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Original Article

Integrating Multi-Agent System Control in Hybrid Microgrid System for Energy Management System

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***Abstract** - Microgrids are decentralized power systems installed at customer locations, featuring a range of generating units and operational modes. These systems are designed to meet the specific energy requirements of users while also supplying surplus power back to the main grid. Often incorporating Renewable Energy Sources (RES) such as solar PV cells, wind generators, and batteries, microgrids are valued for their compact size and flexible configurations. To maintain stable operation across these diverse energy sources, a Multi-Agent System (MAS) is utilized. This MAS is tailored for modeling and autonomous decision-making. The study focuses on a microgrid equipped with wind power, solar PV power, battery, and a local electrical load, collectively forming the Hybrid Microgrid System (HMGS). The simulation is developed using the Java Agent Development Environment (JADE), which facilitates effective management of the system's varied components. The primary goal of this study is to assess the performance and reliability of the HMGS, with a particular focus on the role of the MAS in managing the complex interactions between different power sources to ensure sustainable and efficient operation.*

***Keywords** - Energy management system, Hybrid microgrid system, Java agent development framework, Multi-agent control system, Solar power, Wind power.*

1. Introduction

Microgrids are compact power systems designed to deliver a stable electricity supply to a limited number of users. They consist of various local and distributed generation sources, consumption equipment, storage systems, and a control and monitoring centre. To maintain energy balance and ensure reliability, the microgrid must carefully manage the relationship between energy consumption and production [1-4]. In a hybrid power system, microgrids primarily leverage renewable energy sources to generate high-quality electricity. They can operate either connected to the main grid (grid-connected mode) or independently (island mode). In [5], the authors applied the Teaching-Learning-Based Optimization (TLBO) technique to address the challenge of minimizing the Total Operating Cost (TOC) of the microgrid.

In [6], the authors proposed a microgrid model incorporating an Energy Management System (EMS) based on Predictive Control. This EMS plays a crucial role in optimizing the microgrid's operation, ensuring efficient energy utilization and grid stability. This model incorporates Photovoltaic (PV) panels and battery storage technology, with the EMS designed to ensure stable and optimal generation from multiple sources within the microgrid. To enhance stability under varying load and voltage conditions, adaptive fuzzy logic and PI controllers have been suggested as effective solutions [7]. For islanded operations, several cooperative control strategies have been proposed, including direct control vector and droop control methods [8]. Additionally, Smart Microgrid (SMG) systems now utilize rule-based EMS to effectively monitor and manage real power flow [9]. In the context of AC/DC microgrids with batteries and Renewable Energy Sources (RES), the EMS plays a critical role in maintaining energy stability [10].

The authors outlined a Photovoltaic (PV) microgrid featuring a hybrid energy storage system that combines batteries and super capacitors [11]. This microgrid is designed to operate both in grid-connected and standalone modes. To ensure optimal performance and stability, a coordinated control-based energy management system is implemented. This system regulates the DC link voltage and maintains voltage and frequency balance at the PCC. Inverter control employs the D-Q reference frame technique, while DC link voltage regulation is achieved through a dual-loop PI controller. Despite these advancements, challenges remain, notably the lack of runtime adaptation and communication overhead. To tackle these issues, the microgrid monitoring

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protocol must incorporate self-regulating systems and efficient communication mechanisms. One proposed solution is the Multi-Agent System (MAS), initially introduced by Bogaraj and Kanakaraj [12]. This approach allows software agents to collaborate on complex problems that are beyond the capability of a single agent. An intelligent MAS approach is recommended for implementing distributed energy management algorithms and control strategies in smart microgrids to meet various real-time objectives.

To reduce peak demand and electricity costs, [13] proposed a model for a Micro-grid Energy Management System (EMS) that integrates distributed storage and disaster recovery techniques. The study highlighted that the decentralized Multi-Agent System (MAS) algorithm could minimize power inequality costs while considering client preferences in decision-making [14]. To address Real-Time Management (RTM) challenges in smart grid systems, [15] employed a communications system linking power management with the electrical power system.

A smart grid design incorporating dynamic energy management and a Multi-Agent System (MAS) implemented in the JADE platform was presented in [16]. This innovative approach aimed to enhance distributed energy management specifically for solar microgrids. The MAS coordination approach was further applied in [17] to manage demand-side control and distributed energy management in solar microgrids. Additionally, [18] proposed a multi-agent system using the JADE environment as an intelligent agent-based control system for hybrid microgrids. The agents within the system work together and exchange information to achieve the desired energy management goals.

This work is primarily focused on developing and implementing real-time intelligent control for microgrids. The paper is structured as follows: Section 2 introduces hybrid microgrids, Section 3 provides a detailed description of MAS, and Section 4 presents the proposed methodology. Section 5 presents the case study and simulation results. Finally, Section 6 concludes the work.

2. Solar PV and Wind Generator Based Microgrid

Hybrid microgrids are innovative energy systems that combine renewable energy sources, like solar and wind power, with energy storage solutions, such as batteries. Cutting-edge energy systems that integrate renewable sources like solar and wind with energy storage, such as batteries. These systems can operate both connected to and disconnected from the main grid, offering enhanced flexibility and reliability. By employing intelligent technologies like Multi-Agent System (MAS), microgrids optimize local power distribution, adapt to changing conditions, and prioritize sustainability.

This approach presents a robust and efficient alternative to traditional centralized power systems. The Line diagram of the hybrid micro control system is shown in Figure 1.

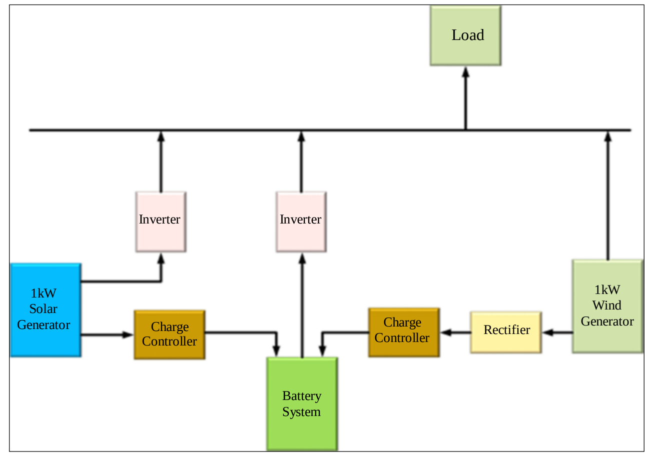

Fig. 1 Line diagram of hybrid micro control system

3. Multi-Agent System Technology

A Multi-Agent System (MAS) achieves its collective objectives through the coordination of intelligent agents, each representing a component within a microgrid. These agents possess a range of capabilities, including proactive, reactive, and social skills, which are supported by an Agent Communication Language (ACL) [19, 20].

They operate autonomously, swiftly adapting to changes in their environment, taking independent, goal-oriented actions, and interacting effectively with both humans and other agents. Intelligent agents are distinguished by their autonomy, reactivity, proactivity, social skills, environmental data collection, well-defined communication protocols, and collaborative nature.

In the field of electrical power system engineering, MAS has gained significant prominence over the past decade, finding applications in various scenarios. The comprehensive application of MAS in power systems is thoroughly discussed in [21], where the authors explore the principles, approaches, technical deliberations, and potential benefits.

4. Proposed Methodology

4.1. Problem Formulation

Hybrid microgrids continuously monitor solar, wind power, load, and battery levels every hour. Considering the variable nature of the load, solar PV, and wind energy, an intelligent agent evaluates all potential actions to optimize energy management. This approach aims to enhance operational efficiency, leading to economic and environmental benefits in advanced, dynamic hybrid microgrids.

4.2. JADE Architecture

JADE is a software platform specifically designed for creating Multi-Agent System (MAS) in Java. It offers a comprehensive suite of libraries and tools for building, implementing, and managing these systems [22-26]. Key features of JADE include:

Agent Communication: JADE offers a robust communication infrastructure that supports various protocols, enabling agents to interact with one another and respond to incoming messages.

Agent Behaviors: Developers can define agent behaviors through a system known as "behaviors" These represent the tasks or activities that agents can perform and can be programmed to react to events or stimuli.

Agent Mobility: JADE supports mobile agents, allowing them to move across different platforms and environments, thus enabling dynamic and flexible Multi-Agent System.

Agent Platform: JADE provides a runtime platform where agents operate, managing their lifecycle, communication, and resource allocation. This platform allows multiple agents to function concurrently, facilitating coordination and cooperation.

Agent Directory Service: JADE features a yellow pages service for agents to advertise their capabilities and discover other agents' services, promoting dynamic agent discovery and collaboration.

FIPA Compliance: JADE adheres to the standards set by the Foundation for Intelligent Physical Agents (FIPA), ensuring interoperability with other FIPA-compliant systems.

Security: JADE incorporates basic security features, allowing for the configuration of authentication and encryption to secure agent communications.

Development Tools: JADE includes a suite of development tools, including a graphical environment for monitoring and managing agents during runtime.

To work with JADE, developers typically define agent classes, behaviors, and communication protocols. JADE's runtime environment manages agent interactions and provides a solid foundation for constructing complex Multi-Agent System. The control architecture of JADE is illustrated in Figure 2.

4.3. JADE Operating Environment

JADE is a pivotal component in implementing the proposed agent-based system. This open-source framework, built on the Java programming language, is meticulously designed to support a diverse range of Multi-Agent System.

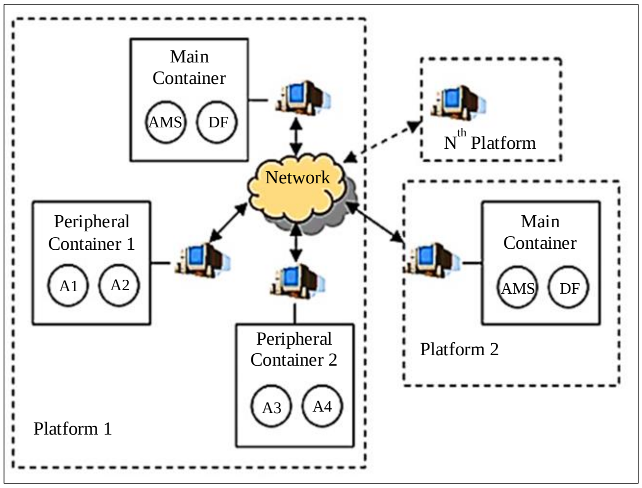

Fig. 2 The control architecture of JADE

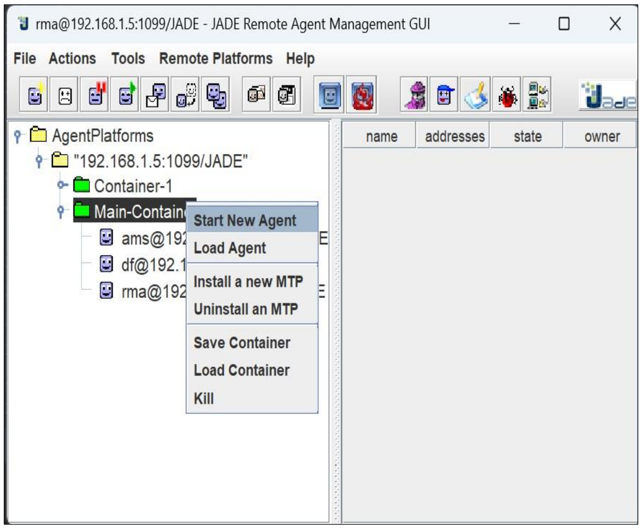

Fig. 3 Snapshot of JADE working environment

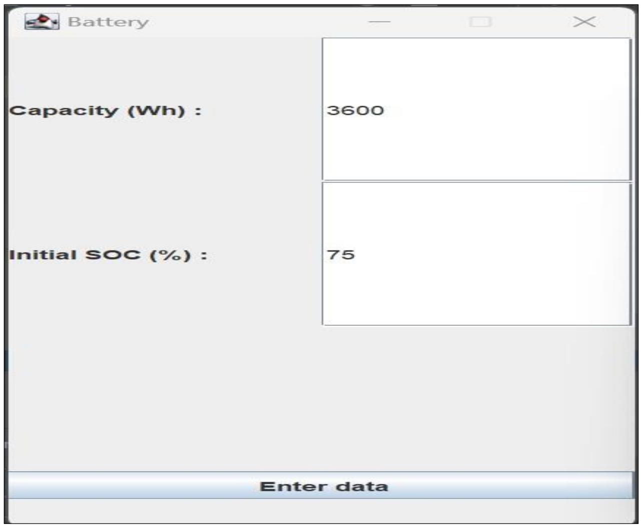

Fig. 4 Snapshot of battery agent GUI

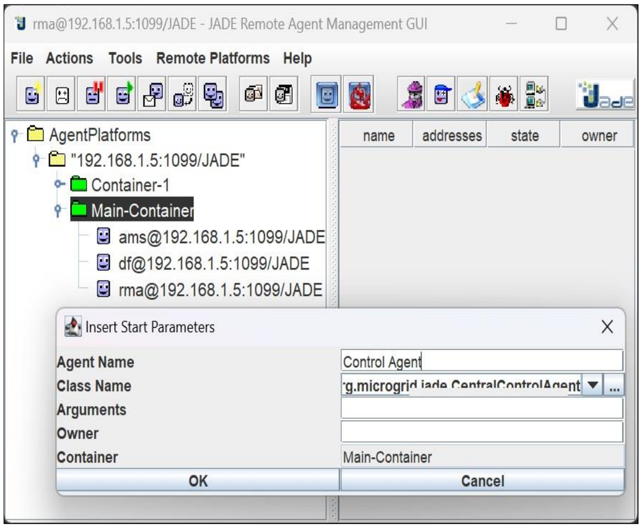

Fig. 5 Snapshot of control agent GUI

JADE utilizes a peer-to-peer architecture that facilitates the equitable distribution of intelligence, initiative, information, resources, and directives across various hosts and devices, whether on wired or wireless networks.

Each agent within this system is equipped to engage in advanced peer-to-peer negotiation and communication, actively seeking mutually beneficial solutions to complex problems [27-32]. Snapshots of the JADE working environment, battery agent GUI and control agent GUI are shown in Figures 3, 4, and 5, respectively.

5. Simulation Results and Discussion

This paper presents a hybrid microgrid system consisting of a wind turbine (1.5 kW), a solar PV (1 kW) system, a localized load, and a battery bank (24 V, 150 AH). The system is installed on the EEE department's rooftop, and the EEE Power System Research Laboratory is equipped with measuring tools, control systems, and sensors. The microgrid provides power to connected loads in rooms Nos. 303, 304, and 305. Figure 6 illustrates the microgrid control scheme. Sensors meticulously track solar and wind energy, as well as wire loads, every hour. Using hourly data on solar PV power, wind energy, load, and State of Charge (SOC) of battery, the agent autonomously determines the optimal energy distribution strategy for the distributed hybrid microgrid. MAS in a JADE environment represents the agents described below:

Load Agent (LA): The LA, queries the Directory Facilitator for power distribution options and contacts the generating agent based on the required electricity.

Solar Agent (SA): The SA represents the solar PV panels that generate power.

Wind Agent (WA): The WA represents the wind generator that generates electricity.

Battery Agent (BA): The BA tracks the battery's charge level, communicates with other agents, and determines power supply and demand.

Control Agent (CA): The CA manages, arranges, mediates conflicts, and executes power swaps among the microgrids. Figure 7 shows the agent relationship map.

Figure 8 is a comprehensive flowchart of potential microgrid applications.

The operational procedure involves the following steps:

Power Request: The SA sends an ACL message to the LA requesting power. If there is excess electricity, it is given to the BA.

Power Procurement Sequence: If electricity is not available from the SA, the LA contacts the WA to determine available power.

Battery Charge Utilization: If power is still required, the LA checks if the BA is fully charged before using it.

Optimal Energy Management: Every hour, the agent selects the most effective energy management strategy based on load requirements and the availability of solar and wind energy.

The JADE platform's multi-agent system dynamically balances energy from solar and wind sources to optimize power distribution in the hybrid microgrid.

5.1. Case Study

For a whole day, the hybrid microgrids were run nonstop, handling every case that the flowchart described. Each of the seven agents in charge of overseeing hybrid microgrids that blended solar and wind power was meticulously programmed using the JADE framework.

The IntelliJ IDEA environment was used to execute the agents. We analyzed agent interactions and transaction data in various situations using sniffer diagrams and console output. Figure 9 illustrates a snapshot of the information transfer between a sniffer agent and a regular agent in a specific scenario. The output window from the command prompt is shown in Figure 10. The console output for a day is given in Table 1.

This case study examines the energy complexity of solar PV power, wind energy, battery, and load for the microgrid at 10:00 AM. The following sequence of operations occurred:

1. The microgrid requires 1200 W of load. However, the total power generated is only 1100 W, with 350 W from wind and 750 W from solar. This results in a 100 W power deficit.
2. In this case, there is a 100 W load deficiency.
3. The Microgrid's batteries are used to supply the extra electricity.
4. The control agent determines the batteries' State of Charge (SoC) and discharges them after drawing the necessary power from the Microgrid.
5. Here, discharging caused the battery's SoC to drop from 72.21822 to 70.72602.
6. If the batteries, as in this case, approach dead storage charge, the control agent ceases discharging.

5.2. Comparative Analysis

This section compares the proposed model with existing state-of-the-art techniques for microgrid energy management using MAS. Table 2 presents the comparison results. Previous research on microgrid energy management has focused on various approaches. For instance, Foo Y.S. Eddy et al. suggested distributed control, or a multi-agent system, for optimizing microgrids [33]. They utilized the NTU microgrid architecture, consisting of a 12-kW load, 10 kW wind, and 5 kW solar. T. Srikanth et al. introduced a centralized SCADA System with Distributed Control Systems for microgrid management [34]. Fengji Luo et al. suggested a distributed control framework for microgrid operation based on Multi-Agent System [35]. Ziqi Shen et al. developed the SACDA platform, a microgrid architecture with information exchange and data services [36]. Roberto Netto et al. proposed integrating energy management with the electrical grid using a telecommunications system [15].

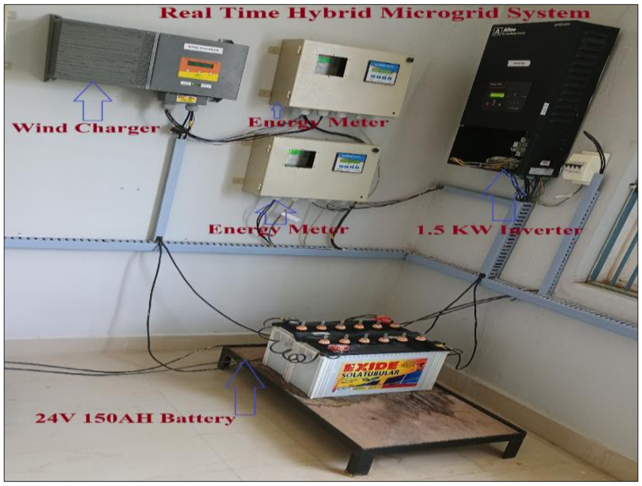

Fig. 6 The micro-grid control scheme

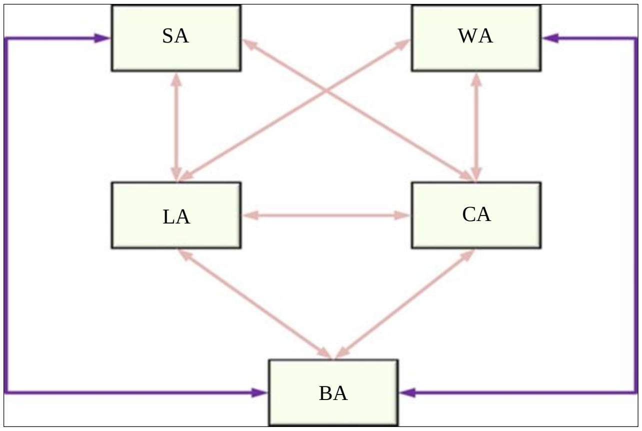

Fig. 7 The agent's relationship map

Table 1. Microgrid operation and control with MAS for a day

Time	Micro Grid Load	Total Generation	Solar Power	Wind Power	Micro Grid Credit (Watts)	Micro Grid Debit (Watts)	Battery SOC	Battery state
0	180	120	0	120		-60.0	75.000	discharge
1	180	180	0	180	0.0	-	74.1071	discharge
2	180	250	0	250	70.0	-	74.1071	charge
3	180	160	0	160	-	-20.0	75.0538	discharge
4	180	90	0	90	-	-90.0	74.7562	discharge
5	180	60	0	60	-	-120.0	73.4166	discharge
6	180	120	50	70	-	-60.0	71.6281	discharge
7	300	380	260	120	80.0	-	70.7322	charge
8	700	720	520	200	20.0	-	71.8128	charge
9	900	910	670	240	10.0	-	72.0830	charge
10	1200	1100	750	350	-	-100.0	72.2182	discharge
11	1150	1350	800	550	200.0	-	70.7260	charge
12	1200	1240	830	410	40.0	-	73.4274	charge
13	900	1170	860	310	270.0	-	73.9682	charge

14	900	1100	880	220	200.0	-	77.6195	charge
15	1200	1200	910	290	0.0	---	80.3275	charge
16	1150	1230	880	350	80.0	-	80.3275	charge
17	900	750	230	520		-150.0	81.4116	discharge
18	450	710	50	660	260.0	-	79.1919	charge
19	400	420	0	420	20.0	-	82.7141	charge
20	180	310	0	310	130.0	-	82.9853	charge
21	180	200	0	200	20.0	-	84.7484	charge
22	180	120	0	120	-	-60.0	85.0197	discharge
23	180	110	0	110	-	-70.0	84.1343	discharge

Table 2. Comparative analysis of the proposed model with the existing techniques

Reference	Control System	Tools Used	Number of Microgrids	No. of Agents Developed in JADE	Simulation/ Real-Time
Foo Y.S. Eddy et al. [33]	MAS	JADE	1	6	Simulation
T. Srikanth et al. [34]	SCADA	GUI MATLAB	1	NA	Simulation
Fengji Luo et al. [35]	MAS	JADE	1	6	Simulation
Ziqi Shen et al. [36]	SCADA	NA	1	NA	Simulation
Roberto Netto et al. [15]	MAS	JADE	1	5	Simulation
Proposed Research Paper	**MAS**	**JADE**	**1**	**5**	**Real-Time**

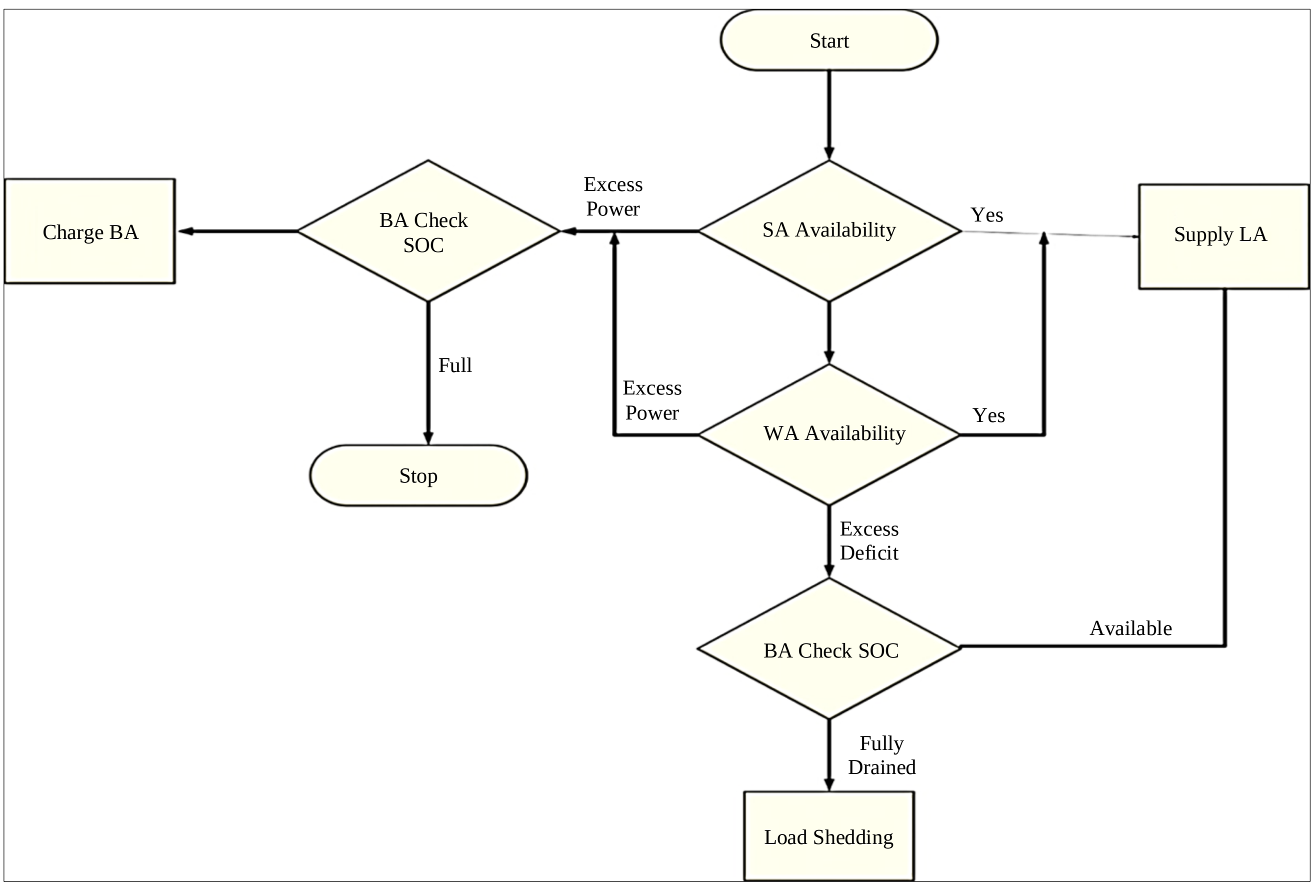

Fig. 8 Flow chart of the algorithm

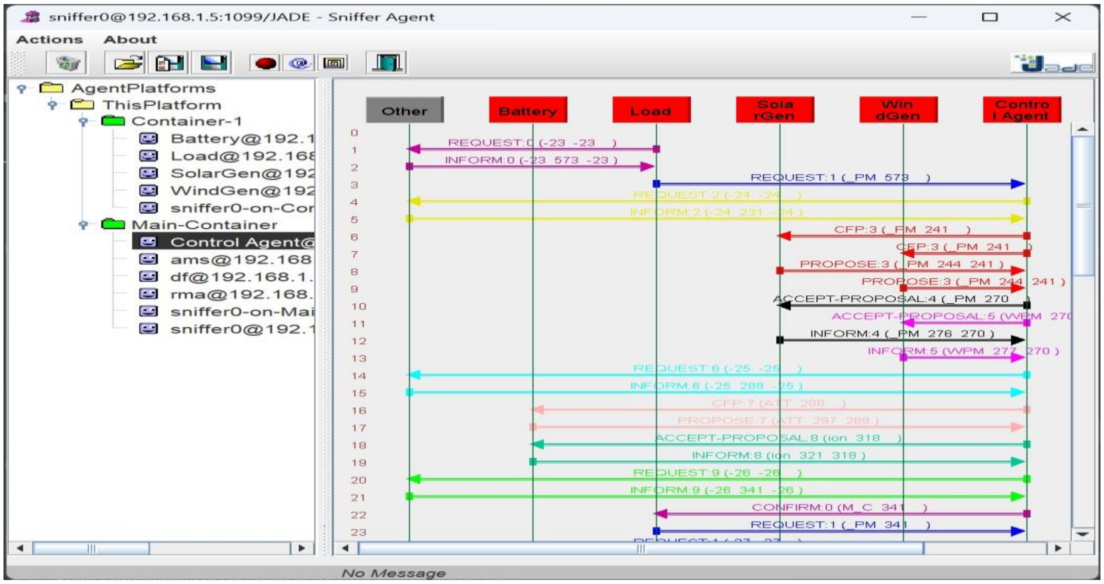

Fig. 9 Snapshot of sniffer agent and agent message exchange

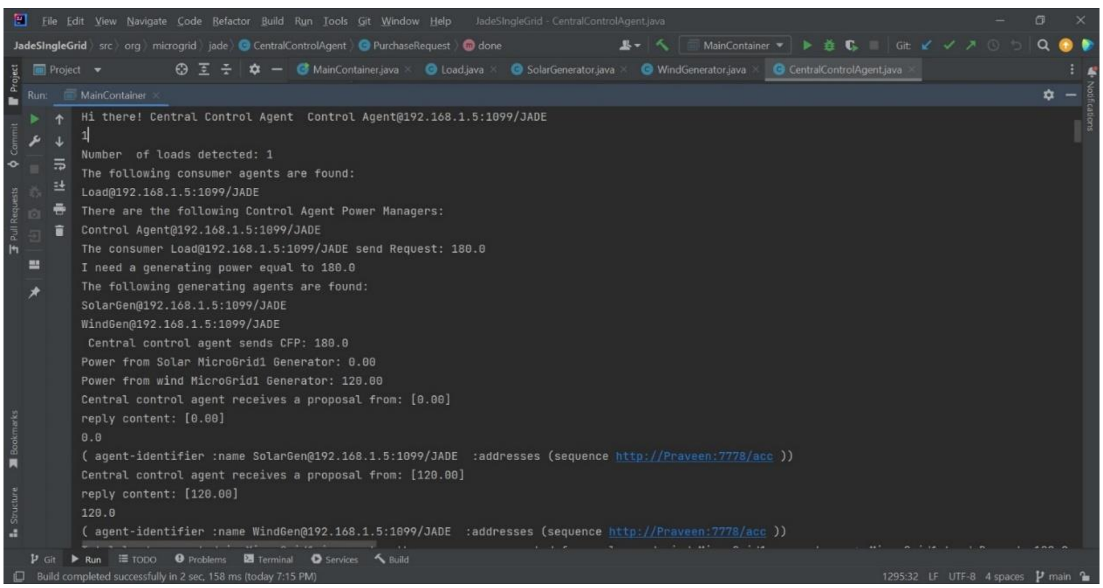

Fig. 10 Output window from the command prompt

6. Conclusion

This research paper has presented an outline of the AITS microgrid architecture and highlighted the benefits of a Multi-Agent System (MAS)-based control scheme. We have efficaciously established agents capable of communicating and making decisions using data from our simulations. The results demonstrate that the proposed MAS-based control system effectively manages energy during real-time microgrid operations. Future research will emphasise enhancing the resilience of the microgrid control system by integrating JADE with MATLAB/Simulink/LabVIEW and exploring the potential benefits of incorporating the Internet of Things (IoT). This integration aims to expand the system's functionalities, with a strong emphasis on software verification prior to hardware validation on the AITS microgrid.

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