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Research Article

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Investigation of Multi-Agent System Control and Management of Power Distribution Systems

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Abstract: Modern power distribution networks' growing complexity calls for advanced control and management solutions to ensure reliability, efficiency, and resilience. This study investigates the application of Multi-Agent Systems (MAS) for the control and management of power distribution networks. MAS, characterized by decentralized, intelligent agents, offer a robust approach to handling dynamic and intricate power systems with minimal human offers intervention. This study investigates MAS models developed for key functionalities like fault detection, system reconfiguration, voltage regulation, reactive power management, and integration of distributed generation (DG). By leveraging the communication, coordination, and negotiation capabilities of agents, various models that are investigated facilitate real-time decision-making and adaptive responses to system disturbances. Simulations conducted on a prototype power distribution network, known as the Circuit of the Future, demonstrate the efficacy of MAS. This investigated models efficiently identified fault locations, executed optimal reconfiguration strategies, and maintained voltage levels within tolerance limits. Notably, the learning capabilities of agents enhanced system performance over time by enabling quick recall of past solutions, thereby reducing operational delays and computational effort. The results underscore the potential of MAS to revolutionize power distribution system management, offering a scalable and resilient solution to meet the demands of modern energy infrastructure. Future research will focus on further refining these models, improving scalability, integrating renewable energy sources, and developing comprehensive MAS frameworks to address all aspects of advanced power system management.

Keywords: Control, Multi-Agent, Management, Power Distribution, Systems

1. Introduction

An agent denotes a computerized entity situated within an environment, capable of autonomously operating within that environment to achieve its specified objectives. This method improves the dependability and effectiveness of distribution operations [1]. A multi-agent system (MAS) is designed to accomplish diverse objectives in accordance with a specified framework of rules and regulations. A MAS is a framework in which a group of agents cooperates, communicates, and synchronizes their actions to achieve specified goals. Self-coordination refers to the method by which the system's agents independently collaborate to attain the objective of resource conservation. Communication is a crucial component of MAS. The core tenets of communication and self-organization remain intact from their initial formulations. An agent is a computer system located in a defined context, capable of independent activities to fulfill its designated goals [2,3]. Subsequent definitions encompass the aggregation of agents to attain objectives and their adaptability to the environment [4]. An agent may be a real or virtual creature capable of acting, perceiving its environment (however partially), and communicating with others. It is autonomous and possesses the abilities necessary to accomplish its objectives and inclinations. A MAS comprises an environment, objects, and agents (with agents being the sole actors), interrelations among all entities, a collection of operations executable by the entities, and the temporal alterations of the universe resulting from these actions. Agents must possess the ability to engage, negotiate, and coordinate to attain a shared objective and are characterized as intelligent entities endowed with social skills that enable them to solve problems [5]. The notion of an agent has been widely utilized in the social sciences as a substitute for mathematical models. In the domain of energy optimization within buildings, the capacity to model social behaviors is a crucial tool for assessing whether the established goal (such as minimizing energy consumption) within a defined framework (including economic constraints and non-intrusive methods) affects user comfort (sustaining preferred levels of lighting, heating, cooling, and ventilation). However, the MAS has developed to encompass more than merely serving as model scenarios. The agents' talents have been refined on the notion and advancement of the MAS have progressed [6] provided a solution created by the agent community researchers to enhance the learning capabilities of belief-desire-intention (BDI) agent architectures (deliberative). They utilized case-based reasoning (CBR) methods to assist agents in problem-solving, facilitating adaptation to environmental changes and the identification of novel potential solutions [6]. Propose an agent-based architecture that leverages the benefits of cloud computing platforms to address the unresolved challenges inside the learning object paradigm. Equipping agents with learning capabilities has allowed MAS to participate in various scenarios, including various configurations of illumination, thermal regulation, air conditioning, or ventilation inside a smart building (IB). This encompasses autonomous decision-making, adaptation to novel circumstances, learning from previous mistakes (such as modifying temperature settings for optimal energy efficiency despite user alterations), task programming, and forecasting future scenarios. The framework of multiple agent systems (MAS) offers extensive opportunities in the domain of building control. The MAS arose as a solution to challenges in distributed artificial intelligence. MAS facilitates the simulation of human organizational behaviors and interactions by deconstructing issues into manageable elements [7,8]. Contend that this facilitates the establishment of a more natural mechanism for problem resolution, a desirable asset as contemporary systems becomes increasingly complicated and equipment proliferates. An organizational structure of agents simulates human interaction by designating certain duties to agents and providing them sufficient autonomy to execute those tasks efficiently. The primary aim is to deconstruct an issue to facilitate autonomous action by each actor and their interaction with other agents. Conversely, supervisory control systems have a dispersed hierarchy. Distributed power systems refer to the generation and distribution of electricity from many sources. It entails the management and regulation of power generation, storage, and distribution across multiple locations. This methodology enhances the dependability, efficiency, and resilience of the electricity system. It is an innovative method to address the increasing energy demands while incorporating renewable energy sources. The control system manages the power flow between the distributed power system and the primary distribution system. It manages the disconnection and reconnection procedure, enables market involvement, and simplifies the use of heat for local installations. The control system must possess black-start functionality during islanded mode operation. The primary responsibilities of energy management in distributed power systems include forecasting electrical load and heat demand, predicting renewable energy production capabilities, coordinating generation schedules, performing emissions evaluations, executing demand-side strategies, and assessing system security. The control and management function of the electricity distribution system fundamentally relies on the operational mode [9]. The multi-agent system methodology offers numerous advantages compared to conventional methods for the control and administration of distributed power systems [10]. A multi-agent system improves overall performance, particularly in computing efficiency, dependability, extensibility, maintainability, adaptability, and resilience. Numerous techniques exist in the literature for the construction of multi-agent systems [11]. However, their underlying principles are frequently analogous. Design strategies have evolved for the specifications and design of multi-agent systems by enhancing or expanding standard Software engineering and knowledge engineering methodologies. For instance, MAS-CommonKADS was used in [12]. The authors augmented methodology of the CommonKADS knowledge engineering framework, derived from object-oriented paradigms in their work.

Furthermore, several techniques, suggestions, and tools [13] exist for the design and execution of multi-agent systems in power system engineering.

2. Materials and Methods

Software Integration for Multi-Agent System Implementation

This research utilized JADE and Matlab as core software tools to model and implement the multi-agent system (MAS) for fault detection and reconfiguration in power distribution systems. JADE, a flexible framework for building MAS applications, was employed to implement agents tasked with fault detection. Matlab, a high-performance computing platform, handled the reconfiguration processes, including optimization and simulation. DEW (Distribution Engineering Workstation) was used to model the power distribution system, as it supports three-phase system modeling and unbalanced power flow analysis, which are crucial for realistic power system simulations. To integrate these tools, a data exchange method was developed, where DEW outputs power flow results to a text file. This file served as an interface, allowing JADE and Matlab to access and process the data. The agents used this information to make decisions about fault detection and reconfiguration, enabling seamless communication between the MAS and the power system model. This approach ensured a practical and effective integration of power system analysis with agent-based applications, enhancing system reliability and fault management efficiency.

Mathematical framework for multi-agent systems

The foundation of this research is based on the mathematical framework for multi-agent systems (MFS), which precedes the software implementation phase. A novel algorithm for fault detection and reconfiguration was developed using graph theory, a robust tool for modeling and analyzing networked systems. In this model, the power distribution network is represented as a graph, where nodes represent components like substations and transformers, and edges represent power lines. Graph traversal techniques are employed to detect faults by analyzing the network's connectivity and power flow patterns, allowing for the rapid isolation of the affected section with minimal disruption. Additionally, the algorithm determines optimal reconfiguration strategies to restore power to as many loads as possible, rerouting power through alternative paths in the network while ensuring system balance and reliability.

Graph theory application in power systems

Graph theory provides a structured representation of the power distribution system, facilitating the application of advanced algorithms for fault detection and network reconfiguration. The power grid's graph-based representation enables efficient analysis of relationships and interactions between components. Fault detection leverages graph traversal techniques to locate and isolate faults, while reconfiguration strategies use graph optimization methods to determine alternate power flow paths. This structured approach enhances system reliability by ensuring that faults are managed dynamically and efficiently. The proposed mathematical model integrates seamlessly with JADE and Matlab, enabling real-time monitoring and management of fault scenarios.

Simulation and validation

The algorithms for fault identification and reconfiguration were evaluated in simulated scenarios to validate their performance. A detailed illustration of a fault scenario demonstrated the practical application of the proposed approach. Execution times averaged 22.4 milliseconds for fault detection and 14.5 seconds for reconfiguration, highlighting the efficiency of the system. Voltage profiles remained within tolerance limits, confirming the robustness of the solution.

3. Results and Discussions

The new fault detection and reconfiguration algorithms underwent testing across diverse scenarios. Fault detection simulations were conducted using JADE, and reconfiguration tests were performed using Matlab. The results from both simulations were then integrated Utilizing DEW for power system simulation, the outcomes were evaluated for adherence to voltage norms. Figure 1 illustrates a comprehensive model for the deployment of Multi-Agent Systems (MAS) in power distribution systems. The proposed MAS architecture is seen in Figure 2. This architecture comprises Load Agents (LAGs), each designated for a certain Load and Switch Agents (SAGs) associated with each switch or disconnector in the system.

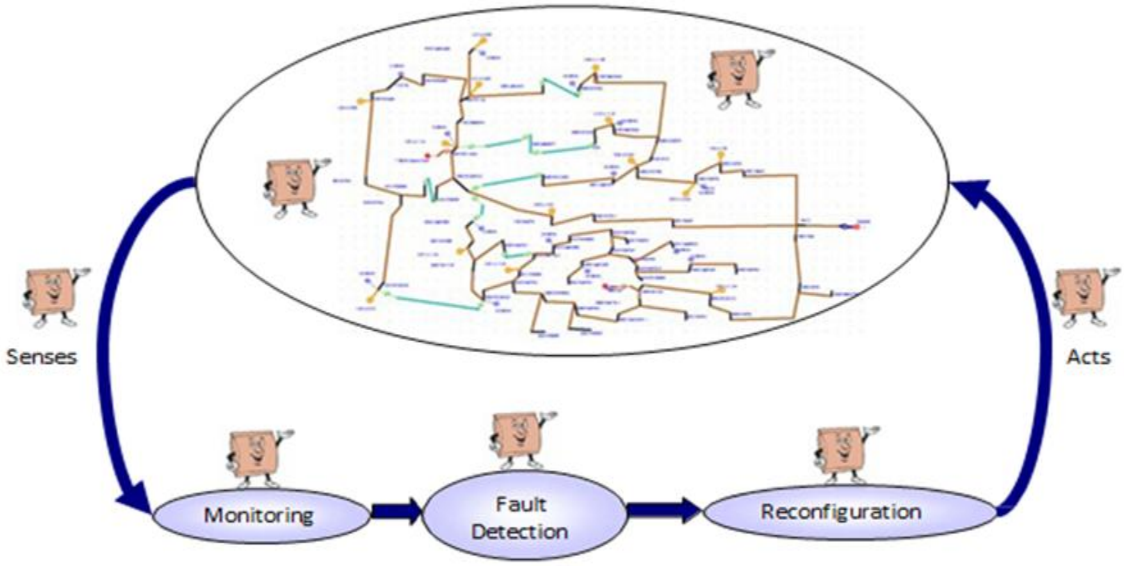

Figure 1: Generic model of the MAS application in P D S.

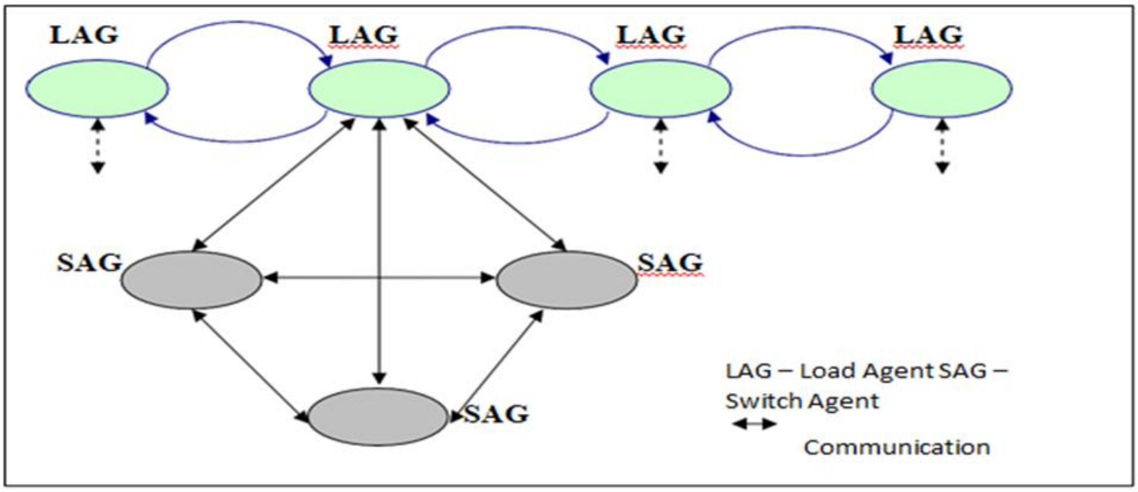

Figure 2: Architecture of the Proposed MAS

Circuit of the Future

Simulations were executed on a prototype power distribution system referred to as the Circuit of the Future (CoF), created by Southern California Edison (SCE). The CoF, represented in DEW, is depicted in Figure 3. The Circuit of the Future (CoF) comprises a singular substation with three primary feeders, interconnected to facilitate adaptable power flow re-routing via seven typically open switches/disconnectors. This circuit accommodates 14 loads with a cumulative real power need of 24 MW and a reactive power requirement of 12.96 MVar. Furthermore, it has 14 capacitor banks for reactive power support and two distributed generators (DGs), one providing real power and the other supplying reactive power. The simulations concentrate exclusively on active power flow, as the capacitor banks adequately satisfy the system's reactive power demands and losses. To streamline the simulation, the original circuit is modified by consolidating specific loads. This adjustment does not affect the seven switching sites nor change the original system structure.

The revised Circuit of the Future (CoF) comprises 11 loads, 7 switches, 18 nodes, a substation, and a distributed generation source that supplies real electricity. The power factor of the system is presumed to be 0.85, utilized for calculating the true power capacity of the distribution network. The distribution system is classified as a radial system in every configuration. To accommodate high-priority loads during power shortages, three loads (L3, L8, and L11) are classified as high priority, whereas two loads (L7 and L10) are classified as low priority. The residual loads are designated medium priority.

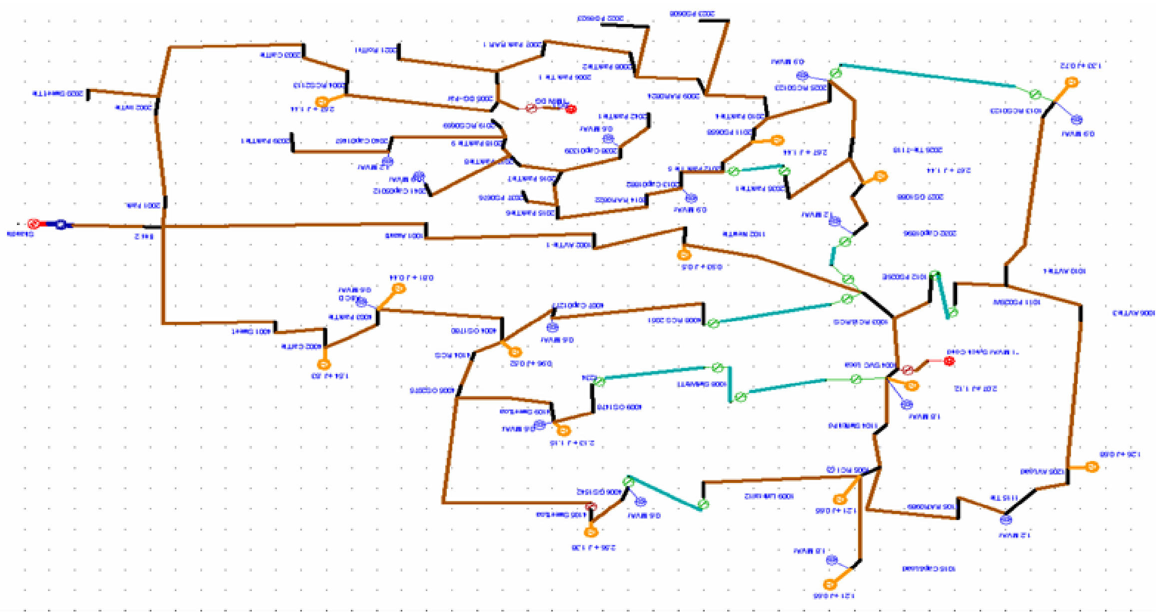

Figure 3: The Circuit of the Future modeled in DEW

JADE Fault Detection Simulation

The simulation for JADE fault detection commenced with the creation of JADE agents, utilizing the text file produced by DEW following the execution of the load flow application.

Test Case 1: For a singular fault

We shall examine the system for a defect in line N1N2 within Feeder 1, when the JADE MAS operates, the load agents collaborate to pinpoint the fault location, with the message exchange between agents visibly depicted in the JADE Sniffer agent GUI as shown in Figure 4.

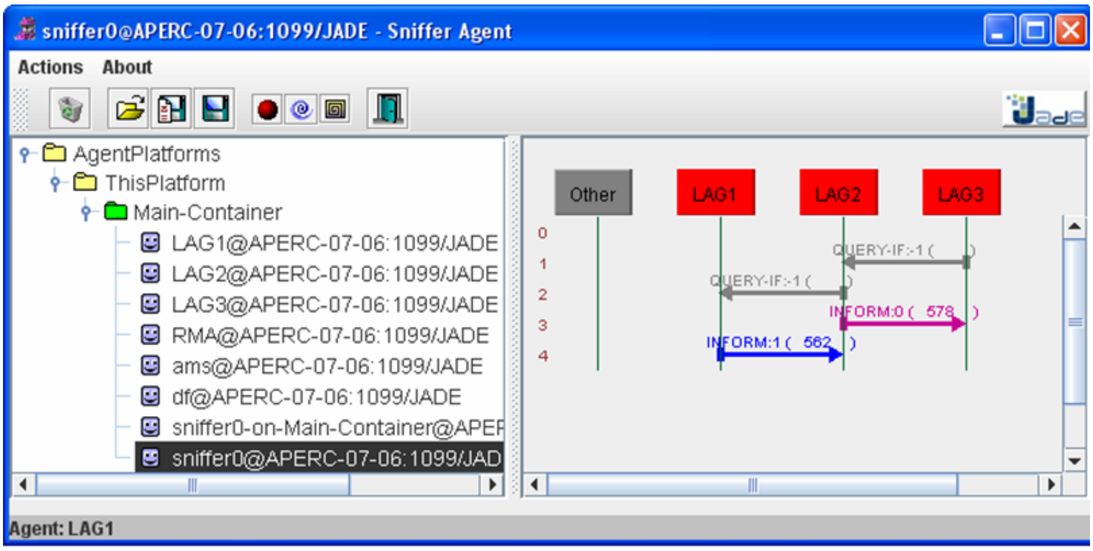

Figure 4: JADE Message Passing to Identify the Fault Location for a Single Fault in N_1N_2

All LAGs are established within the designated feeder. Only LAGs that detect no power flow will issue a request message to their incoming adjacent agents, inquiring whether their loads are supplied, and thereafter await a response. In this situation, none of the three LAGs are supplying power to their loads because of the problem at N1N2. As a result, the LAGs that obtain the request message will to the sender together with their flow values. Given that all LAGs indicate zero flows, the fault site may be accurately determined. Should a fault transpire at N2N3, LAG3 and LAG2 will experience a loss of power supply to their respective loads. They will next engage in communication with their adjacent LAGs, LAG2 and LAG1, respectively. In this scenario, LAG2 will indicate 'zero', whereas LAG1 will disclose its true non-zero power flow. This procedure facilitates the identification of the fault location as the segment between LAG1 and LAG2, particularly the N2N3 link.

Test Case 2: For Multiple Faults

To test a scenario with multiple faults, assume there are faults at N2 N3, N1 N5, and N13N15 across all three feeders. This scenario was simulated using the JADE fault detection program, and the communication between the LAGs is illustrated in the Figure 5 and Figure 6.

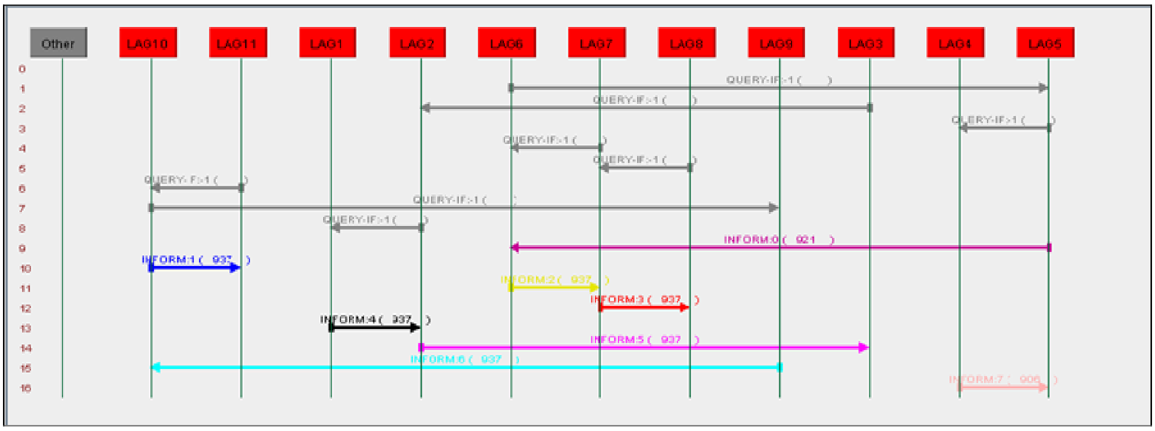

Figure 5: Sniffer Agent GUI for Multiple Fault Scenarios

The locations of the faults are provided in the Java console as follows.

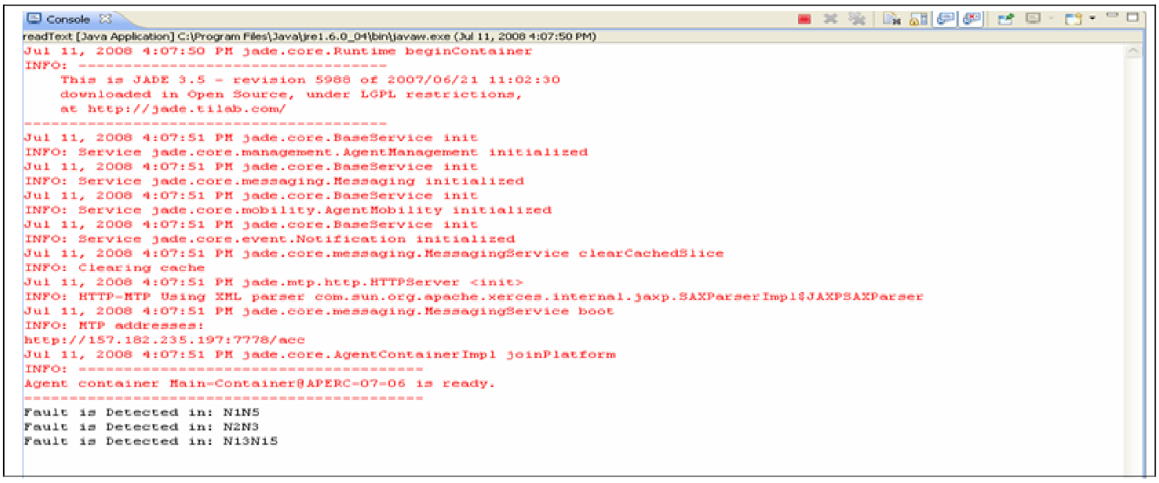

Figure 6: Display Interface of the Resolution for Test Case 2

The simulation and results for the application of a Multi-Agent System (MAS) in the control and management of power distribution systems demonstrate significant promise. The MAS models developed and tested for various functionalities, such as fault detection, system reconfiguration, voltage regulation, and reactive power management, showcase the potential of MAS to enhance the efficiency, reliability, and resilience of power distribution networks.

4. Conclusion

This research presents multi-agent system (MAS) models for problem detection and reconfiguration in a prototype power distribution circuit, developed for the "Circuit of the Future." The system, consisting of three feeders, various loads, and switches, utilizes a graph theory-based mathematical model to regulate switching operations, guaranteeing an uninterrupted power supply during breakdowns. Load agents and switch agents function in a decentralized fashion, utilizing local information for communication, coordination, and decision-making. The fault detection model, executed in JADE, locates faults, while the reconfiguration model, created in MATLAB, discovers optimal switching operations to sustain power to the maximum number of loads. Simulations of diverse failure scenarios revealed the system's efficacy, with an average fault detection time of 22.4 milliseconds and a reconfiguration time of 14.5 seconds. Critical failures, such as those in line N1N2, can diminish load supply by 12.24%; however, this issue could be alleviated by augmenting line capacity. Voltage profiles consistently adhered to tolerance limits in all evaluated circumstances, highlighting the system's reliability and its potential to enhance MAS applications in power distribution.

5. Recommendation

The examination of multi-agent systems (MAS) for the regulation and administration of contemporary power distribution networks is an essential study domain that tackles significant issues and enhances energy management technologies. Existing studies usually assume that distribution systems have a radial topology. However, in the real world, networks often have looped or other complicated configurations, especially in cities or places with distributed generation (DG). This means that models need to be able to handle these issues for better operational efficiency. The development of multi-agent systems (MAS) for voltage management is essential, as sustaining voltage stability is vital for ensuring power quality and averting system failure. Incorporating learning processes into multi-agent systems boosts their efficiency, allowing agents to utilize past experiences to resolve reoccurring problems swiftly and effectively. A comprehensive method that integrates functionalities including defect detection, system reconfiguration, voltage regulation, and reactive power manage distributed generation integration, and protection coordination into a cohesive framework would markedly enhance system dependability, flexibility, and efficiency. By tackling these difficulties, MAS research corresponds with smart grid progress and digital transformation, providing scalable, resilient, and sustainable solutions for future energy systems, thus representing a significant domain for both academic innovation and practical implementation.

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Conflict of interest: The authors declare that they do not have any conflict of interest.

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