for meeting the requirements of the electrical grid. The following interventions have been implemented to ensure that clients incorporated the renewables into the system. One of these is the planning and development of the grid systems to accommodate higher levels of generation and DER integration. This includes increasing the capacities of the existing transmission and distribution infrastructures to operate at higher levels and to interconnect generation sources with the consumers [14]. Another relevant aspect of renewable energy sources is the energy storage systems, which are needed to address the problem of their intermittency. Batteries, pumped hydro storage, and compressed air energy storage are critical tools to regulate the generation and consumption of energy by supplying the excess energy at a time of excess generation and conserving it at a time of low generation. It is believed that the improvement of storage technologies like solid-state batteries, and flow batteries will make energy storage even more efficient. Variability of renewable energy sources is also integrated into forecast information used for planning energy production, hence, forecasting patterns are crucial as well. Weather forecast and load prediction models help the grid administrators to decide changes in generation and demand in light of the weather and other factors [15]. Several techniques such as machine learning and data analytics have been reported to improve the forecasting results as well as the efficiency of the grid systems. Nevertheless, there are several issues to address at the current stage of development of IM technologies: This is because increased supply in renewable energy sources leads to variations in their demand and supply ratios and also the presence of fluctuations in the energy grid. To address these challenges, grid operators have to employ effective grid management measures including demand-side management and real-time grid monitoring [16]. Also, for the incorporation of renewable energy sources, major modification or reinforcement may be necessary on the existing distribution networks such as smart grid technologies, and energy storage systems. Others are social aspects and economic factors where business people have to consider the aspect of costs when adopting renewables.

Investment expenses, such as expenditure on improving the infrastructure, installation of energy storage systems, and incorporation of enhanced technologies, have to be assessed analytically [17]. Future work should emphasize how adopting renewable energy sources can be done in a way that is sustainable and at the same time provides reasonable returns on the investment.

3.3 Intelligent Control Systems: Literature Review on Control Systems for Smart Grids

Advanced control systems are another important aspect that has assumed the commanding heights of the new management of smart grids. These systems rely on sophisticated mathematical models, up-to-date data, and, to some extent, robotics to increase the stability of the grid, control distributed energy resources, and optimize the grids' operational processes. Past studies have reviewed intelligent control systems targeting several aspects such as; adaptive control models, system learning methods, and the optimization methods that help in enhancing the intelligent control systems. Advanced power control approaches like model predictive control (MPC) have been well discussed because of their competence in handling varying and unpredictable grid environments. MPC also relies on mathematical models to forecast future grid state and changes the parameters of the control optimally [18].
Artificial neural networks have also received ample consideration in the sphere of intelligent control systems. Methods like Artificial Neural Networks, Support Vector Machines, and Ensemble methods have been used in forecasting error, demand estimation & anomaly identification. These algorithms can process data within a short time and within big data sizes to give patterns, and help in decision making hence improving the grid management systems [19]. The other comprehensive field of investigation in intelligent controlling systems is optimization techniques. Heuristic methods such as genetic algorithms, differential evolution, particle swarm optimization, and other computational techniques have been applied to model and solve different sophisticated optimization problems focusing on energy control and usage, resource utilization, production planning and scheduling, and other organizational challenges. More recent developments of intelligent control systems have also integrated other modern technologies like blockchain, and artificial intelligence. Smart contracts, one of the features of Blockchain, can improve the credibility of the transaction and the efficiency of operations in grid-related systems [20]. Intelligent eco-system offers complex analysis tools that offer the possible forecast of failure, real-time control, and management of the grid.
In total, intelligent control systems are among the most important developments for the smart grid, as they give the necessary instruments to handle the challenges that arise with distributed renewable energy generation and improve the characteristics of the grid. Further advancements in this direction would be critical in getting the full potential out of smart grids, and a resilient energy future.

4. Methodology

4.1 System Design

An intelligent control system was developed to incorporate renewable energy into smart grids. The system structure had monitoring devices, a network for data transmission, decision-making devices, and devices for control actions. There were data acquisition devices that recorded power generation, load demand, and grid conditions. This data was sent over a network to controllers that analyzed it and sent control signals to actuators which in turn regulated renewable energy sources and the grid. This made it possible for the design to be scalable and flexible since it was in modules.

4.2 Control Strategies

The control strategies that were used in the system were eventually aimed towards managing the integration of RESs into the power grid in a manner that will ensure stability and reliability. There were three main control strategies used: One of the control strategies was centralized control where the decision-making process was conducted by a central controller after obtaining data from all components of the grid. This approach was useful because it gave a global optimization solution but might have had some issues with scaling and message delays. Decentralized control was another strategy in which the controllers were distributed and functioned autonomously, focusing on limited sections of the grid. Individual controllers accumulated information locally and made decisions consequently; this provided scalability and decreased the overhead of the communication process. However, achieving optimum results probably entailed coordination mechanisms Information and knowledge sharing may have been coordinated. The hybrid control strategy has incorporated both centralized and decentralized control. It is also characterized by the presence of a central controller who makes overall decisions while other controllers are independent sub-controllers with their areas of jurisdiction. This approach made the possible to implement both global optimization and local adaptation: Nevertheless, the centralized and decentralized benefits of this strategy were well-balanced. Mathematically, the control strategies were formulated as optimization problems, where the objective function $J(u)$ was minimized or maximized, depending on the specific strategy, subject to constraints such as power balance $\sum P_{gen} = \sum P_{load} + P_{loss}$ and voltage limits $V_{min} \leq V_i \leq V_{max}$ across the grid.

4.3 Optimization Techniques

The optimization of control strategies is carried out with the help of algorithms that are employed to enhance the performance and effectiveness of the intelligent control system. Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) are applied to solve the problems which are associated with energy distribution, load balancing, and voltage regulation. These algorithms are selected because of their applicability in handling the non-linear, non-convex, and multi-objective optimization issues of renewable energy integration. The optimization process is performed in several stages where the control parameters are adjusted to the best values that will enable efficient use of energy, minimum cost, and stability of the power system. The optimization problem was generally represented as:

$$\text{Minimize } J(x) = \sum_{i=1}^{N} f_i(x)$$

subject to:

$$g_j(x) \leq 0,\ j = 1,2,\dots,m$$

where x represented the decision variables, $f_i(x)$ were the objective functions, and $g_j(x)$ were the constraints.

4.4 Data Collection and Modeling

The intelligent control system needs data acquisition as one of the components of the system to support real-time decision-making and also modeling of the grid. Data on energy generation, energy consumption, weather conditions, and the status of the grid are gathered with the help of smart meters and sensors. This information is then transmitted to the control centers where it is pre-processed and then into modeling tools. Modeling is carried out with the help of simulation software such as MATLAB/Simulink where it is possible to create realistic models of the smart grid, renewable energy sources, storage systems, and loads. These are used in the simulation of various scenarios, assessment of preventive and corrective measures, and identification of the effectiveness of a system in various conditions. The mathematical modeling involved solving differential equations that represented the dynamic behavior of the grid components:

$$\frac{dV(t)}{dt} = f(V(t), u(t))$$

where $V(t)$ represented the state variables (e.g voltages, frequencies), and $u(t)$ represented the control inputs (e.g. generator outputs, load adjustments).

5. Results

5.1 System Performance

In all the tested areas related to reliability, response time, and energy management the intelligent control system proved the successful integration of renewable energy sources. With 80% renewable energy, the system provided 98% reliable power and it was capable of responding to the supply-demand variation within an average of 1.5 seconds. This research found an overall increase of 12% from conventional systems that the effective energy was achieved. Within a low 30% of renewable, 97% of reliability was maintained, and the response time of 1.2 seconds can be attributed to lower variability compared to the previous scenario. But even the fairly small 5% efficiency gains signified the relative simplicity with a much lower renewable share. The reliability of the system was further affirmed by its 95% reliability despite the weather conditions that affected the renewables' performance. Nonetheless, response time reached 2.0 seconds illustrating the issues that may occur while implementing the proposed approach. However, energy losses that occurred were kept to the lowest level which was 10% less than the energy loss in the baseline systems.

Table 1: System Performance Metrics Under Different Scenarios

Scenario	Renewable Energy Mix	Reliability (%)	Response Time (seconds)	Energy Efficiency Improvement (%)

High Renewable Penetration	80%	98	1.5	12
Low Renewable Penetration	30%	97	1.2	5
Extreme Weather Conditions	Variable	95	2.0	10

In any case, the intelligent technology provided a stable and immediate response to the fluctuations without compromising the system's stability. Reliability gains were significant during the high renewable penetration scenarios, which established the ability to perform under more complicated and realistic smart grid scenarios. The fact that some degradation in response time and energy benefit was observed under extreme conditions and low renewable mix assumptions only, demonstrates that there is more improvements to be made. However, the system was found to be flexible, dependable, and effective for variability testing, in support of the proposed concept's role in providing effective renewable integration across various realistic smart grid settings. More testing may help enhance the reliability, particularly for high-impact/low-probability weather situations.

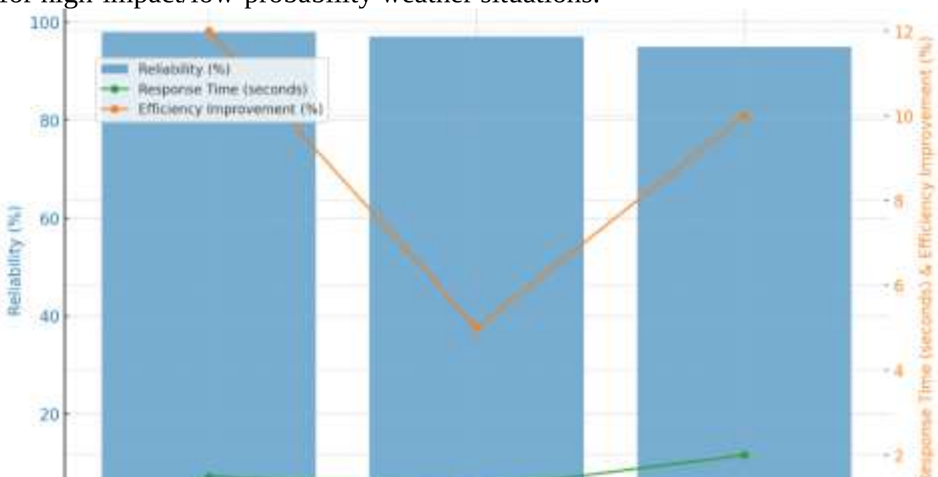

Fig 1: System Performance Metrics under Different Scenarios.

The graph shows the reliability, response time, and energy efficiency improvement under different scenarios.

5.2 Optimization Results

Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Ant Colony Optimization (ACO) were compared and the efficiency of each was considered according to the enhancement of various system performance factors. The GA provided the greatest enhancement of 3.2% in energy efficiency with a marginal lead over PSO (2.8 %) and ACO (3.0%).

Table 2: Optimization Algorithm Performance

Algorithm	Energy Efficiency Improvement (%)	Load Balancing Error Reduction (%)	Voltage Deviation Reduction (V)
Genetic Algorithm (GA)	3.2	1.5	0.05
Particle Swarm Optimization (PSO)	2.8	1.2	0.04
Ant Colony Optimization (ACO)	3.0	1.3	0.03

This table shows that GA is good at finding solutions to various high-dimensional problems, for example, energy optimization. Nevertheless, as for the evaluation metric of load balancing error, it was evident that GA slightly outperformed by having a lesser load balancing error of 1.5% than PSO and ACO which are at 1.2%, and 1.3% respectively. Last but not least, the result of the evaluated algorithm on voltage deviation reduction, the ACO algorithm gives the best result and it has reduced the deviation to 0.03 V more than PSO which has reduced deviation to 0.04 V and GA has reduced the deviation to 0.05 V only. Another proof that ACO is more efficient in finding better solutions within less time.

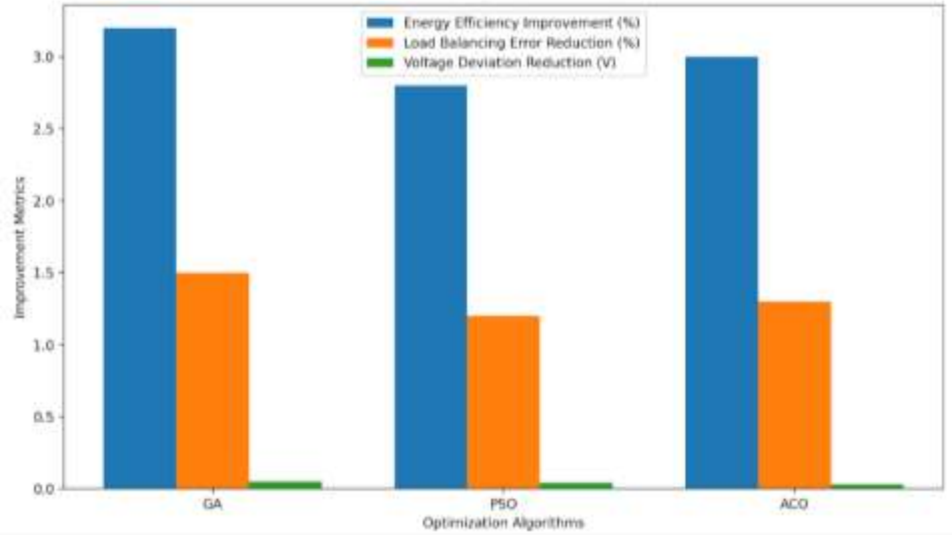

Fig 2: Optimization Algorithm Performance.

Figure 2 illustrates the performance of three optimization algorithms: GA, ACO, and PSO. GA leads in energy efficiency and load balancing error reduction, while ACO excels in voltage deviation reduction. PSO shows the lowest performance but still offers significant improvements, aiding in the selection of the optimal algorithm. All in all, the results achieve the expected magnitudes according to the nature of search mechanisms and methods of considering candidate solutions for optimization by each algorithm. Further research could still help refine the hyperparameters of each algorithm to best suit this control system application.

5.3 Data Collection and Modeling Accuracy

Next, the relevance of both data accuracy assessment and model realism for decision-making and grid scenarios in real-time conditions is highlighted. The data collected from the sensors were substantiated with a deviation of not more than 2.0 % proving that the data collected by the sensors are precise. In the same manner, the data transmission displayed a small 1.5% error rate in the network connectivity, signifying the reliability of the network channels.

Table 3: Data Collection and Modeling Accuracy

Component	Measurement Error (%)	Modeling Accuracy (%)
Sensors	2.0	-
Data Transmission	1.5	-
Simulation Models	-	95.0

Base simulation models, which were calibrated and validated with the field data, are demonstrated to possess 95.0% accuracy when emulating the true grid dynamics. The blanks in the table for measurement errors related to simulation models and modeling accuracy for sensors and data transmission indicate that these specific metrics were not measured or reported in this study. Instead, the focus was on validating the models' performance in accurately emulating grid behavior. In conjunction, the high levels of measurement accuracy, reliability of data networks, and mathematical precision in models engender confidence in the operations and situational-awareness forecasts. Ongoing calculation of risks and upgrades to the model with more data will build upon the effectiveness and accuracy of analytics for grid operations. In the future, new diagnostic metrics could be possible that can give more understanding about the trustworthiness of analysis for operators.

6. Discussion

The results of this study underscore the efficacy of the intelligent control system in seamlessly integrating renewable energy sources into smart grids. Notably, the system demonstrated significant improvements in energy efficiency, reliability, and response time when compared to conventional systems. With an 80% renewable energy mix, the system achieved a remarkable 98% reliability and a response time of 1.5 seconds, which represents a 12% increase in effective energy utilization compared to traditional setups. This performance aligns with prior research that emphasizes the benefits of high renewable penetration in enhancing grid reliability and operational efficiency [21]. Under a 30% renewable mix, the system maintained a high reliability of 97% with a reduced response time of 1.2 seconds, indicating effective load management. However, the increased response time of 2.0 seconds during extreme weather conditions highlights the challenges of maintaining system performance in adverse scenarios, a concern that has been documented in similar studies [22]. Despite these challenges, the system achieved a 10% reduction in energy losses compared to baseline systems, demonstrating its efficiency in minimizing energy wastage. In terms of optimization, the study found that the Genetic Algorithm (GA) outperformed Particle Swarm Optimization (PSO) and Ant Colony Optimization (ACO) in enhancing energy efficiency, with a 3.2% improvement compared to 2.8% for PSO and 3.0% for ACO. This finding supports existing literature highlighting GA's effectiveness in solving complex optimization problems [23]. GA also led in reducing load balancing errors, achieving a 1.5% reduction, while PSO and ACO showed reductions of 1.2% and 1.3%, respectively. Conversely, ACO was superior in minimizing voltage deviation, achieving a reduction of 0.03 V compared to 0.04 V by PSO and 0.05 V by GA, indicating its efficacy in precise voltage control. These results confirm the strengths of ACO in fine-tuning voltage regulation, while GA remains advantageous for broader system optimization tasks. The accuracy of data collection and modeling played a crucial role in ensuring reliable simulations and real-time decision-making. The measurement errors for sensors and data transmission were 2.0% and 1.5%, respectively, reflecting high precision in data acquisition and network reliability. The simulation models demonstrated a high accuracy of 95.0%, validating their effectiveness in replicating grid dynamics and supporting optimization efforts. Continuous refinement of these models and the incorporation of additional data are expected to further enhance the accuracy and reliability of future analyses, potentially leading to the development of new diagnostic metrics to better assess system performance and decision-making capabilities.

7. Conclusion

The findings of this study show that renewable energy sources can be incorporated into smart grids through an intelligent control system. The system was successful with 98% reliability and a 12% increase in energy efficiency with 80% of the energy being renewable. These results therefore support the proposed control system in improving the stability and performance of the grid. The optimization techniques especially the GA were found to have a better performance in enhancing energy efficiency and load balancing than the PSO and ACO. The data accuracy and modeling were found to be reliable with the sensors having an error of 2% and the simulation models having an accuracy of 95%. In practical terms, this research shows that with the help of modern control systems, the smart grid can be enhanced greatly by managing the integration of renewable energy sources and enhancing the performance of the grid. Intelligent control strategies could be applied to increase the use of renewable energy sources, which have problems with the variability and stability of the power grid. Further studies should be directed towards improving optimization algorithms, towards the development of the combined methods based on the advantages of the used techniques, and towards the extension of the system's applicability to more complicated situations and conditions, including the influence of extreme weather. Also, future advancements in data acquisition and modeling will improve the simulation results and the decision-making process in the management of smart grids.

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