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Firefly Optimization-Based Intelligent Routing for Efficient Power Management in Hybrid Renewable Energy Systems

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ABSTRACT: IoT-based smart grid architectures improve energy management, operational efficiency, and reliability have been developed in response to the growing demand for sustainable energy solutions. High transmission latency, ineffective routing, restricted scalability, and inadequate real-time monitoring are some of the problems that plague traditional smart grid techniques. Hence this research proposes an Internet of Things (IoT) integrated smart grid architecture that utilizes Firefly Optimization Algorithm (FOA) for intelligent energy routing and improved performance in order to overcome these constraints. The smart grid system uses sensors to capture energy inputs from wind and photovoltaic (PV) sources to enable real-time monitoring and data collection. The shortest and most efficient energy transmission path is identified using Firefly Optimization method, which guarantees low energy loss and maximum efficiency. This method minimizes overloading, drastically cuts down on transmission delays, and improves the grid's overall responsiveness. The end user is guaranteed a dependable, economical, and ecologically sustainable power supply of the combination of IoT integration for automation, renewable energy sources, and intelligent routing. This architecture greatly lowers average latency and overhead while achieving high packet delivery ratio (PDR) and throughput. Additionally, it reduces energy use, guaranteeing reliable and effective grid operation.

Keywords: Smart grid, Photovoltaic (PV), wind turbine, Firefly Optimization (FO), Internet of Things (IoT).

1. Introduction

The growing demand for energy has significantly accelerated the exhaustion of fossil fuel reserves over time. This raise the cost of generation and promote the release of more hazardous carbon dioxide. Renewable Energy Resources (RERs) are starting to be incorporated into electrical networks in order to alleviate the above listed problems [1]. Modern grid systems are developing into smart grids that make use of automation and digital communication technologies in order to efficiently handle the integration of RERs. Load balancing, effective energy distribution, and real-time monitoring are made possible by these technologies. Grid responsiveness to fluctuating renewable sources, sustainability, and reliability are thus greatly improved [2]. Intelligent smart systems, which provide effective and flexible solutions to the operational constraints and stability problems that conventional microgrids frequently encounter, are being developed to further improve these capabilities. In dynamic grid contexts, these systems use data-driven control strategies and sophisticated algorithms to guarantee optimal performance and energy management [3]. Continuous real-time monitoring, control, and automation of grid assets are made possible by the IoT, which offers scalable infrastructure for remotely and reliably tracking generating sources, storage systems, loads, and power quality measurements [4]. To enable these IoT-based processes, Wireless Sensor Networks (WSNs) serve as the fundamental communication layer that permits dependable data collection and transfer throughout the grid environment. WSNs have gained widespread attention due to their versatility and applicability in numerous domains, especially in modern energy systems. These networks are made up of distributed sensor nodes that continuously monitor grid components collect vital metrics such as voltage, frequency, and temperature. Affordable, tiny sensor nodes that sense, analyze, and wirelessly transfer data make up a typical WSN [5]. WSNs are among the best methods for moving vital data from inaccessible locations to a central data processing station because these low-power devices work especially well in hostile or isolated circumstances. By enabling the real-time flow of operational data, WSNs play a pivotal role in ensuring seamless communication, faster defect detection, enhanced system observability, and adaptive real-time control. Their integration significantly boosts the performance of IoT-based smart grids, thereby improving the overall intelligence, adaptability, and reliability of the modern energy infrastructure [6]. Despite their advantages, wireless communications have inherent drawbacks, such as low data speeds, limited transmission power, limited communication channel capacity, and vulnerability to security breaches and interference [7]. The efficient deployment and operation of WSNs in actual smart grid scenarios are severely hampered by these limitations [8]. Effective routing techniques are used to get around these problems and guarantee dependable data transfer in such situations. Routing improves the overall effectiveness and lifespan of the network by minimizing communication overhead, establishing dependable data transmission channels, and decreasing the energy consumption of sensor nodes [9]. However In contexts with limited resources, traditional routing protocols and transmission methods rely on all randomly placed sensor nodes to detect, transmit, and forward data, which increases energy consumption, shortens network lifetime, and creates inefficiencies [10]. In order to overcome these constraints, the suggested system presents a brand-novel routing technique based on Firefly Optimization that improves network performance and energy efficiency.

The following points summarize the key contributions of this proposed work. They emphasize the innovative aspects and improvements over existing approaches.

- To promote energy-aware data routing and communication protocols that support a greener and more sustainable smart grid environment.
- To minimize energy losses and improve system efficiency, a new routing technique based on the FO algorithm is used to determine the shortest and most effective energy transmission routes.
- To achieve high Packet Delivery Ratio (PDR) and throughput, ensuring robust and reliable transmission of data and control signals within the smart grid.

2. Literature Survey

Dung Nguyen Quoc *et al* [2022] [11] have developed a hybrid fault-tolerant routing system to find the hierarchical topology-based fault-tolerant problem in WSNs. The hierarchical topology is created by combining the clustering and labeling of sensor nodes as Gaussian integers. The network region is separated into tiny square grids, with a Gaussian integer cluster head for each grid. The fault-tolerant clustering routing protocol for wireless sensor networks based on Gaussian networks aims to increase fault tolerance, reduce energy consumption, and improve data dependability. However, sensor nodes often contain low amounts of energy, memory, and processing capability.

H. L. Gururaj *et al* [2023] [12] have presented, a collaborative energy-efficient routing protocol (CEEPR), for 5G/6G WSNs to enable sustainable communication. The data for this investigation first acquired at the sink node. The R.L is utilized to cluster the nodes of the network. Using an algorithm based on residual energy, cluster head selection is used to improve data transfer. CEEPR considerably lowers energy usage and increases network lifespan by using R.L for cluster formation and residual-energy-based cluster-head selection. Furthermore, in large-scale Network installations, the coordination overhead from clustering and optimization increase, which have an impact on latency and performance.

Nguyen Duy Tan *et al* [2023] [13] have established a two-level tree-based clustering (EE-TLT) energy-efficient routing protocol that stabilizes and effectively uses the energy of the sensor node. The network is logically separated into polygons and balanced clusters. The Kruskal algorithm creates minimal spanning trees (MSTs), which are used to route data over short links. A two-level routing tree connects the sub-cluster heads (sub-CHs), which function as local roots, to the base station. Long-range transmissions are decreased and load balance is improved by this structure. Frequent re-clustering, however, affects the network's response to time-sensitive events by introducing delays and control overhead.

Carlos Lester Duenas Santos *et al* [2023] [14] have developed an innovative ML-RPL machine learning-based routing protocol concept for wireless smart grid networks. The primary goal of the proposal is to improve the parent selection technique of the Routing Protocol for Low-Power and Lossy Networks, a widely used protocol in this type of network. This model learn to avoid overburdening specific nodes, thus distributing traffic more evenly and extending network lifetime. The quality and representativeness of the training dataset are critical to the protocol's success. Degraded performance and less-than-ideal routing predictions might arise from incomplete or skewed data.

Shahid Iqbal *et al* [2023] [15] have suggested a Predicting Link Quality Estimation (PLQE) to deal with network partitioning caused by node mobility and dependable data transfer. The PLQE dynamically identifies the efficient links using the beta probability density function, link quality, and link delay estimation (LDE). The protocol adapt in real time to node relocation and mobility due to the expected probability indicator (EPI) and dynamic link reliability factor (LRF). Additionally, Link metrics are used to route sensitive personal information. Secure estimates and encryption are not mentioned, leaving open the possibility of privacy issues or possible tampering.

3. Proposed System Modelling and Description

Block Diagram

An intelligent energy management system integrates IoT with renewable sources for efficient power control. It captures and processes energy using power converters and smart monitoring techniques. As shown in Figure 1, the system utilizes intelligent routing to minimize losses and delays. This ensures reliable, real-time, and eco-friendly power delivery to the end users. Let's examine this process's intricate workflow in more detail.

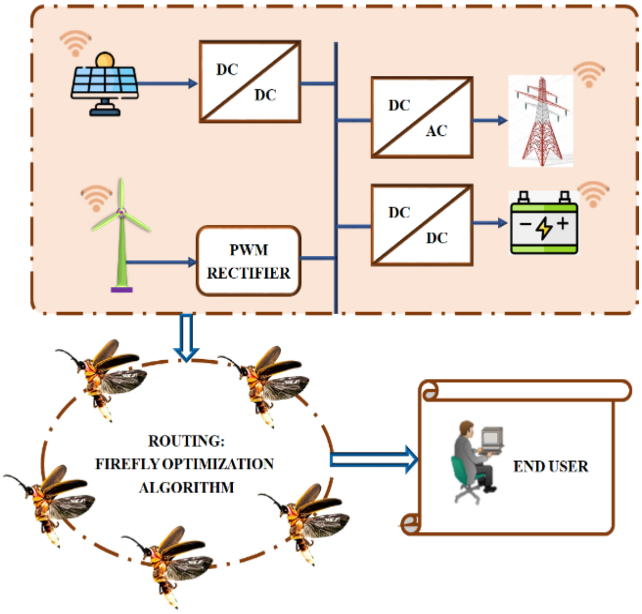

Figure 1: *Architecture of proposed system*

In order to facilitate real-time monitoring and data collection, the smart grid system initially employs sensors to gather energy inputs from PV and wind sources. Real-time monitoring of these energy resources and storage components guarantees reliable operation, fault identification, and ideal load balancing. The control and routing unit receives the sensed data from the grid, wind turbine, battery, and PV system. Here, the most efficient and shortest route for energy transmission is found using the FO algorithm. This bio-inspired optimization technique finds the best pathways with the least amount of energy waste and the highest efficiency by simulating the flashing behavior of fireflies. The system uses the chosen path to send the energy to the end user after the best route has been determined. This improves response time, avoids overload, and decreases transmission latency. Automation, renewable energy integration, and intelligent energy routing work together to guarantee a dependable and environmentally responsible power supply for the final consumer.

3.1 Smart Grid System

Smart grid communication solutions improve system intelligence, security, and load balancing by facilitating quick, safe, and dependable data exchange across the energy internet. These networks, which are backed by a strong infrastructure consisting of distribution-level communication networks and an optical fiber backbone, combine a variety of wireless technologies with power line communication systems. Crucially, wireless communication is necessary for users to communicate with the grid, even those are not directly connected to the energy network, such as owners of electric vehicles, residential users, and operators of renewable energy sources.

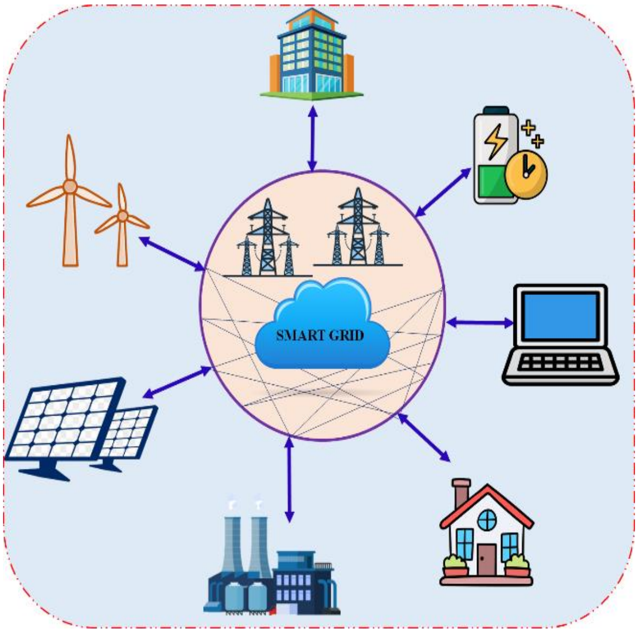

Figure 2: *Smart grid system*

These users control their energy output or consumption using mobile devices in order to take part in power market and demand-side response activities. Such users are quite prevalent in the energy internet environment, which has resulted in a proliferation of communication terminals. As a result, there are considerably more linked devices in this scenario of large-scale Machine-to-Machine (M2M) communication than in traditional 5G mobile networks. Power communication terminals, in contrast to human-centric communication, are primarily concerned with data reporting, necessitating the use of specific, high-capacity access technologies.

3.2 Routing- Firefly Optimization

A metaheuristic optimization method inspired by nature, the FO finds the best routing routes for wireless sensor networks. It functions according to two fundamental ideas: attraction and variations in light intensity. Each firefly in the routing context represents a potential communication line, and its brightness is assessed using an objective function that takes into account variables such as link quality, energy usage, and hop count. By attracting other fireflies, those with more light (better routing performance) direct the network toward the most effective routing routes.

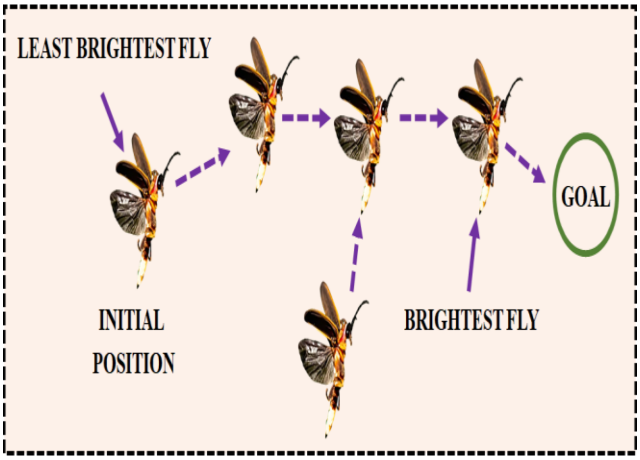

Figure 3: *Firefly Optimization based on brightness*

Brightness of a firefly (i.e.I) at a particular position x is I$(x) \propto f(x)$. Moreover attractiveness (i.e.β) is relative and based on the distance r_{ij} between $firefly_i$ and $firefly_j$.

Furthermore, the light intensity decreases if the firefly is far from the light source. Additionally, light is absorbed by the medium. Furthermore, the degree of absorption determines attractiveness. The inverse-square law, which is represented in Eq. (1), often governs the variation of the light intensity I(r):

$$I(r) = \frac{I_s}{r^2} \quad (1)$$

where I_s denotes source's intensity.

Eq. (2) calculates I based on the distance r, assuming a particular medium with a constant light absorption coefficient γ:

$$I(r) = I_O e^{-\gamma r} \quad (2)$$

where, I_o represents the initial intensity of the light at r=0. Eqs. (1) and (2) are estimated as Eq.(3) in order to avoid the singularity at r=0 in the phrase $\frac{I_S}{r^2}$:

$$I(r) = I_O e^{-\gamma r^2} \quad (3)$$

Also, Eq. (4) computes β of a firefly:

$$\beta = \beta_0 e^{-\gamma^{r^2}} \quad (4)$$

Where β_0 is the attractiveness at r=0. Equation (4) is essential as Eq. (14) because $\frac{1}{1+r^2}$ is computed faster than an exponential function:

$$\beta = \frac{\beta_0}{1+\gamma^{r^2}} \quad (5)$$

Equation (6) shows the distance between $firefly_i$ and $firefly_j$ at Z_i and Z_j, respectively:

$$r_{ij} = \|Z_i - Z_j\| = \sqrt{\sum_{k=1}^{d}(Z_{i,k} - Z_{j,k})^2} \quad (6)$$

where, $Z_{i,k}$, is the kth component of the spatial coordinate Z_i of ith firefly. According to Eq. (7), the $firefly_i$ is attracted to more attractive $firefly_j$:

$$Z_i^{t+1} = z_i^t + \beta_0 e^{-\gamma^{r_{ij}^2}}(Z_j^t - Z_i^t) + \propto \varepsilon_i^t \quad (7)$$

where the second phrase expresses attraction. Additionally, the third phrase is used to produce randomness. This is accomplished by use of the randomization parameter α. Additionally, i denotes a path of arbitrary numbers. It should be noted that rand −1 2 can be used in place of ῑi to cause rand to produce a random number in [0, 1]. In general, it is represents that α ∈[0,1] and β0 = 1.

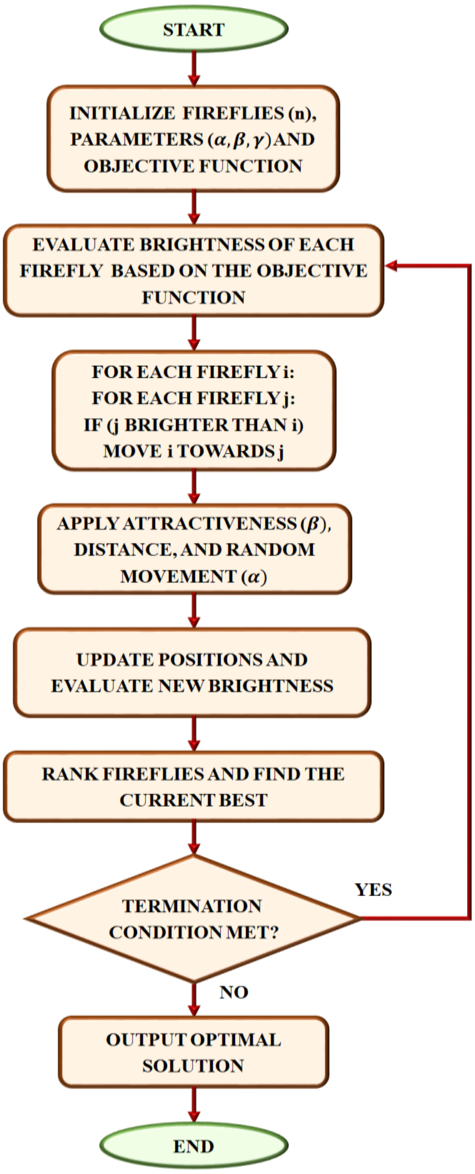

Figure 4: *Flow chart for Firefly Optimization Algorithm*

Figure 4 illustrates the working of the FO, a bio-inspired metaheuristic technique used to solve optimization problems. The algorithm begins by initializing a set of fireflies along with key parameters such as the quantity of fireflies (n), attractiveness (β), randomization factor (α), light absorption coefficient (γ), and the objective function to be optimized. The brightness of each firefly, which stands for a possible solution, is assessed using the objective function; the brighter the fireflies, the better the solution. In the next phase, the algorithm compares each firefly with all others. If a firefly j is brighter than firefly$i$ then firefly$i$ is attracted towards j. The movement of firefly$i$ is influenced by the attractiveness of j the distance between the fireflies, and a randomization factor that helps maintain diversity in the population and avoid local optima.

A firefly uses the goal function to recalculate its brightness and update its position after each movement. The current best option is then determined by ranking the firefly based on their brightness. After that, the algorithm looks for a termination condition, like achieving convergence or the maximum amount of iterations. The ideal solution is generated if this requirement is met. If not, the procedure is repeated until the required degree of solution quality is reached. The Firefly Algorithm efficiently explore the space and find optimal or nearly optimal solutions due to this iterative process.

4. Results and Discussion

The results and discussions are detailed in this section. Important performance indicators are carefully examined, including throughput, average delay, overhead, and energy usage. The comparative evaluation highlights the efficiency of the proposed method.

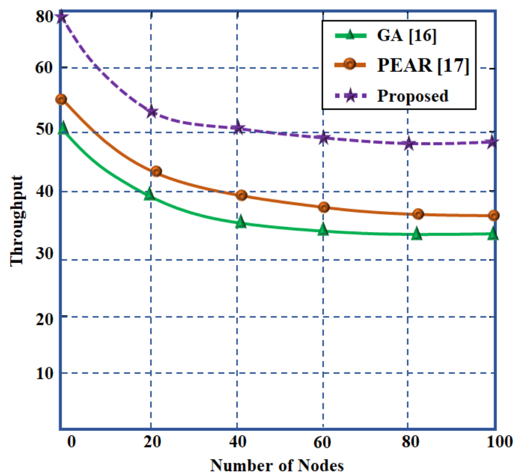

Figure 5: *Throughput*

The throughput against node count comparison for Genetic Algorithm (GA) [16], Predictive Energy-efficient Adaptive Routing (PEAR) [17], and the suggested approach is shown in Figure 5. The throughput of GA and PEAR drastically decreases as the number of nodes rises, however the throughput of the suggested approach continuously rises. This demonstrates the suggested method's greater scalability and efficiency over a range of network sizes.

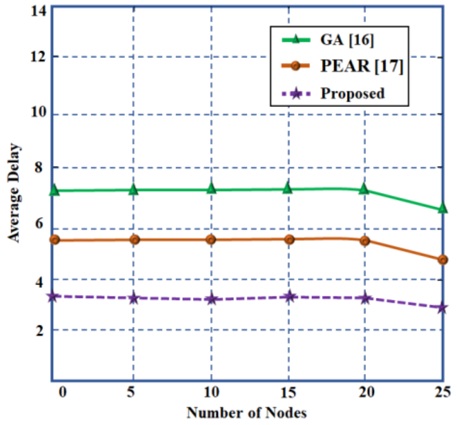

Figure 6: *Average Delay*

For all three approaches GA [16], PEAR [17], and the proposed method Figure 6 demonstrates that the average delay rises with the number of nodes. In contrast to GA and PEAR, the suggested approach consistently achieves a noticeably lower delay. This demonstrates to maintain effective data transmission even as the network's size grow. An improved routing efficiency of the suggested technique is shown in the decreased delay.

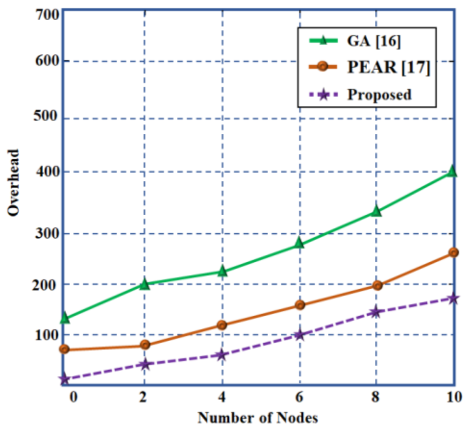

Figure 7: *Overhead*

Figure 7 illustrates that overhead for GA [16] and PEAR [17] rises as the No.of nodes increases, whereas overhead for suggested approach stays comparatively constant and lower. Because GA transmits more control packets than PEAR, it has the highest overhead. The suggested approach reduces routing overhead, resulting in improved scalability and efficiency.

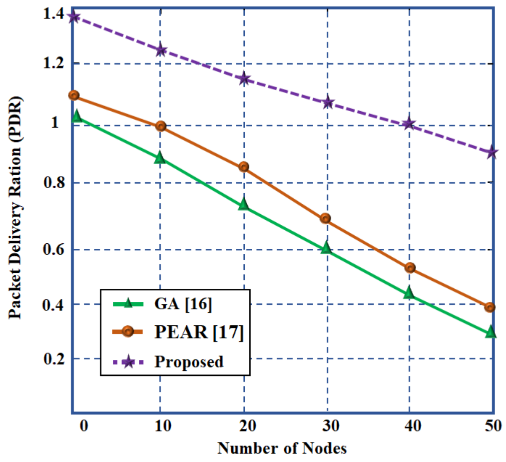

Figure 8: *Packet Delivery Ratio*

Figure 8 illustrates that the PDR marginally drops as the number of nodes rises. But when compared to GA [16] and PEAR [17], the suggested approach consistently yields the highest PDR. This shows how robust the suggested approach is at guaranteeing dependable data transfer. Better routing and less packet loss are highlighted by its exceptional PDR performance.

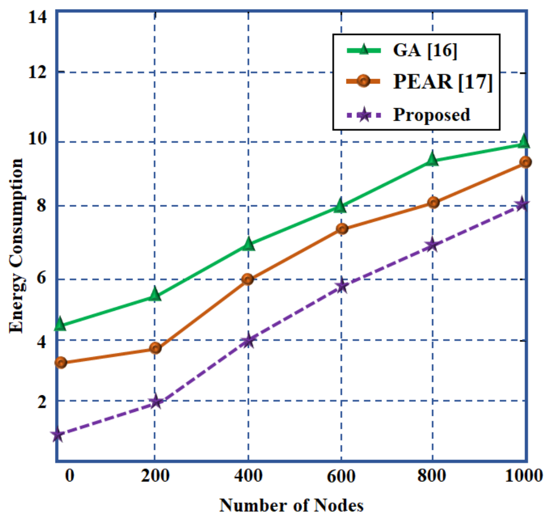

Figure 9: *Energy Consumption*

Figure 9 demonstrates that for all three approaches GA [16], PEAR [17] and the proposed method energy usage enhance as the No. of nodes increases. Nevertheless, all node counts, the suggested approach consistently shows the lowest energy consumption. This demonstrates how well it saves energy when transmitting data. The outcomes validate that the suggested approach is appropriate for network operations that use less energy.

5. Conclusion

In this research, an IoT-integrated smart grid architecture is proposed to enhance intelligent energy management and transmission efficiency. This system utilizes the FO algorithm to determine the shortest and most effective energy transmission paths, resulting in reduced energy losses and improved routing performance. By incorporating real-time monitoring through IoT-enabled sensors, the system dynamically captures operational data and adapts to changing load demands. This intelligent approach minimizes transmission delays, prevents overloading, and enhances the overall responsiveness of the grid. The combination of automation, smart communication, and efficient routing ensures a dependable, cost-effective, and environmentally sustainable power supply. Additionally, the architecture significantly reduces communication latency and system overhead. It also achieves a high PDR and throughput, confirming its robustness and reliability in data transmission. The reduced energy consumption further supports efficient and optimized grid operation. Overall, the proposed model addresses key challenges in modern smart grid systems and offers a scalable, reliable solution for future power networks.

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