

Article

Multi-Agent-Based Controller for Microgrids: An Overview and Case Study

Necmi Altin ¹, Süleyman Emre Eyimaya ² and Adel Nasiri ^{3,*}¹ Department of Electrical-Electronics Engineering, Faculty of Technology, Gazi University, Ankara 06560, Turkey² Department of Electronics and Automation, TUSAS-Kazan Vocational School, Gazi University, Ankara 06560, Turkey³ Electrical Engineering Department, College of Engineering and Computing, University of South Carolina (USC), Columbia, SC 29208, USA

* Correspondence: nasiri@sc.edu; Tel.: +1-803-576-7796

Abstract: A microgrid can be defined as a grid of interconnected distributed energy resources, loads and energy storage systems. In microgrid systems containing renewable energy resources, the coordinated operation of distributed generation units is important to ensure the stability of the microgrid. A microgrid needs a successful control scheme to achieve its design goals. Undesirable situations such as distorted voltage profile and frequency fluctuations are significantly reduced by installing the appropriate hardware such as energy storage systems, and control strategies. The multi-agent system is one of the approaches used to control microgrids. The application of multi-agent systems in electric power systems is becoming popular because of their inherent benefits such as autonomy, responsiveness, and social ability. This study provides an overview of the agent concept and multi-agent systems, as well as reviews of recent research studies on multi-agent systems' application in microgrid control systems. In addition, a multi-agent-based controller and energy management system design is proposed for the DC microgrid in the study. The designed microgrid is composed of a photovoltaic system consisting of 30 series-connected PV modules, a wind turbine, a synchronous generator, a battery-based energy storage system, critical and non-critical DC loads, the grid and the control system. The microgrid is controlled by the designed multi-agent-based controller. The proposed multi-agent-based controller has a distributed generation agent, battery agent, load agent and grid agent. The roles of each agent and communication among the agents are designed properly and coordinated to achieve control goals, which basically are the DC bus voltage quality and system stability. The designed microgrid and proposed multi-agent-based controller are tested for two different scenarios, and the performance of the controller has been verified with MATLAB/Simulink simulations. The simulation results show that the proposed controller provides constant DC voltage for any operation condition. Additionally, the system stability is ensured with the proposed controller for variable renewable generation and variable load conditions.

Keywords: control; distributed control; microgrid; multi-agent systems; renewable energy systems



Citation: Altin, N.; Eyimaya, S.E.; Nasiri, A. Multi-Agent-Based Controller for Microgrids: An Overview and Case Study. *Energies* **2023**, *16*, 2445. <https://doi.org/10.3390/en16052445>

Academic Editors: Alexander Micallef and Zhaoxia Xiao

Received: 7 February 2023

Revised: 25 February 2023

Accepted: 27 February 2023

Published: 3 March 2023



Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

In the electricity sector, distributed generation is becoming more common day by day, with the increasing energy demand and technological developments [1]. Distributed generation units, which have become widespread, have also demonstrated the microgrid concept. Microgrids are small-scale energy networks that can be operated independently or connected to the grid. They have their own energy resources and loads with certain limits [2]. Microgrids offer various advantages, such as providing energy supply in remote areas with on-site generation, reducing transmission losses between regions, increasing service quality by detecting faults instantly, using resources efficiently by supporting demand management, commissioning more domestic resources, and having a more reliable

network. Microgrids can consist of renewable energy resources such as photovoltaic (PV) modules and wind turbines, energy storage systems, and controllable loads, which are among the distributed power generation tools. They can be installed at points close to the user. Additionally, they can operate in grid-connected or off-grid mode and can be independently controlled. These superior features are making them popular in small-scale grid systems [3]. This also shows a pathway for the future grid structure. The inclusion of different types of technological integrations such as distributed generation, electrical energy storage units, power system management applications, microgrid structures, and information and automation technologies in the system allows conventional power systems to operate more efficiently and flexibly [4]. A microgrid consisting of renewable energy resources, conventional generation resources, electric vehicles, energy storage systems, conventional grid connection, and loads is depicted in Figure 1.

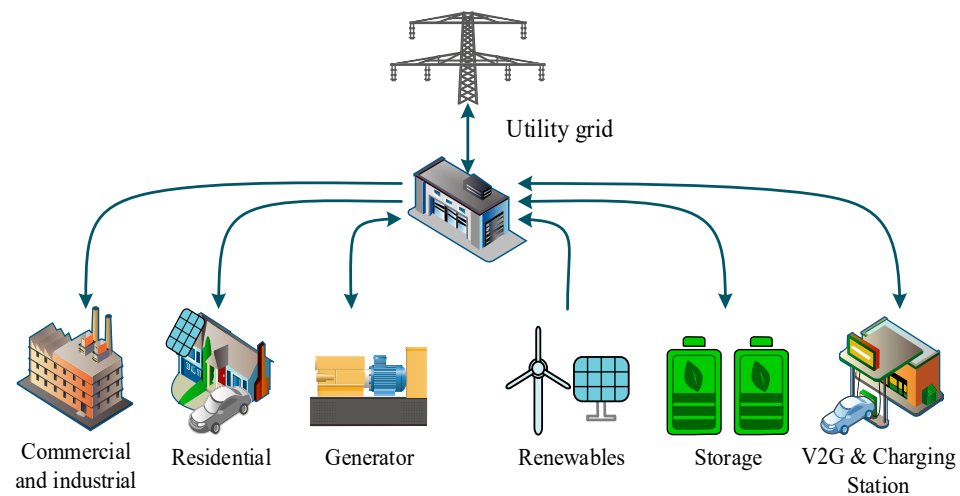


Figure 1. Architecture of a typical microgrid system.

Although AC microgrids are more common, DC microgrids have become popular in recent years with the significant increase in DC loads in applications such as LED lighting, computers and electric vehicles. The following are a few advantages of DC microgrids over AC microgrids:

- The DC microgrid is simpler due to the absence of reactive power flow control;
- Integrated distributed generations can be coordinated more easily because their control is based on DC voltage without the need for synchronization;
- Due to the prevalence of DC electronic domestic loads, the majority of DGs today produce DC outputs; this prevents the need for unnecessary AC/DC power conversions. This has a direct impact on the system's cost and losses, further reducing the size and cost of the system due to the fact that the majority of the converters used for the DC micro-source interface do not use transformers.
- In DC systems, issues such as reactive power and frequency-synchronized power management become unimportant. Additionally, skin effect, harmonics, proximity effect, and inrush current problems are absent from the DC system because it has no frequency. DC systems are thought to be safer than AC systems because they have a lower electromagnetic field.
- Compared to an AC microgrid, voltage regulation is superior.

As a result of energy generation using distributed generation units in microgrids, many economic, political, and environmental benefits are obtained. In order to obtain these benefits and to obtain the most effective use of microgrids, it is important to provide optimal design with the proper control of all components within the microgrid [3]. In microgrids, control strategies are used to control voltage and frequency, balance supply and demand, and improve the power quality by using communication between microgrid components.

Different control approaches termed centralized, decentralized, and distributed control are used in microgrids. The decentralized and distributed control strategies provide more flexible and effective control features [3]. Multi-agent systems, with their inherent features, are suitable for implementing these control strategies to achieve a more effective and flexible power system and higher power quality.

Computer systems placed in a particular environment that can take autonomous action to meet design objectives are called agents. Artificial intelligence and agent concepts emerge by transferring human characteristics, such as learning by experience and making logical decisions, into the computer environment [5]. The concept of intelligence, which is the ability to perceive and interpret an environment and situation, make decisions, and control behaviors, forms the basis of intelligent agents, which are defined as “anything that can notice and affect its environment through sensors”. Agents produce output actions with the inputs they receive from their environment, as shown in Figure 2. The main purpose of using agents is to create autonomous systems that give automatic and appropriate responses to events detected from the environment. To achieve this goal, agents use their autonomous, social, reactive, and proactive features. Thanks to their autonomy, agents exercise partial control of their actions and internal states and try to influence outcomes without interference. Agents use their social features to communicate with other agents or units, coordinate actions, and achieve their goals. While their timely response to changes in their environment results from their reactive nature, their target-oriented behavior and taking the initiative to achieve goals emerge as a result of their proactive nature. The system in which many agents come together is called a multi-agent system, and offers control strategy approaches for microgrids [6].

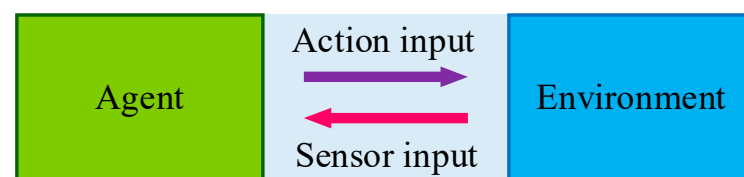


Figure 2. General relationship between an agent and environment.

With the aforementioned features, the multi-agent-based system seems a good solution for the microgrid control problems. Therefore, it has attracted the attention of researchers in recent years. This study provides an overview of agents and multi-agent systems concepts. In addition, application of multi-agent systems for microgrid operation and control are introduced, and recent studies in the literature are reviewed. The advantages of microgrid control systems designed based on multi-agent systems, their superiority over other methods, their limitations, and trends in this direction are discussed. In addition, to highlight multi-agent-based control system performance in DC microgrids, a case study is provided. For this purpose, a DC microgrid is designed in the study. In the designed microgrid, there is the PV system, the wind turbine, the synchronous generator, the battery-based energy storage system, the critical DC load, and the non-critical DC load. Moreover, a multi-agent-based controller is designed to control this DC microgrid. The proposed multi-agent-based controller has a distributed generation agent, a battery agent, a load agent and a grid agent. The DC microgrid and proposed multi-agent-based controller are modelled and simulated with MATLAB/Simulink. The simulation results carried out for different operation conditions validate the performance of the multi-agent-based controller in terms of system stability and power quality at the common DC bus.

The rest of the paper is organized as follows. A general overview of multi-agent systems is given in Section 2. The applications of multi-agent systems for microgrid control are discussed in Section 3. In Section 4, a case study is performed, including the modeling of the DC microgrid and the design of the multi-agent-based controller for the microgrid. The simulation results are provided for different scenarios in Section 5. Finally, the conclusion is drawn in Section 6.

2. Multi-Agent Systems

A multi-agent system is a complex system of autonomous agents with local knowledge and limited capabilities that are able to interact to achieve a global goal. This system, created with artificial intelligence-based techniques as well as traditional control methodologies, offers an additional advantage in creating hybrid controllers in microgrids. Fast communication possibilities such as fiber optic, microwave, and 4G are now becoming integral parts of power systems. This integration makes it easier and more convenient to integrate the multi-agent system into power system applications [7]. The main features that distinguish multi-agent systems from other distributed systems are as follows:

- Any one agent in the system does not have all the information about the solution to the problem.
- None of the agents in the system have all the required capabilities to solve the problem.
- The system control is distributed.
- The data are not kept at a central location; they are distributed.
- The operation is asynchronous.

Software or hardware-based agents and multi-agent systems are designed with different features, such as working with a certain degree of autonomy in a certain environment in order to fulfill their duties, perceiving the dynamic changes in the environment with their sensors and re-evaluating their knowledge and goals according to the perceptions they have obtained, planning in line with their goals and taking actions regarding these plans, and having the ability to communicate with other agents through the language of communication [8–10]. The conceptual design process for building a multi-agent system includes the following four-stage development process:

- Analysis: modeling agent roles and behaviors, identifying the application domain and the problem.
- Design: defining the solution architectures for the problems defined in the analysis step.
- Development: programming agent targets, ontologies, and functionalities.
- Deployment: initialization of the created multi-agent system, runtime agent management, message, and data processing.

Multi-agent systems have emerged as a powerful technology that can overcome the difficulties encountered during the application of information and communication technology in a wide variety of fields. They are considered autonomous software environments and defined as a system that detects the environment with the help of its sensors, and affects the environment they perceive. They are also considered software components that have the ability to act on behalf of the user to perform certain tasks [11]. Agents must be able to deal with changes in the environment appropriately and in a timely manner, address multiple targets, change active targets according to the situation, and perform tasks from a broad perspective. In addition, agents should interact with other agents because goals are achieved by collaborating and competing with other agents. Agents have a planning mechanism that shapes their behavior, and their behavior is formed by the way the planners use the plans in the plan library, alone or in combination with other plans, at the appropriate time and condition.

Systems formed by agents that come together to solve problems that a single agent cannot solve effectively using their own knowledge and individual abilities, in a coordinated manner, by cooperating with each other are called multi-agent systems. In multi-agent systems, each agent has partial knowledge of its environment. The agent in the system can obtain various information about other agents, monitor the actions of other agents or share information with other agents. In this context, one of the most important elements in multi-agent systems is the trust between agents. There are many studies in the literature on how to model the trust and relationship between agents in a multi-agent system [12–14].

The skills of agents are often limited, as is their knowledge. Each agent may need other agents to perform an action related to its own task. Therefore, the characteristic feature of

multi-agent systems is their ability to interoperate. An important problem in the cooperation of agents in the system is the need to ensure that the agents work in coordination within a plan. There are various approaches in the field of multi-agent systems to achieve this coordination [15,16]. For example, in a centralized approach, one agent undertakes the task of coordinating other agents [17]. In multi-agent systems, approaches within the framework of virtual organizations are very important to determine this responsible agent to ensure coordination among agents. Multi-agent systems in which multiple agents interact with each other are included in many studies in different disciplines [18,19]. An e-commerce multi-agent system includes buyer and seller agents representing buyers and sellers. Buyer and seller agents try to achieve their own goals by interacting with other agents in various ways in the same environment. Suppliers, shippers, etc. and many other agendas are included in this system [20]. An environment intelligence-based multi-agent system has been proposed to improve assistance and healthcare services for patients who suffer from Alzheimer's. It utilizes various context-aware agent technologies that allow it to automatically and evenly receive information from users and the environment, each focusing on defined concepts such as ubiquity, awareness, intelligence, and mobility [21]. A multi-agent system application is presented for distributed energy resource management in a microgrid consisting of distributed generation units, storage units, and controllable loads. In order to coordinate the distributed energy resources, an agent-based approach based on coordination and networking has been developed, and its performance is demonstrated by software simulation [22].

Communication is another important subject in multi-agent systems. Agents must be able to communicate successfully with each other in order to perform all kinds of actions, such as sharing information, coordinating, and negotiating. The main way to achieve this is to develop communication methods that will support the features of agents, such as autonomy. Communication methods have been studied in the literature of distributed systems for many years [23–25]. The general approach in this field is to provide communication between components via network protocols at various levels [26]. However, this approach is insufficient when the needs of multi-agent systems and the properties of agents are considered. Here, the main problem is the autonomous structure of agents in the multi-agent system. In a communication approach based on network protocols, there are expressions that can be used during communication. The contents of these expressions, and details on how these expressions can be used (in which situations and in what order) are determined by precise rules. However, rule-based communication methods defined in this way are not suitable for multi-agent systems because they constrain the autonomous nature of agents. In applications that a single agent cannot solve or effectively solve using his own knowledge and individual abilities, multi-agent systems, in which many agents come together to solve them in a coordinated manner, are becoming more and more important. Each role given to the agents in the system has responsibilities, abilities, authorizations, and rules depending on the goals of the system.

3. Multi-Agent Systems for Microgrid Control

Multi-agent systems consist of multiple intelligent agents that interact to solve problems that may be beyond the capabilities of the system. For many years, multi-agent designs and architectures have been proposed for applications in power systems and power engineering [27–29]. Distributed energy resources used in microgrid applications are increasing day by day, and making microgrid control more complex. The multi-agent system is well suited for managing this complexity.

There are many advantages of multi-agent systems in microgrid control applications [30]:

Distributed architecture: The structure of distributed generation resources conforms to multi-agent system architectures based on local knowledge and decision making.

Flexibility: In the microgrid system modeled with distributed energy resources and loads, agents can be easily deployed and provide flexibility for future expansion in the system, thanks to its “plug and play” capabilities.

Resilience: The multi-agent system can respond quickly and adapt to faults. In addition, changes in grid topology (disconnection of a load or generator) do not interrupt both local and global system goals (for example, stability and efficiency).

Multi-agent-based control systems for microgrids have some limitations that hinder their widespread adoption but also offer an opportunity for future research [30]:

Emerging behavior: The autonomous and distributed nature of intermediaries can lead to unpredictable consequences. While the intents and targets of agents are programmable, the effect of runtime interactions is not always predetermined. Such immediate behavior may be beneficial in some situations (e.g., market transactions). However, in some applications, this uncertainty can be a disadvantage.

Portability: Hardware implementation of multi-agent system designs and architectures can be difficult. The most recent applications of multi-agent system-based control of microgrids are virtual test software simulations (e.g., MATLAB Simulink). The performance of many multi-agent systems approaches on real microgrid hardware has not been widely tested yet.

Scalability: The higher computational power available today allows researchers to model larger microgrids with many agents coordinating actions on a single platform. However, the ability of multi-agent systems to scale with increases in problem size (with agents across multiple platforms) or diversity (with agents of multiple types) is not well understood.

Security: The massive shift from physical infrastructure to smarter technology increases the risk of security and privacy breaches from malicious outside actors and disruptors.

When examining the active research areas of multi-agent systems in the context of microgrids presented in the literature in order to understand their current involvement in microgrid development, it can be seen that most studies have focused on distributed microgrid control [31–35]. Electrical energy trading, optimization, and power restoration are other popular application areas. The areas wherein multi-agent systems are used in microgrid control, and their properties, are presented in Table 1.

Table 1. Control subjects in the microgrid in which multi-agent system-based control is applied.

Author and Year	Applications of MAS in Microgrid	Aim	Application
Victorio et al., 2021 [31] Chung et al., 2013 [32] Almada et al., 2021 [33] Jabeur et al., 2022 [34] Zheng and Cai, 2010 [35]	Distributed Control	Solving the real and reactive power mismatch arising from distributed generation and maintaining the balance between supply and demand in microgrid.	Multi-agent system-based microgrid control models are created using artificial neural networks and fuzzy systems for tasks such as generation planning and load forecasting for operations planning
Logenthiran et al., 2010 [36] Jin et al., 2021 [37] Khan et al., 2019 [38] Khan and Wang, 2017 [39]	Optimization	Increase efficiency by optimizing the actions of microgrid components.	An artificial immune system-based algorithm is used to optimize the efficiency of renewable energy sources in the system and maximize power generation.
Alhasnawi et al., 2021 [40] Wang et al., 2020 [41] Mohamed et al., 2019 [42]	Power Restoration	Provide power restoration in the event of a large-scale power outage in microgrids.	A hierarchical control strategy is implemented along with a multi-agent immunity algorithm for rapid restoration of strength.

Table 1. Cont.

Author and Year	Applications of MAS in Microgrid	Aim	Application
Luo et al., 2018 [43] Gomes et al., 2020 [44] Sesetti et al., 2018 [45]	Electrical Energy Trading	Maximizing the revenue from the microgrid.	Creates a pricing mechanism for the microgrid in the competitive electricity market and algorithms for price determination based on demand and supply strategies.

Many studies have used multi-agent system-based controllers to optimize microgrid operations [36–38]. Awareness of green energy technologies in microgrids has been widely adopted for reducing CO₂ emissions and for a clean environment. Distributed energy resources such as the PV system, diesel engines, gas turbines, small wind turbines, and fuel cell technologies are developing within the power system. The control and maintenance of this power have a great impact on power systems. Multi-agent system technology is adopted for optimum use of electrical power in microgrids. In [39], multi-agent system technology used for microgrid control, optimization, and market distribution [39]. In [42], the multi-agent system with a time-varying microgrid topology is expressed as the best control strategy to address all data restoration problems in microgrids.

Because loads and resources within a microgrid can be diverse and distributed, the real-time response and the distributed generation resource management are critical in preventing local power outages. It is also important to do this efficiently and cost-effectively to achieve an economically viable microgrid. In addition, some studies consider the characteristics of source or load types, and self-regulate themselves with other agents to optimize for cost and efficiency globally. Multi-agent systems have also been used for the power restoration of microgrids [40,41]. The load restoration algorithm consists of agents that make synchronized load restoration decisions based on information learned directly from their neighbors. The global knowledge is discovered based on the mean consensus theorem, although only direct connections are made to neighbors. Multi-agent systems have been applied for electrical energy trading or market model analysis [43–45]. Efforts have been made to establish a power market model for the efficient operation of the microgrid. A multi-agent system electricity trading algorithm is proposed to maximize the revenue from the microgrid [46].

4. The Case Study: Multi-Agent-Based Control of DC Microgrid

4.1. Designed DC Microgrid

As a case study, the multi-agent-based control of a DC microgrid is designed and presented in this study. The designed DC microgrid model is shown in Figure 3. The microgrid includes the wind turbine, the solar PV system, the battery energy storage system (BESS), the synchronous generator, DC loads, and the grid. This system is designed with MATLAB/Simulink.

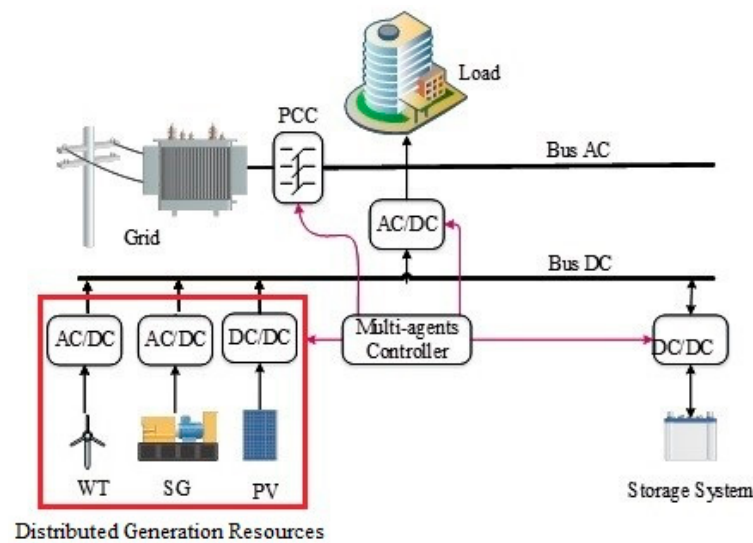


Figure 3. The configuration of the DC microgrid under study.

4.1.1. PV System Model

The PV system model consists of 25 series-connected Suntech STP270S-24 PV modules. The solar irradiation to the system is defined as time-varying. The PV modules produce direct current when the solar irradiation falls on them. However, the voltage and current values depend on natural conditions such as solar irradiation and ambient temperature. Therefore, a maximum power point tracking (MPPT) algorithm is used to ensure maximum power generation for any operation condition. The parameters of the designed PV system in the MATLAB/Simulink model are shown in Table 2.

Table 2. The block parameters of the designed PV system.

The Block Parameters of PV	Value
Open circuit voltage	44.49 (V)
Short-circuit current	8.19 (A)
Voltage at maximum power point	35.00 (V)
Current at maximum power point	7.71 (A)
Temperature coefficient of open circuit voltage	0.1504% (V/°C)

4.1.2. Wind Turbine Model

The wind energy system model, whose parameters are given in Table 3, consists of a three-phase salient pole permanent magnet synchronous generator (PMSG), a wind turbine and a blade angle control system with an output power of 10 kW. PMSG produces three-phase alternating current with the kinetic energy generated by the rotation of the blades with the wind. However, the voltage and frequency values depend on the wind speed. The wind speed is defined to the system in a time-varying manner. These values are set to change at certain time intervals. Since the PMSG generates variable voltage and frequency, a rectifier is used next to the PMSG. Additionally, similar to the PV system, a MPPT algorithm is utilized with a DC-DC converter to get the maximum available power from the wind system and to ensure maximum energy conversion efficiency. The MPPT algorithm generates a current reference for the DC-DC converter by using the torque reference, output DC voltage (the common DC bus voltage) and the wind speed. A hysteresis controller compares this current reference and the actual current value to generate the switching signal for the DC-DC converter.

Table 3. The block parameters of the designed wind turbine.

The Block Parameters of Wind Turbine	Value
Nominal mechanical output power	10 (kW)
Base power of electrical generator	10/0.9 (kVA)
Base wind speed	12 (m/s)
Maximum power at base wind speed	0.8 (pu)
Base rotational speed	1.2 (pu)

4.1.3. Synchronous Generator Model

A synchronous generator is included in the system to take precautions against natural variables and sudden output power changes occurring in the output power of the wind turbine and PV system. Actually, it is used to support the sustainability and stability of the microgrid. The block parameters of the synchronous generator are given in Table 4.

Table 4. The block parameters of the designed synchronous generator.

The Block Parameters of Synchronous Generator	Value
Nominal power	1000 (VA)
Line-to-line voltage	400 (V)
Frequency	50 (Hz)
Stator resistance	0.00285 (pu)

4.1.4. Battery Energy Storage System (BESS)

The BESS is connected to the common DC bus via a bidirectional DC-DC converter to balance the differences between the instant supply power and the demand. Thus, it provides sustainable energy to the loads. Besides, it also mitigates power fluctuations in the wind energy conversion system output power. The block parameters of the 650 V, 20 Ah Li-ion battery used as a BESS are given in Table 5.

Table 5. The block parameters of the Li-ion battery used as a BESS.

The Block Parameters of Li-Ion Battery	Value
Nominal voltage	650 (V)
Rated capacity	20 (Ah)
Initial state-of-charge (SoC)	60 (%)

In the system, the energy management is carried out together with the battery control system, and the balance between the generated power and the demand is ensured. The voltage control action is performed with the common DC bus reference voltage value. If the total output power of the generation units is higher than the load power, the DC bus voltage will increase. Similarly, if the total output power of the generation units is lower than the load demand power, then the DC bus voltage will decrease. This change shows the imbalance between the generation and demand. Based on this variation, a simple voltage controller is used as an energy management system. If the common DC voltage is higher than the specified reference voltage level, the controller generates a negative power reference for the BESS, and the BESS is charged. Conversely, when the common DC bus voltage is lower than the reference voltage level, the controller generates a positive power reference for the BESS, and the BESS is discharged.

4.2. Proposed Multi-Agent-Based Control Strategy

The conventional power systems use a master controller that collects all system information to manage the network and make decisions. With the increase in distributed energy

resources in power systems, the power network is getting more complex. In a microgrid, the central control may introduce many drawbacks while it manages and controls many distributed energy resources, loads and storage units [3]. In this study, a distributed control with a multi-agent system is proposed instead of centralized control to overcome the problems caused by diversity in production and load resources. In addition to providing power quality and supply–demand balance by creating an effective management and control mechanism in the microgrid controlled by a multi-agent system, tasks such as battery charge–discharge, battery life improvement, reference bus voltage control, and reduction of voltage fluctuations are also performed by agents. A distributed generation agent, battery agent, load agent and grid agent are designed in the system. Agents communicate with each other to perform their role in the control of the microgrid. The roles of agents in the system can be described as follows:

Distributed Generation Agent: This agent represents distributed generation units such as wind turbines and PV modules in the microgrid. It receives the voltage and current information separately from PV modules, wind turbines and synchronous generators, and uses these data in control. It performs MPPT for the PV systems and wind turbines. It also controls the total power produced in the PV systems, wind turbines and synchronous generators, and share the data with other agents.

Battery Agent: This agent represents the BESS in the microgrid. It controls the battery charge and discharge action by using the battery, the generation and consumption data that it receives from other agents. It also shares the BESS power information (produced/stored) with other agents. It monitors the state of charge (SoC) level and requests power from the distributed generation agent and/or the grid agent when the SoC level is low.

It also controls the charging and discharging of the battery and ensures that the common DC bus voltage is stabilized. P_S refers to the supply power in the microgrid system, and its equation is given in Equation (1). P_S is the sum of the wind turbine output power (P_{wt}), the photovoltaic system output power (P_{pv}), the synchronous generator power (P_{sg}), and the battery power (P_b).

$$P_S = P_{wt} + P_{pv} + P_{sg} + P_b \quad (1)$$

P_d refers to the demand power in the microgrid system, and its equation is given in Equation (2). P_d is the sum of the power of DC loads (P_{dc_load}) and power of AC loads and the grid (P_{ac_load}).

$$P_d = P_{dc_load} + P_{ac_load} \quad (2)$$

In cases in which P_S is greater than P_d , the battery is charged by communicating with other agents thanks to the battery agent, due to the excess power produced in the microgrid system. However, in cases in which P_S is smaller than P_d , the battery is discharged by communicating with other agents due to the lack of enough power generation in the microgrid system.

Load Agent: This agent represents loads in the microgrid. It receives the consumed power information from all loads in the system and transfers it to other agents. It has the ability to monitor, control and negotiate the power level and link status of the controllable load. Particularly when the microgrid is in island mode, it may interrupt, depending on the available power and SoC of the BESS. It has critical load and non-critical load separation capability. In addition, it plays a critical role in the system by sending the information on whether or not the supply–demand balance is provided to other agents.

Grid Agent: This agent represents the grid side within the microgrid. It monitors the grid voltage, phase angle and frequency, and is responsible for notifying other agents of changes in the microgrid state. It provides power and current control exported to or imported from the grid. With the data it receives from other agents, the PCC point is disabled, allowing the system to operate in island mode. It is responsible for monitoring and negotiating power from generation units and importing or exporting power when the microgrid is in on-grid mode.

The cooperation diagram between the agents in the designed multi-agent system is shown in Figure 4. Additionally, Table 6 gives a general idea of how and for what tasks these agents are designed, and also contains the necessary messages for interactions.

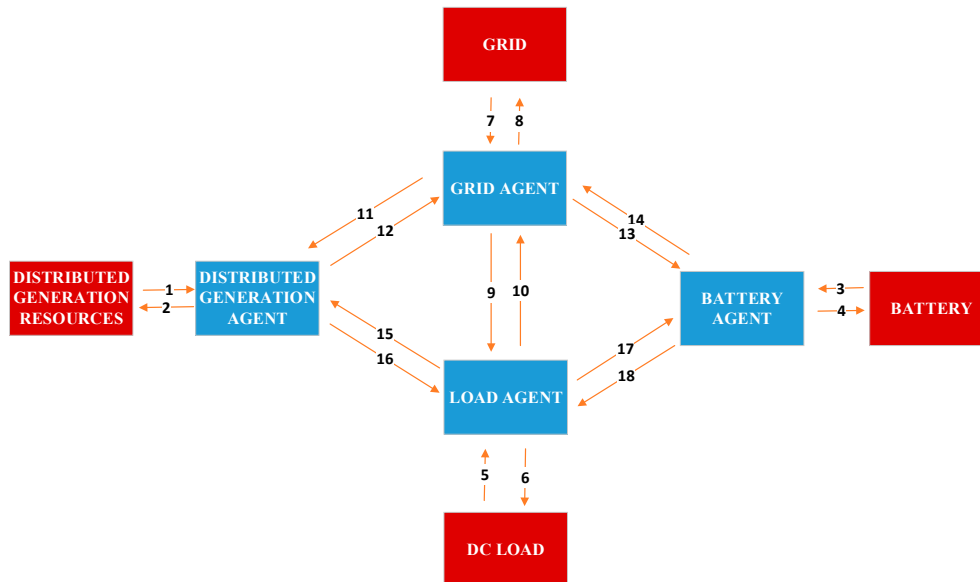


Figure 4. General overview of the proposed multi-agent-based control for the microgrid.

Table 6. Communication and coordination of agents.

Number	Communication and Coordination
1	Distributed generation agent receives power, voltage and current information from distributed generation sources.
2	The distributed generation agent makes MPPT with the information it receives and transfers it to the resources.
3	Battery agent receives voltage, current, power and SoC information from the battery.
4	Battery agent implements the battery control algorithm and transfers it to the battery.
5	Load agent receives power consumed from critical and non-critical loads.
6	Load agent transmits information for the exit of non-critical loads according to the system supply/demand situation.
7	Grid agent receives voltage, current and power information from the grid.
8	Grid agent converts the common DC bus voltage to AC with DQ control and transfers it to the grid.
9	Load agent requests network agent to open/close PCC.
10	Grid agent notifies the installation agent of the mode of the system (on/off grid).
11	Grid agent notifies mode to distributed generation agent (on/off grid).
12	Distributed generation agent transmits the generated power to the grid agent.
13	Grid agent notifies battery agent mode (on/off grid).
14	Battery agent reports common DC bus voltage information to the grid agent.
15	Load agent requests power from the distributed generation agent.
16	Distributed generation agent gives production information to the load agent and requests load shedding in underproduction.
17	Load agent requests power from the battery agent.
18	Battery agent provides production information to load agent and requests charge shedding when SoC is low.

5. Simulation Results

The designed DC microgrid and proposed and multi-agent-based microgrid controller are modelled with MATLAB/Simulink, and simulations representing different cases are carried out. Natural variables such as solar irradiation and wind speed affect the generated power level of the microgrid system. Therefore, the system has been tested on different scenarios depending on the renewable generation unit's situation to test the effectiveness of the designed multi-agent-based control.

5.1. Scenario I: Solar and Wind Power Are Both Available

In order to test the performance of the system in variable solar irradiation conditions, the solar irradiation is changed from 400 to 1000 W/m² in the simulation studies, as given in Table 7.

Table 7. Variable solar radiation values.

Time (sn)	Value (W/m ²)
0–2	1000
2–4	400
4–6	800

Similarly, the variable wind speed, defined in Table 8, is used in the simulations to validate the performance of the proposed controller for different operation conditions.

Table 8. Variable wind speed values.

Time (sn)	Value (m/s)
0–0.5	5
0.5–2.5	12
2.5–6	10

The output power of the solar PV system, together with the solar irradiation value that changes with time, is given in Figure 5. Since the available solar power increases and decreases with the solar irradiation level, thanks to the MPPT controller, the output power of the PV system also tracks it and generates maximum power for any operation condition.

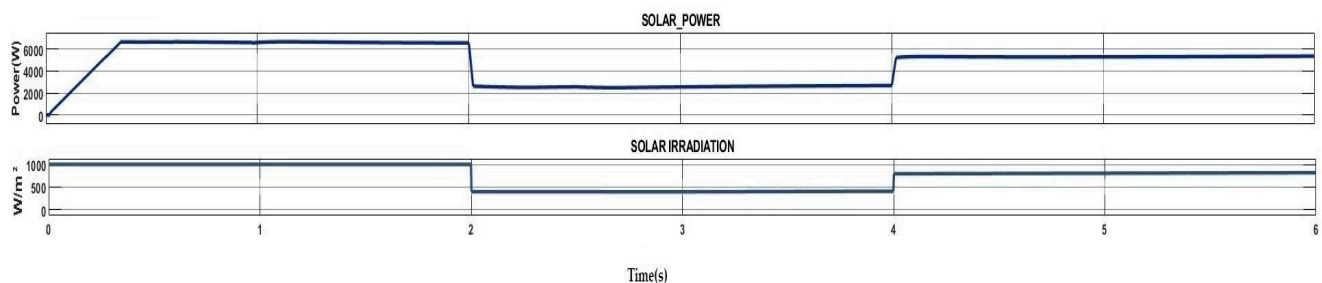


Figure 5. The output power of the PV system.

Simultaneously, the wind speed also varies and the available wind power changes. To achieve maximum use of the renewable energy resources, the microgrid controller should control these units properly. Figure 6 shows the changes of power values of all components in the system. The PV and wind system power levels are obtained with variable values of wind speed and solar irradiation as mentioned before. The controller controls the BESS's charge and discharge condition and power of the batteries to ensure the power sustainability and stable common DC bus voltage. AC and DC loads are the loads in the system. One can observe that for variable generation (because of variable wind speed and solar irradiation) and variable load conditions, the DC bus voltage is kept constant, and the microgrid stability is ensured. It is seen that the system still works efficiently in the time period when the load increases. In the system, the synchronous generator is programmed to run if the battery SoC level is below a certain limit. Since the supply and demand balance can be achieved and the SoC is not below this limit, the synchronous generator is not activated, except at the start. In addition, it is proven in the figure that the agents provide full control and take an active role in the system.

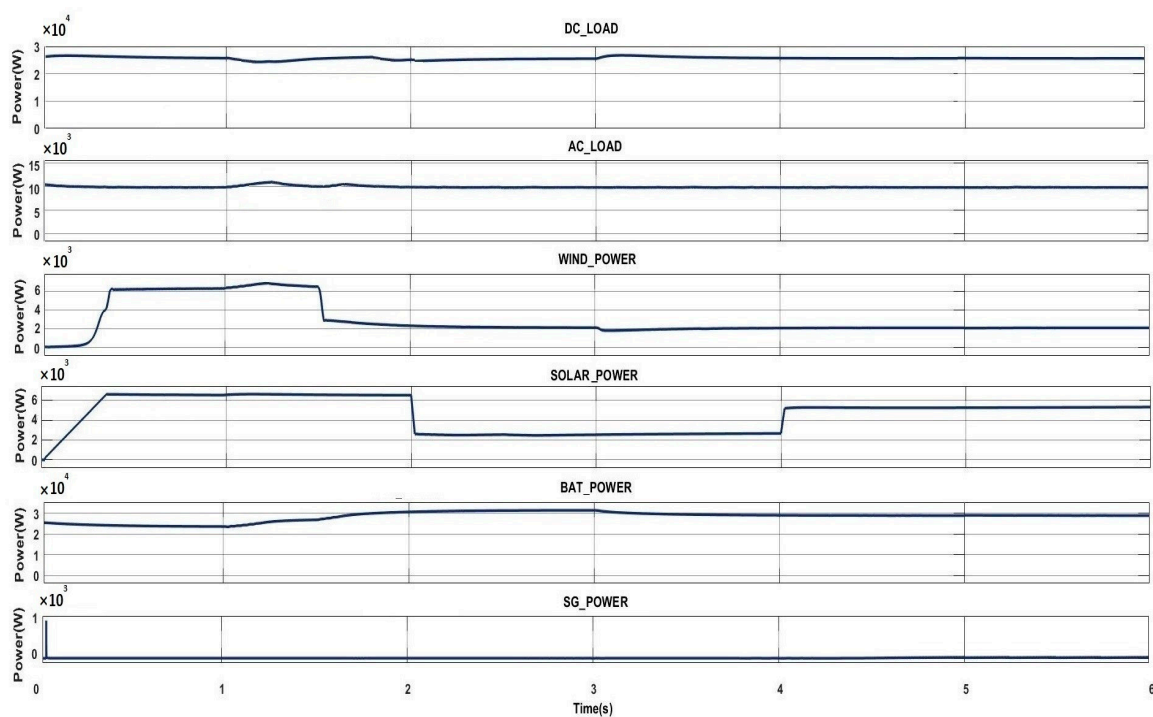


Figure 6. The variation in system components' power level for different conditions.

Figure 7 shows the voltage level of the common DC bus. The reference value for the common DC bus voltage is determined as 800 V, and it is controlled by the battery agent in the system. Thus, it is possible to provide the voltage and current values demanded by the grid agent. As can be seen in the figure, the DC bus voltage is well controlled for any operation condition.

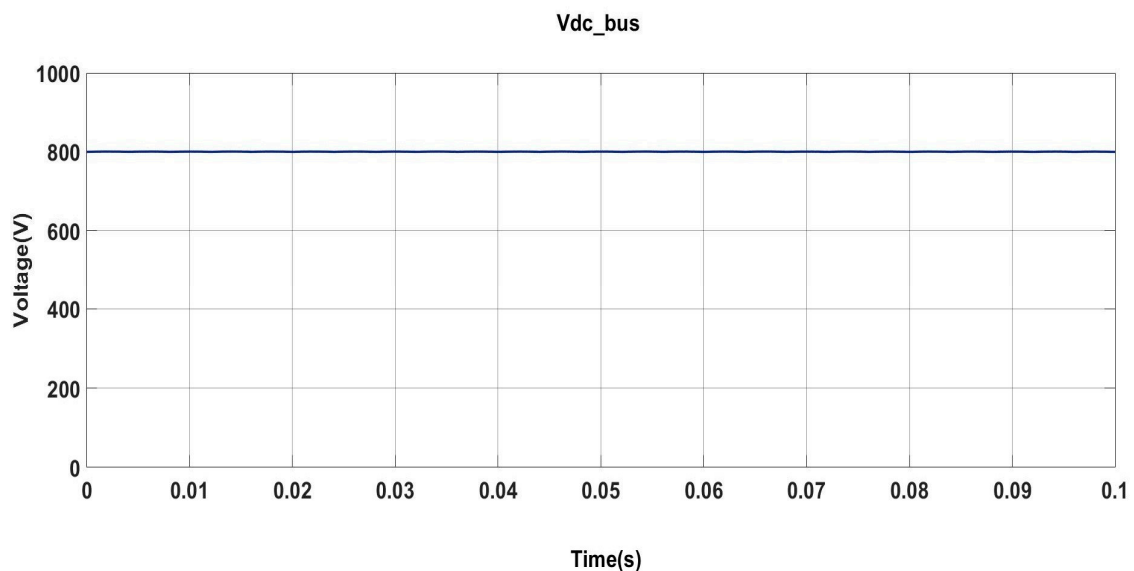


Figure 7. The voltage of the common DC bus.

To explore the operation of the other units, the voltage, current, charge level and power values of the BESS are given in Figure 8. The BESS is controlled by the battery agent. When the generated power cannot meet the total load in the system, the BESS discharges and transfers power to the system, in light of the information transferred by the distributed generation agent and the load agent to the battery agent. The battery current, voltage and power values vary with the generated and load power level.

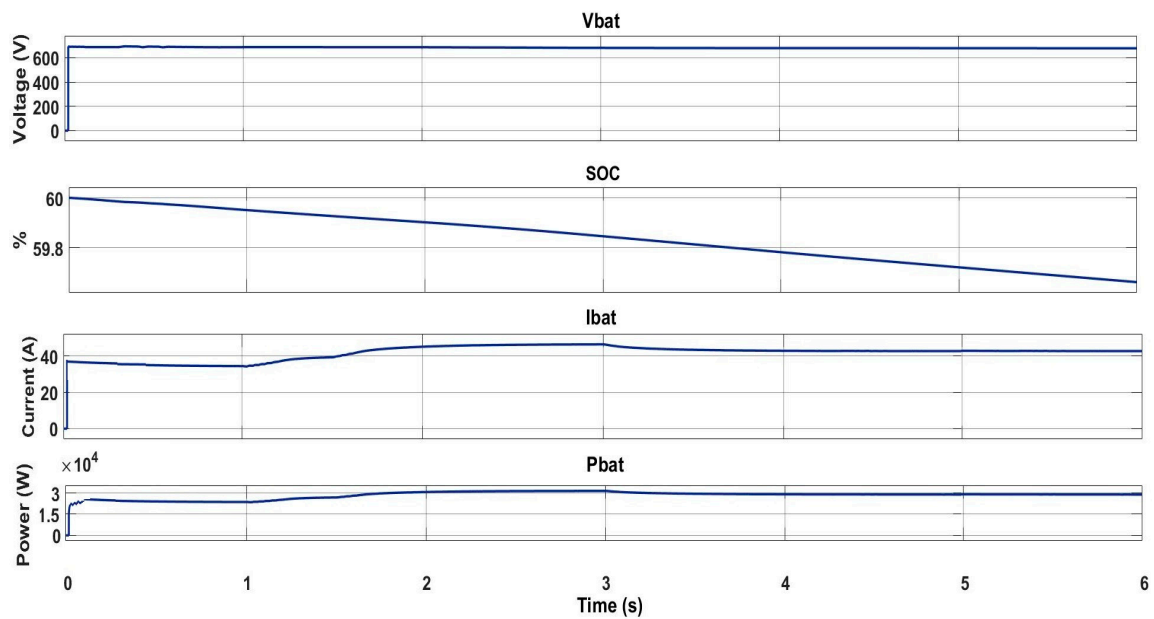


Figure 8. The battery voltage, current, SOC level and charge/discharge power variation.

In Figure 9, the supply, demand and the supply demand difference in the designed microgrid system are given. Accordingly, the generation in the system can always meet demand. Thanks to the monitoring of the difference between supply and demand by the load agent, non-critical DC loads are removed from the system when the power obtained from the distributed generation sources and the battery does not meet the consumption; at the same time, the microgrid is switched to the island mode operation by deactivating the grid connection at the PCC. When the supply power is more than the demand, the system continues to feed the non-critical DC loads and the grid and operation in grid-connected mode.

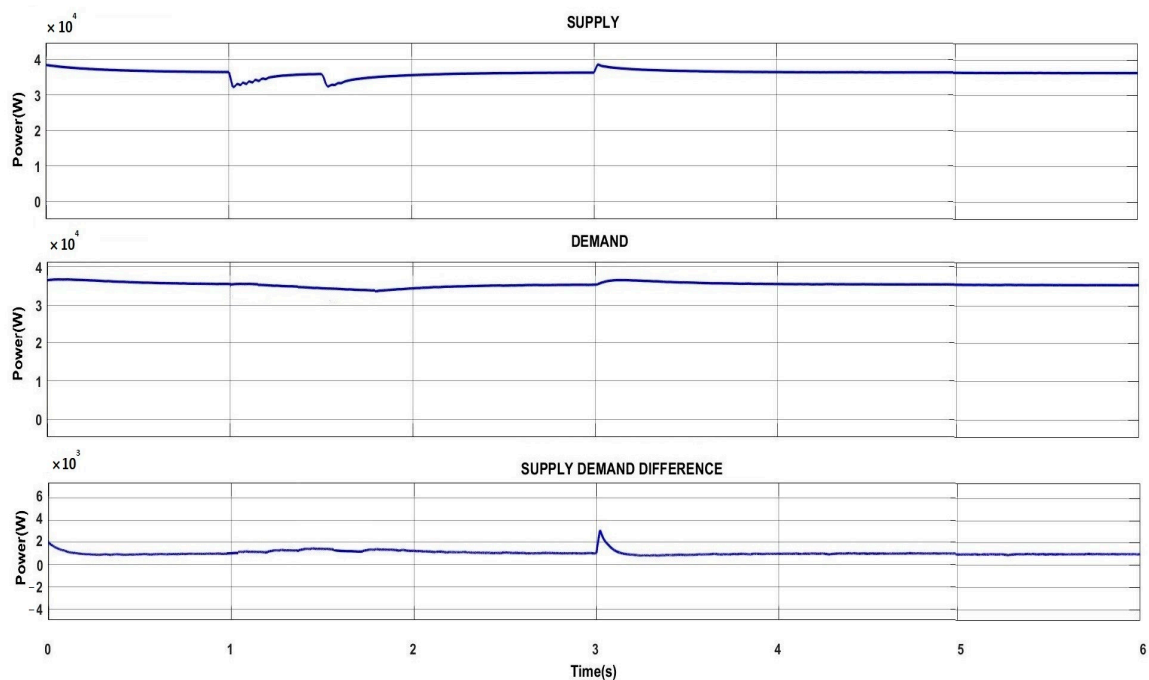


Figure 9. Variation in the generated power and load power in the system.

5.2. Scenario II: Only Solar Power Is Available

In this scenario, while the same solar irradiation value defined as in Table 7 is used for PV system, the wind speed is kept at 0 during the simulation. Therefore, the wind turbine was disabled during the simulation of this scenario. Figure 10 shows the variation in the power values of all components in the system for this condition. While there is no change in the PV system power level, AC and DC load, compared to the first scenario, it is observed that more battery power is required to supply the system. It is determined that the maximum power level provided by the battery (discharge power) to the microgrid system increased from 30 kW to 36 kW, representing a 20% increase compared to the first scenario. As mentioned before, the system is used to provide power if the renewable resources and the battery cannot supply the load. The PV system and BESS supply power to the microgrid system in this scenario, and the synchronous generator does not run again except at the start, because the SOC level of the BESS is bigger than the SOC limit.

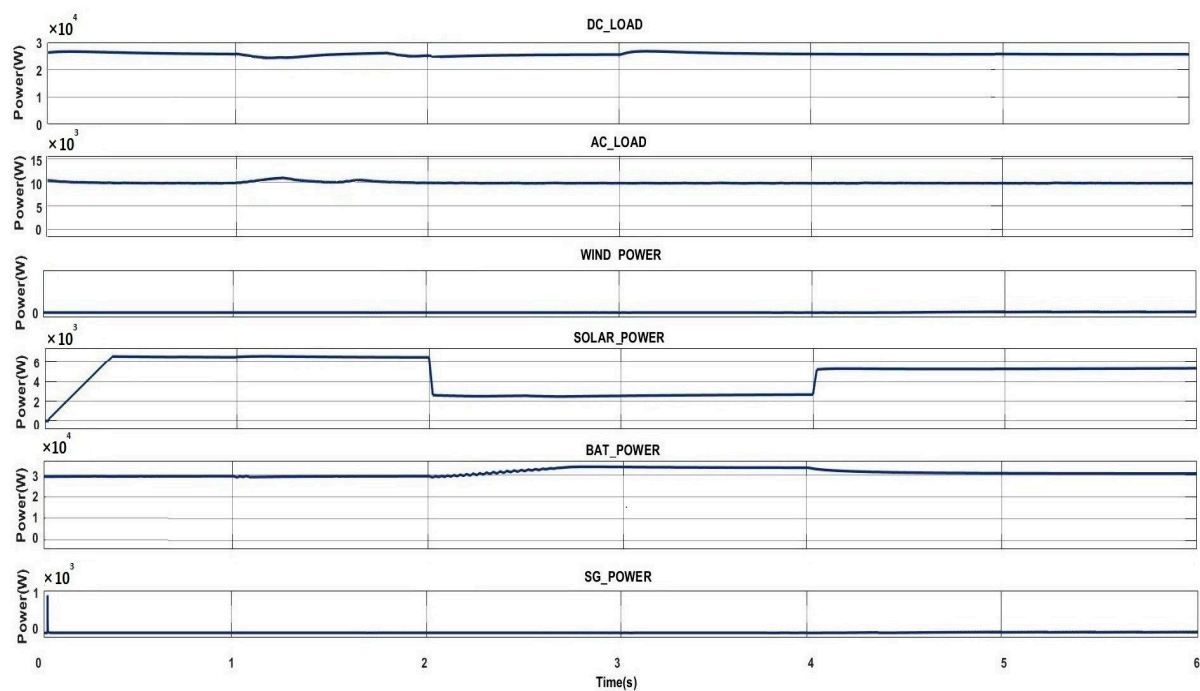


Figure 10. The variation in the power level of each unit in the microgrid for different operation conditions with no wind speed.

Figure 11 shows the voltage level of the common DC bus. A reference value of 800 V is ensured for any solar irradiation and load level thanks to the multi-agent-based microgrid control system. The controller agents define the operation point and determine the required operation mode for any unit. Thus, it is possible to keep the bus voltage constant in order to supply the loads. In addition, it has been proven that the agents provide full control even when the PV power is variable and there is no wind power, and ensure system stability and stable DC bus voltage for any condition.

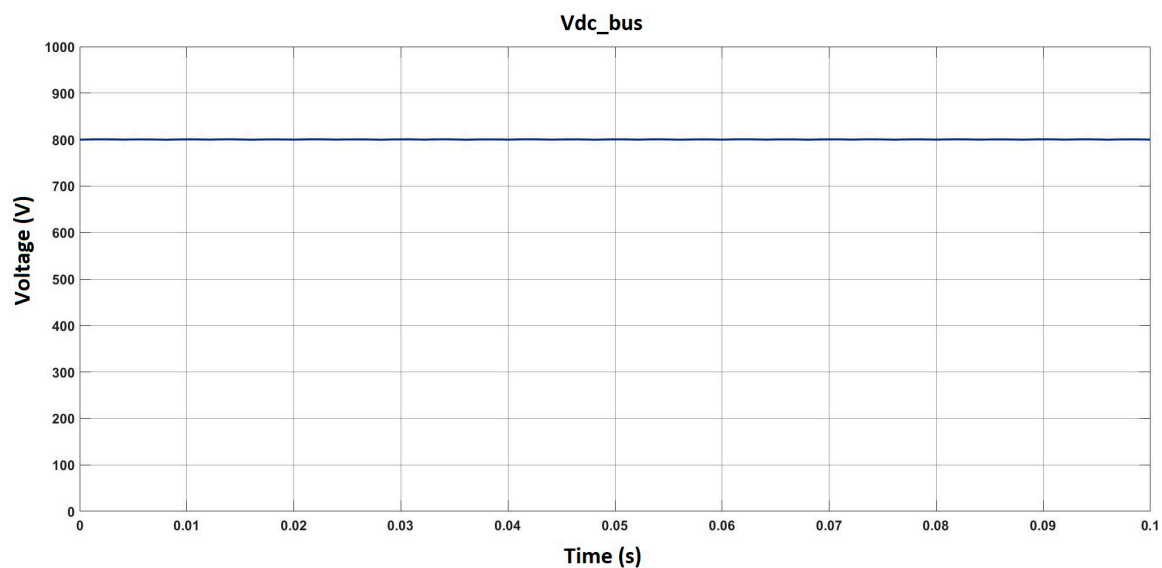


Figure 11. The common DC bus voltage for no wind speed.

6. Conclusions

In this study, an overview of multi-agent-based system applications in microgrids is presented. Agent theory, multi-agent systems and concepts that facilitate microgrid operation and control are introduced, and agent interaction, coordination, and cooperation are discussed in the context of multi-agent system features. The application of multi-agent systems in microgrids for different purposes such as market operations, fault detection, and fault location has been highlighted. In addition, a multi-agent-based controller for the DC microgrid system is proposed and tested as a case study. The presented DC microgrid consists of a solar PV system, wind turbine, synchronous generator, BESS, loads and grid connection. To control this microgrid, agents, their roles and interactions were designed. This system was tested in MATLAB/Simulink, and the performance of the multi-agent-based system was validated. The simulation results show that the multi-agent-based controller improves the stability and power quality of the microgrid.

With the growing interest in distributed generation systems and control of microgrids, multi-agent system-based control development studies are becoming more and more important. Microgrid control and protection applications using multi-agent systems, intelligent distribution control, modeling, and optimization have good research potential. Agent communications continue to evolve, adapting to changing network communication protocols. The improved agent provides a faster response time and adaptability. The standardization of multi-agent system architecture and applications will lead to more system interoperability in the microgrid and a smart grid environment. However, the inherent uncertainty of software complexity, hardware incompatibility, and security risk of malicious external actors limit the widespread adoption of the multi-agent systems to control microgrids.

Author Contributions: Conceptualization, S.E.E., N.A. and A.N.; methodology, N.A. and A.N.; software, S.E.E. and N.A.; validation, S.E.E. and N.A.; formal analysis, A.N.; investigation, S.E.E.; resources, N.A.; data curation, S.E.E.; writing—original draft preparation, S.E.E.; writing—review and editing, N.A. and A.N.; visualization, S.E.E.; supervision, N.A.; project administration, N.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Altin, N.; Eyimaya, S.E. A combined energy management algorithm for wind turbine/battery hybrid system. *J. Electron. Mater.* **2018**, *47*, 4430–4436. [\[CrossRef\]](#)
- Hirsch, A.; Parag, Y.; Guerrero, J. Microgrids: A review of technologies, key drivers, and outstanding issues. *Renew. Sustain. Energy Rev.* **2018**, *90*, 402–411. [\[CrossRef\]](#)
- Altin, N.; Eyimaya, S.E. A Review of Microgrid Control Strategies. In Proceedings of the 2021 10th International Conference on Renewable Energy Research and Application (ICRERA), Istanbul, Turkey, 26–29 September 2021; pp. 412–417.
- Espina, E.; Llanos, J.; Burgos-Mellado, C.; Cardenas-Dobson, R.; Martinez-Gomez, M.; Sáez, D. Distributed control strategies for microgrids: An overview. *IEEE Access* **2020**, *8*, 193412–193448. [\[CrossRef\]](#)
- Shabbir, J.; Anwer, T. Artificial intelligence and its role in near future. *arXiv* **2018**, arXiv:1804.01396.
- Dou, C.X.; An, X.G.; Yue, D. Multi-agent system based energy management strategies for microgrid by using renewable energy source and load forecasting. *Electr. Power Compon. Syst.* **2016**, *44*, 2059–2072. [\[CrossRef\]](#)
- Khan, M.W.; Wang, J.; Xiong, L.; Huang, S.; Lopez-Ruiz, R. Architecture of a microgrid and optimal energy management system. In *Multi Agent Systems-Strategies and Applications*; Intechopen: London, UK, 2020.
- Muise, C.; Belle, V.; Felli, P.; McIlraith, S.; Miller, T.; Pearce, A.R.; Sonenberg, L. Efficient multi-agent epistemic planning: Teaching planners about nested belief. *Artif. Intell.* **2022**, *302*, 103605. [\[CrossRef\]](#)
- Shahinzadeh, H.; Nikolovski, S.; Moradi, J.; Bayindir, R. A Resilience-Oriented Decision-Making Model for the Operation of Smart Microgrids Subject to Techno-Economic and Security Objectives. In Proceedings of the 2021 9th International Conference on Smart Grid (icSmartGrid), Setubal, Portugal, 29 June 2021–1 July 2021; pp. 226–230.
- Qasem, M.H.; Hudaib, A.; Obeid, N.; Almaiah, M.A.; Almomani, O.; Al-Khasawneh, A. Multi-agent systems for distributed data mining techniques: An overview. In *Big Data Intelligence for Smart Applications*; Springer: Berlin/Heidelberg, Germany, 2022; pp. 57–92.
- Merabet, G.H.; Essaaidi, M.; Talei, H.; Abid, M.R.; Khalil, N.; Madkour, M.; Benhaddou, D. Applications of multi-agent systems in smart grids: A survey. In Proceedings of the 2014 International Conference on Multimedia Computing and Systems (ICMCS), Marrakech, Morocco, 14–16 April 2014; pp. 1088–1094.
- Huynh, T.D.; Jennings, N.R.; Shadbolt, N.R. FIRE: An integrated trust and reputation model for open multi-agent systems. In Proceedings of the 16th European Conference on Artificial Intelligence, Valencia, Spain, 22–27 August 2004.
- Bagherzadeh, L.; Shahinzadeh, H.; Gharehpetian, G.B. Scheduling of distributed energy resources in active distribution networks considering combination of techno-economic and environmental objectives. In Proceedings of the 2019 International Power System Conference (PSC), Tehran, Iran, 9–11 December 2019; pp. 687–695.
- Khalid, R.; Samuel, O.; Javaid, N.; Aldegeishem, A.; Shafiq, M.; Alrajeh, N. A secure trust method for multi-agent system in smart grids using blockchain. *IEEE Access* **2021**, *9*, 59848–59859. [\[CrossRef\]](#)
- Consoli, A.; Tweedale, J.; Jain, L. The link between agent coordination and cooperation. In Proceedings of the International Conference on Intelligent Information Processing, Adelaide, Australia, 20–23 September 2006; Springer: Boston, MA, USA, 2006; pp. 11–19.
- Castelfranchi, C. Modelling social action for AI agents. *Artif. Intell.* **1998**, *103*, 157–182. [\[CrossRef\]](#)
- Andreadis, G.; Klazoglou, P.; Niotaki, K.; Bouzakis, K.D. Classification and review of multi-agents systems in the manufacturing section. *Procedia Eng.* **2014**, *69*, 282–290. [\[CrossRef\]](#)
- Bellifemine, F.L.; Caire, G.; Greenwood, D. *Developing Multi-Agent Systems with JADE*; John Wiley & Sons: Hoboken, NJ, USA, 2007.
- Ferber, J.; Gutknecht, O. A meta-model for the analysis and design of organizations in multi-agent systems. In Proceedings of the Proceedings International Conference on Multi Agent Systems (Cat. No. 98EX160), Paris, France, 3–7 July 1998; pp. 128–135.
- Bhavsar, V.C.; Boley, H.; Yang, L. A Weighted-Tree Similarity Algorithm for Multi-Agent Systems in E-Business Environments. *Comput. Intell.* **2004**, *20*, 584–602. [\[CrossRef\]](#)
- Tapia, D.I.; Corchado, J.M. An ambient intelligence based multi-agent system for alzheimer health care. *Int. J. Ambient. Comput. Intell. (IJACI)* **2009**, *1*, 15–26. [\[CrossRef\]](#)
- Nematollahi, A.F.; Shahinzadeh, H.; Nafisi, H.; Vahidi, B.; Amirat, Y.; Benbouzid, M. Sizing and Sitting of DERs in Active Distribution Networks Incorporating Load Prevailing Uncertainties Using Probabilistic Approaches. *Appl. Sci.* **2021**, *11*, 4156. [\[CrossRef\]](#)
- Ding, Z.; Huang, T.; Lu, Z. Learning individually inferred communication for multi-agent cooperation. *Adv. Neural Inf. Process. Syst.* **2020**, *33*, 22069–22079.
- Hägg, S. A sentinel approach to fault handling in multi-agent systems. In *Australian Workshop on Distributed Artificial Intelligence*; Springer: Berlin/Heidelberg, Germany, 1996; pp. 181–195.
- Rangwala, M.; Williams, R. Learning multi-agent communication through structured attentive reasoning. *Adv. Neural Inf. Process. Syst.* **2020**, *33*, 10088–10098.
- Roscia, M.; Longo, M.; Lazaroiu, G.C. Smart City by multi-agent systems. In Proceedings of the 2013 International Conference on Renewable Energy Research and Applications (ICRERA), Madrid, Spain, 20–23 October 2013; pp. 371–376.
- Albarakati, A.J.; Azeroual, M.; Boujoudar, Y.; ELIysaouy, L.; Aljarboubh, A.; Tassaddiq, A.; ELMarkhi, H. Multi-Agent-Based Fault Location and Cyber-Attack Detection in Distribution System. *Energies* **2023**, *16*, 224. [\[CrossRef\]](#)

28. Stennikov, V.; Barakhtenko, E.; Mayorov, G.; Sokolov, D.; Zhou, B. Coordinated management of centralized and distributed generation in an integrated energy system using a multi-agent approach. *Appl. Energy* **2022**, *309*, 118487. [\[CrossRef\]](#)
29. Domyshev, A.; Sidorov, D. Optimization of the Structure of Power System Multi-Agent Control. *IFAC-Pap* **2022**, *55*, 250–255. [\[CrossRef\]](#)
30. McArthur, S.D.; Davidson, E.M.; Catterson, V.M.; Dimeas, A.L.; Hatziargyriou, N.D.; Ponci, F.; Funabashi, T. Multi-agent systems for power engineering applications—Part I: Concepts, approaches, and technical challenges. *IEEE Trans. Power Syst.* **2007**, *22*, 1743–1752. [\[CrossRef\]](#)
31. Victorio ME, C.; Kazemtabrizi, B.; Shahbazi, M. Price Forecast Methodologies Comparison for Microgrid Control with Multi-Agent Systems. In Proceedings of the 2021 IEEE Madrid PowerTech, Madrid, Spain, 28 June 2021–2 July 2021; pp. 1–6.
32. Chung, I.Y.; Cheol-HeeYoo SJ, O. Distributed intelligent microgrid control using multi-agent systems. *Engineering* **2013**, *5*, 1–6. [\[CrossRef\]](#)
33. Almada, J.B.; Leao, R.P.; Almeida, R.G.; Sampaio, R.F. Microgrid distributed secondary control and energy management using multi-agent system. *Int. Trans. Electr. Energy Syst.* **2021**, *31*, e12886. [\[CrossRef\]](#)
34. Jabeur, R.; Boujoudar, Y.; Azeroual, M.; Aljarboubh, A.; Ouaaline, N. Microgrid energy management system for smart home using multi-agent system. *Int. J. Electr. Comput. Eng.* **2022**, *12*, 2088–8708. [\[CrossRef\]](#)
35. Zheng, W.D.; Cai, J.D. A multi-agent system for distributed energy resources control in microgrid. In Proceedings of the 2010 5th International Conference on Critical Infrastructure (CRIS), Beijing, China, 20–22 September 2010; pp. 1–5.
36. Logenthiran, T.; Srinivasan, D.; Khambadkone, A.M.; Aung, H.N. Multi-Agent System (MAS) for short-term generation scheduling of a microgrid. In Proceedings of the 2010 IEEE international Conference on Sustainable Energy Technologies (ICSET), Kandy, Sri Lanka, 6–9 December 2010; pp. 1–6.
37. Jin, S.; Wang, S.; Fang, F. Game theoretical analysis on capacity configuration for microgrid based on multi-agent system. *Int. J. Electr. Power Energy Syst.* **2021**, *125*, 106485. [\[CrossRef\]](#)
38. Khan, M.W.; Wang, J.; Ma, M.; Xiong, L.; Li, P.; Wu, F. Optimal energy management and control aspects of distributed microgrid using multi-agent systems. *Sustain. Cities Soc.* **2019**, *44*, 855–870. [\[CrossRef\]](#)
39. Khan, M.W.; Wang, J. The research on multi-agent system for microgrid control and optimization. *Renew. Sustain. Energy Rev.* **2017**, *80*, 1399–1411. [\[CrossRef\]](#)
40. Alhasnawi, B.N.; Jasim, B.H.; Sedhom, B.E. Distributed secondary consensus fault tolerant control method for voltage and frequency restoration and power sharing control in multi-agent microgrid. *Int. J. Electr. Power Energy Syst.* **2021**, *133*, 107251. [\[CrossRef\]](#)
41. Wang, Y.; Nguyen, T.L.; Xu, Y.; Tran, Q.T.; Caire, R. Peer-to-peer control for networked microgrids: Multi-layer and multi-agent architecture design. *IEEE Trans. Smart Grid* **2020**, *11*, 4688–4699. [\[CrossRef\]](#)
42. Mohamed, A.; Lamhamdi, T.; El Moussaoui, H.; El Markhi, H. A multi-agent system for fault location and service restoration in power distribution systems. *Multiagent Grid Syst.* **2019**, *15*, 343–358. [\[CrossRef\]](#)
43. Luo, F.; Dong, Z.Y.; Liang, G.; Murata, J.; Xu, Z. A distributed electricity trading system in active distribution networks based on multi-agent coalition and blockchain. *IEEE Trans. Power Syst.* **2018**, *34*, 4097–4108. [\[CrossRef\]](#)
44. Gomes, L.; Vale, Z.A.; Corchado, J.M. Multi-agent microgrid management system for single-board computers: A case study on peer-to-peer energy trading. *IEEE Access* **2020**, *8*, 64169–64183. [\[CrossRef\]](#)
45. Sesetti, A.; Nunna, H.K.; Doolla, S.; Rathore, A.K. Multi-agent based energy trading platform for energy storage systems in distribution systems with inter-connected microgrids. In Proceedings of the 2018 IEEE Industry Applications Society Annual Meeting (IAS), Portland, OR, USA, 23–27 September 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 1–8.
46. Dong, X.; Li, X.; Cheng, S. Energy management optimization of microgrid cluster based on multi-agent-system and hierarchical stackelberg game theory. *IEEE Access* **2020**, *8*, 206183–206197. [\[CrossRef\]](#)

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.