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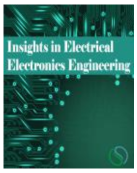

Designing a Multi-Agent System for Smart Grid Management

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Abstract
This paper addresses the claim that by enabling intelligent, flexible, and autonomous decision-making at the local scale, a multi-agent system (MAS) can substantially strengthen the performance, reliability, and durability of smart grid operations. We discuss the design and implementation of a MAS for smart grid management through an in-depth case study, emphasizing particular design decisions, difficulties faced, and results achieved. Among MAS's main benefits are its capacity to guarantee grid stability, reduce overload, and maximize the utilization of resources.

Keywords: multi-agent systems; smart grid; micro grid; distributed generation; energy management; demand response; soft grid; intelligent power systems

Abbreviations: MAS: multi-agent system; DERs: distributed energy resources; VPP: virtual power plant; CHP: combined heat and power; SCADA: Supervisory Control and Data Acquisition; TSO: transmission system organization; EVs: electric vehicles; DG: distributed generation; DR: demand response; IDAPS: intelligent distributed autonomous power system; FIPA: Foundation for Intelligent Physical Agents; CIM: Common Information Model; AMF: agent-based middleware framework; AIS: artificial immune system; RE: renewable energy

1. Introduction

The introduction of smart grids, a major breakthrough in the energy sector, has been fueled by the adoption of new technologies such as sensors, algorithms for control, and intelligent systems inside utility power networks. Increasing reliance on renewable energy (RE) sources like solar and wind power, along with new grid-dependent technologies like electric vehicles (EVs) and heat pumps, provide numerous challenges. To better track and regulate the generation of electricity, the current infrastructure must be upgraded to develop 'smart grids', which include automated meters and cutting-edge communication technology.

Smart grids come with various creative features including demand response (DR), RE integration, vehicle-to-grid capabilities, microgrids, advanced metering, and improved communication. They aim to make electricity networks more effective, reduce pollution, enhance security and reliability, and explore new market opportunities.

Recently, there's been interest in using intelligent algorithms supported by multi-agent systems (MASs) for scheduling tasks in smart grids. These algorithms help minimize costs and efficiently maximize the distribution of resources, particularly for large-scale hydropower stations. Using decentralized pattern search strategies to address issues like economical demand dispatch, MAS also simplifies how resources are allocated in smart grids.

This study explores the implementation of MAS technology in association with complex scientific management principles to create a smart grid data management system. In order to determine how the suggested framework may support the management analysis of the smart grid industry, we first leverage the appropriate information management system and then make use of real-world data to verify and assess it.

2. MAS for Smart Grid Management

The structure of the MAS for smart grid management is designed to support the complex and high-powered operations and goals of modern electric grids. The architecture consists of multiple layers, each playing a crucial role in ensuring effective, dependable, and secure grid management. Here are some key terms to understand before we dive into this section-

Smart grids: A smart grid is a network of electrical power that uses digital and other advanced technologies to oversee and manage the transport of electricity from all sources of its generation to meet the fluctuating electricity demands of clients.

Microgrids: A microgrid is a confined and self-supporting energy system that can operate independently from the main power grid (in off-grid mode) or as a responsive agent with respect to the main power grid (on-grid mode). It consists of distributed energy resources (DERs), such as solar PV plants, wind turbines, and storage systems like batteries, all incorporated and managed by up-to-date software tools and communication technologies.

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The main difference between the smart grid and microgrid is scale. As the name suggests, the microgrid is structured to work in small local areas whereas the smart grid is designed to manage power supply for large communities and is the automated technology used for two-way communication between services and their customers, and sensors across transmission lines.

VPP: A virtual power plant (VPP) is a network of decentralized, medium-scale power generating units as well as adjustable power consumers and storage systems. Their main objective is to interconnect these units to track, anticipate, maximize, and distribute the power of widespread energy resources like wind farms, solar parks, and combined heat and power (CHP) units.

SCADA systems: A control architecture consisting of hardware and software protocols is central to the operation of any power system for exchanging system status and command signals. In traditional electric grids, this is accomplished by Supervisory Control and Data Acquisition (SCADA) systems.

2.1. Design goals

The initial design goals of the MAS for smart grid management were centered on ensuring efficient, reliable, and sustainable operations. These goals can be elaborated through specific use cases that highlight the practical applications of the system:

1. In order to enhance grid stability and credibility, the system needs to react fast to power outages and other disturbances. For example, in the event that a producer detects a power outage, the producer calls all flexible consumers and requests that they lower their power usage to balance the grid. Early involvement and rapid response contribute to grid stability, preventing blackouts and guaranteeing an ongoing supply of electricity.

2. Proper control of electrical supply and demand is crucial for improving energy transportation and usage. In the use case where a customer notifies the producer of a power outage, both parties look into the matter collectively. This collaborative strategy makes it possible to analyze the issue thoroughly, guaranteeing that the underlying cause is found and quickly dealt with. By doing this, the system ensures efficient power distribution, reducing waste, and maximizing consumption.

3. In order to manage high peak loads and make sure that electricity demands are satisfied without overloading the system, demand fulfillment and load balancing must be made easier. For instance, the producer needs to get in touch with other accommodating consumers and request that they cut back on their use when a consumer needs more power — like a large factory needing greater electrical power. Demand is constantly modified to balance the load across the grid, making sure that no consumer puts excessive strain on the system and that all consumers receive the power they are looking for.

4. Appropriate use of resources and decreases in emissions are key components of minimizing operating costs and impact on the environment. A MAS encourages customizable consumption habits to enable these kinds of benefits. When possible or desired, open consumers — represented by system agents with roles specified in the INGENIAS MAS methodology — are expected to cut down on their use of energy. In doing so, the system lowers the carbon footprint and establishes cost savings by lowering the need for additional power generation, which may be expensive and destructive to the environment.

2.1.1. System architecture and agent roles

The MAS architecture consists of several layers that work together to manage the grid productively. This layered approach is vital for handling the complexity and shielding the ongoing operation of the smart grid. Usually, the architecture includes the following layers:

Component and load level agents: Responsible for measurement monitoring, equipment control, and load switching; they check the accurate control and monitoring of individual grid components, providing foundational data and control functions necessary for higher-level operations.

Prosumer agents: Coordinate between upper and lower-level agents, forecast energy generation and demand, and make decisions about energy purchases or sales; they manage local energy production and consumption, making decisions that balance local supply and demand and combine with a broader grid.

DER agents: Predict future energy pricing based on expected generation and interactions with other DER agents; they focus on optimizing the use of DERs, including forecasting and price prediction, to maximize efficiency and cost-effectiveness.

Microgrid agents: Control micro and macro demands and generation units; they oversee the operations within microgrids, ensuring that local generation and consumption are balanced and that microgrids can operate independently if needed.

Distribution level agents: Act as a bridge between the microgrid and the main utility grid, combining with transmission system organization (TSO) agents; they facilitate communication and coordination between microgrids and the main grid, ensuring smooth energy flow and system stability.

TSO agents: Make market decisions based on energy demand and convey requirements to generation plants; they make strategic decisions based on comprehensive data, guiding the operation of generation plants and managing market interactions.

Main grid agents: Monitor the overall system status and resolve issues that lower-level agents cannot handle; they oversee the entire grid's operation, providing high-level monitoring and control to address issues that impact the broader system.

2.1.2. Design advantages

1. Rapid data transmission and decision-making - Instantaneous exchange of data and decision-making are key components of the MAS architecture for smart grid management. The system employs advanced sensing, control, and communication technologies to facilitate:

- **Data acquisition:** Consistent collection of data from various grid components, such as sensors and meters, ensuring up-to-date information on grid status.

- **Data processing:** Synchronous analysis of collected data to identify trends, detect irregularities, and predict future conditions.

- **Decision-making:** Autonomous agents use analyzed data to make informed decisions, alternating their tasks to maintain stability, optimize performance, and respond to changing conditions.

The MAS architecture stands ahead of traditional SCADA systems by offering more sophisticated supervisory and control applications, allowing for more dedicated and adaptive grid management.

2. Cooperation and control mechanisms - Effective coordination and control of agents is achieved through the hierarchical and collaborative structure of the MAS in smart grids:

    - **Hierarchical coordination:** Agents work in a layered power structure, with each level performing particular functions and support to the levels above and below. This structure ensures that decisions are made at the appropriate level, with high-level agents overseeing broader strategies and low-level agents handling detailed control tasks.

    - **Collaborative control:** Agents work together to achieve common goals, sharing information and coordinating actions. For example, in the case of a power shortage, those consumers who require less may reduce their consumption to balance the load, coordinated by higher-level agents to ensure grid stability.

    - **Active team-forming mechanisms:** Agents can progressively form teams to address specific issues, such as power restoration after an outage. This flexibility allows the system to adapt to changing conditions and manage complicated tasks accurately.

3. Adaptability to dynamic grid conditions - The system is designed to adapt to active grid conditions, allowing for immediate adjustments and responses to changing operational environments and demands. This adaptability is demonstrated in the use of MAS for the improvement of temporary stability in smart grids, which helps avoid the loss of ongoing functioning in the power system. The ability to adjust to varying conditions ensures continuous and stable grid operations.

4. Scalability for future expansions - Scalability is prioritized in the system design to accommodate future expansions and enhancements, enabling effortless incorporation of new functionalities and scaling to meet growing grid requirements. The MAS architecture supports scalability through its layered approach, allowing for the addition of new agents and roles as the grid expands. This ensures that the system can grow and evolve as the demands increase and the technology of the system advances.

5. Decentralization for flexibility and robustness - The system uses a distributed approach to allow for flexibility and robustness, enabling individual agents to make independent decisions based on local information (data stored and shared by agents). In smart grids, decentralization is critical as it helps in achieving control of the system by meeting its technological requirements and dividing it into particular domain-based structures. For example, Ilo's [1] introduction of the concept of Link, which includes Grid-Link, Producer-Link, and Storage-Link architectures, follows the dispersed working structure, ensuring long-lasting and versatile management of the system.

3. MAS Framework for Smart Grids

In this section, we provide a thorough overview of existing MAS, simulation platforms, or potential frameworks that could be employed in the installation of smart grids for their better management and improved functioning. We will be considering numerous literature research and reviews in the smart grid field concerned with its incorporation of multi-agent technology.

3.1. MASGriP

- The research project by Oliveira et al. [2] on a multi-agent-based approach for intelligent smart grid management discusses MASGriP, a multi-agent simulation platform for smart grids that is designed to imitate the internal workings of smart grids. Each player is characterized by an agent that mimics their respective smart grid player's abilities. Through collaboration, MASGriP and MASCEM — a MAS that mirrors competitive electricity markets — allow participants, particularly virtual power players, to engage in market negotiations. Within MASGriP, VPPs supervise internal assets such as storage spaces, EVs, distributed generation (DG), and DR.

- A detailed case study is provided which demonstrates MASGriP's capabilities with two control scenarios for a microgrid. In one, the microgrid controls demands and production units to maximize results. In the other, players adapt based on the VPP's information, using price variations, EV batteries, and DR programs.

- Power system practitioners as well as learners can benefit from MASGriP's multi-agent approach, which successfully models diverse and independent agents and uses distributed intelligence to help guide actions in smart grid and microgrid environments. It provides strong management tools and AI to aid operators and players, offering legitimate action suggestions. MASGriP addresses problems in managing decentralized production, particularly with regard to RE sources, and integrating EVs into power systems.

3.2. MAS architecture for a distributed smart grid

- The paper by Pipattanasomporn et al. [3] on the design and implementation of MASs in a distributed smart grid proposes the development of a multi-agent application that uses an IP-based network following the IEEE FIPA standard for message exchange. The study shows, through experimentation, that MASs can control a distributed smart grid in a simulated environment, supporting smooth transitions to island mode during challenging outages, thus proving effective for microgrid management.

- The focus is on designing and implementing a MAS in an intelligent distributed autonomous power system (IDAPS), a smart grid concept by Virginia Tech's Advanced Research Institute. The MAS in IDAPS enables the microgrid to operate on its own during outages, offering a software alternative to traditional hardware-based defined protection systems and allowing active redefinition of established boundaries.

- Zeus was chosen for the implementation of the proposed MAS due to its user-friendly features that support agent communication and power exchange negotiations. The development process includes agent specification, evaluation of their roles, design, understanding, and implementation, as detailed in the paper.

- The system includes control, DER, user, and database agents. Responsibilities of control agents include registration handling, system voltage monitoring, subscriber updates, grid state analysis, information storage, and graphical display. DER and user agents handle registration, communication, external measurements, progress updates, and user inputs.

- Further, the study presents an actual simulated case study which shows that the suggested multi-agent architecture can disconnect and stabilize the microgrid during outages, providing versatile protection, hence demonstrating a practical application of MASs in a distribution-level smart grid.

3.3. MAS for communication between smart grid agents

- Smart grid collaborations require a two-way data flow for DG, wide-area situational awareness, DR, and advanced dispersing infrastructure, operating on neighborhood, wide area, and local area networks. These networks depend on various infrastructures and standards, with MAS installation details provided by the Foundation for Intelligent Physical Agents (FIPA) standards.

- The Common Information Model (CIM) supports information exchange about electrical network arrangements, while IEC 61850 systemizes the automated design of an electric substation. Intelligent grid nodes use a multi-agent communication language - FIPA ACL - for communication, and message exchanges occur through CIM/IEC 61850. Nieves et al. [4] discussed semantic and syntactic interoperability in smart grids, and Misra et al. [5] presented a learning automata-based fault-tolerance method for productive energy management.

3.4. MAS and soft grids

- Power facilities are upgrading communication and information systems for effective smart grid control through end-to-end coordinated control using software; a concept known as the "soft grid." As experimented in the articles by Mathe et al. [6] and Zhou et al. [7], employing MAS can successfully achieve the needs of a soft gird.

- Dillon et al. [8] used software and web technology to design a grid architecture that overcomes existing limitations of digital grids. In the paper by Kamdar et al. [9], a LabVIEW software-based multi-agent approach was introduced for grid control and restoration during faults and outages.

- In the paper by Tom et al. [10], a MAS was developed for smart energy management in an IoT-based system. The soft grid promotes negotiation among agents to accept the best offers and reduces the demand for power services.

3.5. MAS for voltage maintenance, power trade, and demand response

- Ren et al. [11] proposed an agent-based methodology to maximize system reliability during repair by using load balancing as an obstruction and developed a novel wolf pack algorithm to boost the restoration strategy.

- Klaimi et al. [12] reduced the loss of smart grid users by reflecting power loss effects on the costs of energy and using an energy storage system to meet their daily energy demands.

- The paper by Santos et al. [13] introduced a hierarchical centralized MAS to strengthen emergency response techniques like load shedding. Gomes et al. [14] proposed a microgrid management architecture using a multi-agent strategy for easy fulfillment of various energy procedures.

- Chang et al. [15] developed an agent-based middleware framework (AMF) for improved communication resilience in smart cities. Keshta et al. [16] created a MAS for ideal energy management, voltage regulation, and stability under different conditions for two connected microgrids.

- Moreover, a direct-current MAS using hybrid hydrogen fuel cells and RE was reported by Shulga et al. [17]. Further, Kong et al. [18] proposed a MAS-based excellent bidding procedure using the artificial immune system (AIS) for DER cooperation for power solutions.

4. Challenges and Future Priorities for Research

Challenges in the design and implementation of smart grids include combining heterogeneous devices and protocols, managing large volumes of real-time data, ensuring the security and privacy of sensitive information, and handling uncertainties and active changes in the grid environment.

- Incorporating widespread devices like DERs and DG devices requires powerful strategies for easy communication within the grid. Accurately processing vast data streams demands the need for scalable systems with advanced problem-solving features.

- Establishing security in grids involves tough cybersecurity measures to protect against weaknesses and managing dynamic changes requires adaptive strategies to respond to supply and demand fluctuations, connecting latest predictions and versatile grid frameworks.

- These challenges reflect broader issues in global energy markets, including inaction of specific agents, technological unifications, and evolving consumer behavior, and addressing them is key for the successful, secure, and resilient operation of modern energy grids.

The present focus is on increasing the intelligence of scattered low-carbon energy sources and inserting cargo like EVs and heat pumps into smart grids. This poses major problems, including disruptions of power flow and voltage variations affecting customers and service equipment. Guaranteeing proper functioning while minimizing the negative impacts of these new energy sources and loads is a highly complicated task that requires collective control of smart grids.

MASs offer a better solution than existing SCADA systems for this coordinated control since, as we expand in the above section, they can manage voltage variations, smart grid power markets, demand-side responses, load forecasting, production forecasting, and generation scheduling, especially during high RE inclusion. Additionally, the concept of a "soft grid" can be realized using MAS, offering optimized control and coordination of smart grids with high levels of RE infiltration.

Future research should focus on the prospective use of MAS for maximum and cooperative control of smart grids. Investigations should aim to improve various complex irregularities within these networks. Implementing MAS in smart grids with high RE levels could beneficially coordinate smart events and processes, enhancing grid flexibility to mirror RE fluctuations. This could lead to better performance and higher levels of RE sources in smart grids, creating more permanent and valuable energy systems.

5. Conclusion

To sum up, smart grids represent the evolution of traditional electric grids, featuring two-way circulation of energy and information. It combines advanced technologies like smart measuring infrastructure to precisely measure power consumption. However, controlling smart grids remains a consistent challenge. Researchers are exploring the possibility of collective control through MASs to oversee the operations of these grids. This paper collects existing research in this area to shed light on present achievements and guide future studies. Today's grids are becoming increasingly digital, with sensors, communication systems, and self-monitoring capabilities, making them smart. Various standards like IEEE and IEC offer protocols for efficient grid operation and MAS plays a vital role in managing energy, pricing, and scheduling. It also offers benefits like improved communication and self-healing capabilities and this research paper aims to assist consumers, designers, researchers, and engineers in future smart grid development.

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