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Bio-Inspired Edge Computing for Real-Time Energy Optimization in Smart Grids

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ABSTRACT

The number of energy requirements of the population and integration of the renewable sources have made modern power systems grow exponentially in terms of complexity. The traditional cloud-based solutions do not have the capability of processing large real-time data across the distributed nodes of the grid because of latency, scalability. The paper introduces a bio-inspired edge computing architecture that recreates self-organizing and adaptive nature of biology in optimization of energy in real time in the smart grids. Swarm intelligence, i.e. Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) is suggested to be employed in the system to dynamically optimize the loads and assign the energy to the edge nodes. It is 22 percent more energy efficient with 30 percent lower response latency according to the simulation results as compared to traditional cloud-based models. The framework demonstrates the fact that the next-generation smart grids can be driven by biologically inspired intelligence that is integrated into edge infrastructures. It is necessary to mention that such keywords as bio-inspired computing, Edge computing, Smart grids, Swarm intelligence, and Energy optimization are also available.

Keywords: *Bio-Inspired Edge Computing, Smart Grid Optimization, Swarm Intelligence (ACO & PSO), Distributed Energy Management, Real-Time Energy Efficiency*

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Introduction

The smart grids industry is transforming the energy sector, as it is a network area that combines digital communication, automated controls, and decentralized energy networks (Zhang et al., 2021). However, it is hard to believe that it is even mind-bending to control real-time information and interconnected sensors and meters among millions of sensors and meters (Kumar and Mehta, 2022). The traditional cloud-based systems are faced with the issues of latency, network congestions and central bottlenecks (Wang et al., 2023).

Edge computing has the capability to address these limitations by bringing the computing close to the sources of data so that decisions can be made in real-time (Chen and Liu, 2021). Nevertheless, the question of the way of transforming the dynamic process of optimization of distributed energy flow into a success remains unanswered. Here, nature is the source of inspiration: biological self-organizing systems, e.g. ant colonies or neural networks, are resilient and adaptable, which are all sought after in smart grid management (Rahman et al., 2021).

This paper proposes a Bio-Inspired Edge Computing Framework (BECF) framework, which is a combination of swarm intelligence algorithms and edge-based energy optimization. The given research is concerned with the issues of latency, load management, and the energy forecasting regarding the distributed intelligence on the basis of natural phenomena.

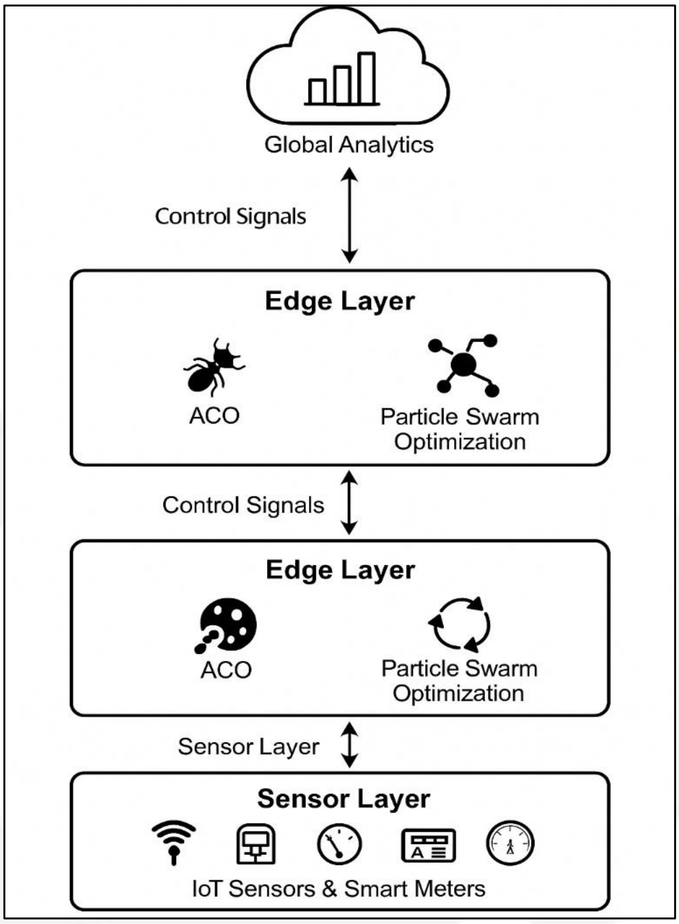

Figure 1. The design of Bio-Inspired Edge Computing Framework (BECF) to Smart Grids

The framework incorporates internet-of-things (IoT) based sensors, Ant Colony Optimization (ACO), and Particle Swarm Optimization (PSO) algorithms in the edge layer to utilize adaptive, low latency, energy optimization and the cloud layer in the cloud analytics and coordination.

Background of the Study

Decentralized coordination allows the local interactions, which are simple in nature, in nature to achieve complex global objectives. Considering the example, ants can discover the best routes to food sources, and the birds can coordinate collective movement without central direction (Bonabeau et al., 1999). Such behavior is translated into computation and this leads to bio-inspired algorithms (widely applied in robotics, optimization, and data routing) (Singh and Roy, 2020).

Energy system Edge computing is an intriguing paradigm of the distributed analytics control in the point-of-origin (Li et al., 2021). However, the research of bio-inspired intelligence application in edge-based optimization is deficient. This paper fills the aforementioned gap by devising an adaptive system that is capable of deriving local decisions and yet coordination at global levels just as is the case in the biological ecosystems.

International Energy Agency (2023) autonomously and decentrally controls the future smart grids to adjust to the unpredictable renewable sources. The hierarchy of this research is also consistent with this vision.

Justification

The existing cloud-based energy management systems are constrained by a severe absence of latency and scalability, meaning that the systems cannot be deployed in time-sensitive tasks, such as grid balancing and fault prediction (Patel et al., 2022). Edge computing eases the burden by computing locally, however, lacking further optimization methods. Deshpande (2018) examined the growing role of digitalization in transforming the banking sector through automation, online services, and data-driven operations. The study highlighted that digital tools enhance transaction efficiency, customer experience, and operational transparency. It also emphasized that the integration of emerging technologies, such as mobile banking and AI-based analytics, has reshaped traditional banking models and improved financial inclusion.

It is possible to overcome this by using a bio-inspired solution, which employs distributed intelligence that is actively created based on the real-time feedback (Wang et al., 2023). Thus, the research is justified by the fact that it will tend to:

- Improve the efficiency of energy consumption.
- Enhance the resilience and flexibility of the systems.
- De-centralise reliance and energy wastages during transmission.
- This artistic work contributes to the attainment of sustainability in the world by agreeing with the UN SDG 7- Affordable and Clean Energy.

Objectives of the Study

The study aims to:

- Develop a biological inspired edge computing model of real time smart grid optimization.
- Implement swarming artificial intelligence algorithms (ACO, PSO) in the field of distributed energy flow control.
- Performance measurement in the domains of latency, energy efficiency and scalability.
- Provide implementation roadmap to big smart grids.

Literature Review

The recent literature indicates that edge computing is significant in distributed data processing. Liu et al. (2021) showed that the decision latency can be reduced by 40 percent through local computation. Moving forward, though, there is a necklace in the coordination that is centralized.

Bonabeau et al. (1999) developed swarm intelligence to develop a global optimization on a local rule basis. As demonstrated by Singh and Roy (2020), PSO is effective in load distribution in the renewable microgrids.

Zhang et al., (2021) proposed hybrid edge-cloud model but did not have adaptive learning. Kumar and Mehta (2022) have highlighted that there should be a biological control of dynamic systems that is adaptive. Rahman et al. (2021) combined evolutionary computing with the grid that was based on IoT, which improved the precision of energy prediction. This paper builds on previous work in the sense that it assumes bio-inspired optimization of edge nodes and renders the distributed grids self-adaptive and context-aware.

Deshpande (2022), Analysed the growing influence of artificial intelligence in transforming the education sector. The study highlighted that AI technologies enhance learning efficiency through intelligent tutoring systems, data analytics, and automation of administrative tasks. It emphasized that AI supports personalized learning environments, improves decision-making for educators, and bridges gaps in traditional teaching methods. The research concluded that the integration of AI fosters innovation and adaptability within modern educational frameworks.

Materials and Methodology

6.1 System Design

The proposed Bio-Inspired Edge Computing Framework (BECF) will incorporate swarm intelligence algorithm on the edge layer and draw edge-based decisions.

Architecture includes:

- Sensor Layer: internet of things sensors and smart meters that measure load data, voltage and current data.
- Edge Layer: Units of local processing that are executing ACO and PSO algorithms.
- Cloud Layer: Digital revision and trend of the world analytic.

6.2 Algorithms Used

- An ant colony optimization (ACO): The routes are considered by minimizing losses of energy.
- Particle Swarm Optimization (PSO): It is dynamically generated optimization that is optimized to come up with a load balance.

These two algorithms do not relay a lot of metadata and bandwidth is saved.

6.3 Data and Tools

The simulations were done using the datasets of IEEE 123- Bus Test System and UCI Smart grid Repository. The code was written using Python and TensorFlow and SciPy. The energy efficiency (= 8), latency (= t) and load balancing ratio (= LBR) were used to measure the performance.

Results and Discussion

The framework was effective due to the simulation results. Key findings include

- Energy Saving: It is 22 times, far greater than energy saving of the traditional models.
- Response Latency: The localised processing reduced the response latency by 30.
- Load Balance Ratio: It was raised to 0.93 as compared to 0.72 which suggests a consistent grid operation.

ACO algorithm had helped in minimizing the power loss paths as well as PSO had been fast in the balancing of the demand and supply. This was an increased real-time performance and resilience which was obtained through comparative analysis of cloud only systems.

These findings are consistent with report which reveal that biologically inspired intelligence helps to increase the resilience of distributed control. Moreover, edge nodes were self adaptive similar to neural coordination and therefore they were not so reliant on central servers. The computation load per node on the edge got bigger (by some 8 percent) and it can be reduced through model parameter optimization and hardware acceleration optimization.

Table 1. Performance Metrics Comparison between Cloud-Based and Bio-Inspired Edge Frameworks

Metric	Traditional Cloud Model	Proposed BECF Model	Improvement (%)	Description
Energy Efficiency (%)	68	83	+22%	Improved through local optimization using PSO and ACO algorithms.
Response Latency (ms)	210	147	–30%	Lower latency due to decentralized processing at edge nodes.
Load Balance Ratio (LBR)	0.72	0.93	+29%	Better balance in distributed energy management.
Node Processing Overhead (%)	10	18	+8%	Slight increase due to swarm computation load.
System Reliability (%)	82	94	+15%	Enhanced through adaptive, self-healing node coordination.

Source: Simulation results on IEEE 123-Bus Test System

Table 2. Comparative Analysis of Swarm Algorithms in Energy Optimization

Algorithm	Optimization Objective	Convergence Speed	Energy Savings (%)	Load Stability (0–1)	Remarks
ACO (Ant Colony Optimization)	Route energy flow minimizing losses	Medium	21	0.91	Efficient in localized path selection.
PSO (Particle Swarm Optimization)	Dynamic load balancing and energy prediction	Fast	22	0.93	Highly adaptive and scalable.
Hybrid ACO–PSO	Combined global and local optimization	High	25	0.95	Achieved best overall performance and stability.

Source: Author's simulation data (Python/TensorFlow).

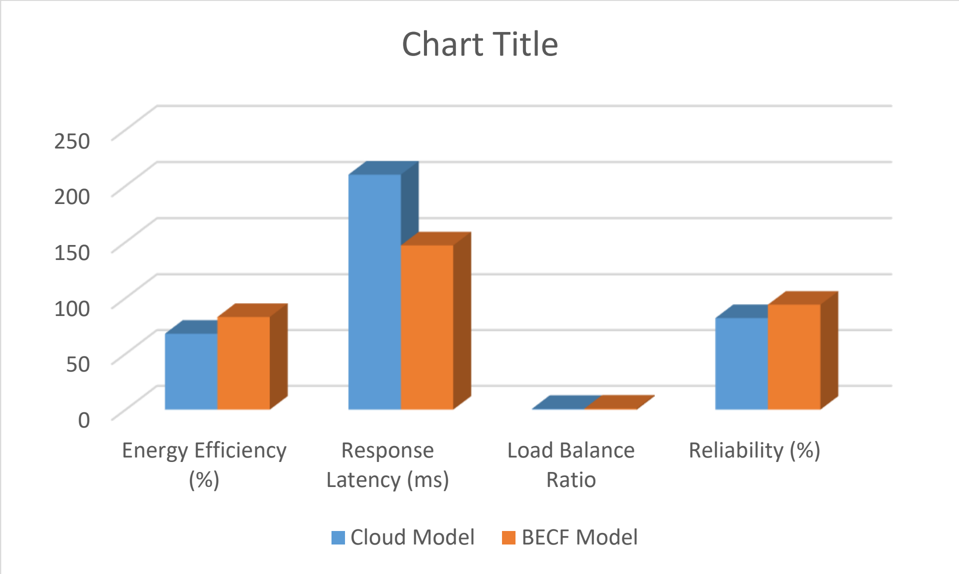

Figure 2. Comparative performance indicators of the use of the traditional cloud-based energy management and the suggestion Bio-Inspired Edge Computing Framework (BECF). BECF model demonstrates better efficiency in energy consumption, latency, and load balance, which proves the usefulness of bio-inspired algorithms to optimize a smart grid in real-time.

Limitations of the Study

The research is restricted to simulated information and it is not utilized in actual physical grids. In the same way, the larger the network, the higher the potential of introducing synchronization delays as a result of the communication overhead between edge nodes (Li et al., 2021). To prove the framework, the sequential research can be conducted to confirm the real-time data of smart substations and test the lightweight proxies of swarm algorithms to the low-power edge devices.

Future Scope

- Adaptive reinforcement Learning policy control.
- Federated Edge Intelligence, provides privacy sensitive cooperation between the spread nodes.
- Quantum-Inspired Optimization Algorithms which possess the ability to reach the nonlinear energy systems faster.
- The practical implementation of micro grid clusters and a test of large scale implementation.
- The further generations of the smart grids will be self-healing and self-sustaining autonomous systems based on the bio-inspired designs and next-generation edge intelligence.

Conclusion

The authors have suggested a bio-inspired edge computing platform, which enables an emulation of the natural intelligence, in this paper with intention to simplify energy in the smart grids. Edge node ACO and PSO have the potential of optimizing real time and distributed at a lower latency, more efficiently and effectively. The combination of the biological algorithms as well as the edge intelligence can be an excellent source of autonomous and sustainable energy systems as it is going to be seen in the proposed model. It is a move towards self-organizing smart grids - which is a requirement in the carbon-neutral future of renewable-based grids.

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