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ARCHITECTURE OF THE ELECTRICITY MANAGEMENT SYSTEM FOR THE MICROGRID NETWORK

Abstract: *The paper presents a comprehensive approach to developing an electricity management system architecture for a microgrid network, based on a layered structure and the integration of modern information and intelligent components. The proposed architecture includes three main levels: basic, information, and software. The basic level provides physical interaction with generators, energy storage systems, and electricity consumers, and is also responsible for basic data collection and transmission. The information level organizes structured storage, processing, and systematization of data, provides access to the knowledge base, and allows the integration of heterogeneous information sources. The application level implements functional services for data analysis, decision-making, and optimization of management processes. Particular attention is paid to the possibility of integrating an ontological model as a tool for formalizing knowledge about energy processes, which ensures data standardization, increases their consistency, and simplifies interaction between system components. The implementation of such a model allows for semantic analysis of information, ensures the logical interdependence of Microgrid elements, and supports intelligent decisions in conditions of uncertainty. The paper describes the principles of architectural construction, interaction between levels, and key functional modules, as well as the role of the ontological approach in improving management efficiency. A review of existing control systems has shown that most of them do not provide for the use of an ontological model, which limits the possibilities for standardization and data integration. The proposed architecture eliminates these limitations, creating a basis for automating monitoring processes, optimizing electricity distribution, and improving the reliability of Microgrid operation. The use of a multi-level structure allows a clear definition of the functions of each element, ensuring transparency of processes, and integrating intelligent modules for analyzing and forecasting energy flows. This approach creates the conditions for the further development of intelligent control systems, improving energy efficiency, and reducing electricity losses. The implementation of the proposed architecture in practical systems can contribute to the creation of sustainable, autonomous, and scalable microgrids capable of adapting to changing conditions of energy generation and consumption, as well as ensuring integration with external energy networks and management platforms.*

Keywords: *Microgrid, architecture, ontological model, level-based approach, decentralized control, energy consumption management system, autonomy*

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АРХІТЕКТУРА СИСТЕМИ УПРАВЛІННЯ ЕЛЕКТРОЕНЕРГІЄЮ ДЛЯ МЕРЕЖІ MICROGRID

Анотація: *У статті представлено комплексний підхід до розробки архітектури системи керування електроенергією для мережі Microgrid, який базується на рівневій структурі та інтеграції сучасних інформаційних та інтелектуальних компонентів. Запропонована архітектура включає три основні рівні: базовий, інформаційний та програмний. Базовий рівень забезпечує фізичну взаємодію з генераторами, системами накопичення енергії та споживачами електроенергії, а також відповідає за базовий збір та передачу даних. Інформаційний рівень організовує структуроване збереження, обробку та систематизацію даних, забезпечує доступ до бази знань та дозволяє інтегрувати різнорідні джерела інформації. Програмний рівень реалізує функціональні сервіси для аналізу даних, прийняття рішень і оптимізації управлінських процесів. Особливу увагу приділено можливості інтеграції онтологічної моделі як інструмента формалізації знань про енергетичні процеси, що забезпечує стандартизацію даних, підвищує їх узгодженість та спрощує взаємодію між компонентами системи. Впровадження такої* *моделі дозволяє проводити семантичний аналіз інформації, забезпечувати логічну взаємозалежність елементів Microgrid та підтримувати інтелектуальні рішення в умовах невизначеності. Стаття описує принципи побудови архітектури, взаємодію між рівнями та ключові функціональні модулі, а також роль онтологічного підходу у підвищенні ефективності управління. Проведений огляд існуючих систем керування показав, що більшість з них не передбачає використання онтологічної моделі, що обмежує можливості стандартизації та інтеграції даних. Запропонована архітектура усуває ці обмеження, створюючи основу для автоматизації процесів моніторингу, оптимізації розподілу електроенергії та підвищення надійності роботи Microgrid. Використання багаторівневої структури дозволяє чітко визначити функції кожного елемента, забезпечити прозорість процесів та інтегрувати інтелектуальні модулі для аналізу та прогнозування енергетичних потоків. Такий підхід створює передумови для подальшого розвитку інтелектуальних систем керування, підвищення ефективності енергоспоживання та зниження втрат електроенергії. Впровадження запропонованої архітектури у практичні системи може сприяти створенню стійких, автономних та масштабованих Microgrid, здатних адаптуватися до змінних умов генерації та споживання енергії, а також забезпечити інтеграцію з зовнішніми енергетичними мережами та платформами управління.*

Ключові слова: *Microgrid, архітектура, онтологічна модель, рівневий підхід, децентралізоване управління, система управління енергоспоживанням, автономність*

1. Introduction

Modern power systems are undergoing a transformation driven by the active introduction of renewable energy sources, increasing electrical loads, and the need to ensure high reliability of the energy supply. In these conditions, the concept of a microgrid—a localized energy system capable of operating both within a centralized network and autonomously—is becoming particularly important. Microgrids allow decentralized generation sources, energy storage systems, and flexible consumers to be combined into a managed intelligent structure that provides stability, efficiency, and adaptability to changing conditions.

Along with the development of Microgrid, the requirements for the control system are growing, which must not only balance generation and load in real time, but also ensure optimization of energy distribution, integration of data from heterogeneous sources, support for decision-making, and interaction with external networks. The formation of such a system requires a clearly defined architecture that guarantees structure and the possibility of further expansion of functional capabilities.

Contemporary research offers various architectural approaches to building Microgrid control systems, but most of them focus on energy management tasks without considering the need for a formalized knowledge model. At the same time, the integration of an ontological approach can significantly increase the level of intelligence of the system by unifying the data structure, formalizing processes, and enabling semantic analysis.

This paper considers the construction of a layered architecture for a microgrid control system that combines traditional functional components (monitoring, communication, data analysis, control optimization) with the possibility of using an ontological model to improve information collection and processing. The developed architecture is designed to ensure consistency, improve decision-making efficiency, and create a basis for the further development of intelligent functions of energy systems.

2. Purpose of the study

The purpose of this study is to develop an architecture for an electricity management system for a microgrid network that provides a structured combination of processes for collecting, processing, and analyzing data from power system elements. To achieve this goal, a layered approach to system construction is proposed, which includes basic, information, and software layers, as well as integrating intelligent information processing modules. Particular attention is paid to the possibility of using an ontological model to formalize knowledge about energy processes, improve data consistency, and support decision-making.

The proposed architecture is aimed at optimizing power distribution, improving the stability of the microgrid, increasing management efficiency, and ensuring the possibility of further expanding the functionality of the system through the integration of intelligent components.

3. Related work

The Energy Management System (EMS) ensures the economical operation of the microgrid by optimizing the use of renewable energy sources and storage devices. This reduces the cost of operating backup fuel installations, such as diesel generators. In most cases, microgrids are designed as energy self-sufficient structures. At the same time, they can operate in both networked and isolated modes, depending on specific conditions and areas of application. Individual neighboring microgrids can be combined for mutual energy exchange, which increases their overall efficiency. For such interconnected systems, especially when several generators are connected to the grid, it is more appropriate to use decentralized EMS architectures [1].

The approach to managing restrictions allows for an increase in the volume of electricity imports from the main grid and, at the same time, a reduction in financial costs through the optimal use of Energy Storage Systems (ESS). In source [2], the issue of power distribution between interconnected microgrids is solved using a centralized controller. It uses an algorithm based on Model Predictive Control (MPC) modeling, which determines the optimal power distribution and charging/discharging schedule for storage devices based on the forecast of electricity costs in both the general grid and adjacent microgrids.

The above works do not take into account the operation of dispatch sources, such as diesel generators, which are widely used in remote microgrids. The presence of such sources and the need to comply with additional system constraints significantly complicate the optimization task. In addition, in real-world conditions, power losses in microgrids can be significant, sometimes making energy exchange less efficient or even impractical.

Work [3] focuses on formalizing the task, which covers the operation of a diesel generator of ESS, as well as wind and solar installations. Additionally, the possibility of electricity exchange with both the main grid and neighboring microgrids is taken into account. To determine the optimal operating modes of generators and rational power distribution, a two-stage decentralized EMS architecture is proposed. A new tertiary-level mechanism based on cost minimization is presented separately, which integrates with the EMS to ensure the individual requirements and advantages of each microgrid during energy exchange.

A multi-level control system that ensures coordinated operation and efficient power distribution between interconnected microgrids minimizes operating costs within each microgrid separately and enables energy exchange between them when beneficial. The second level is responsible for optimizing generation schedules, while the third level determines the optimal distribution of power.

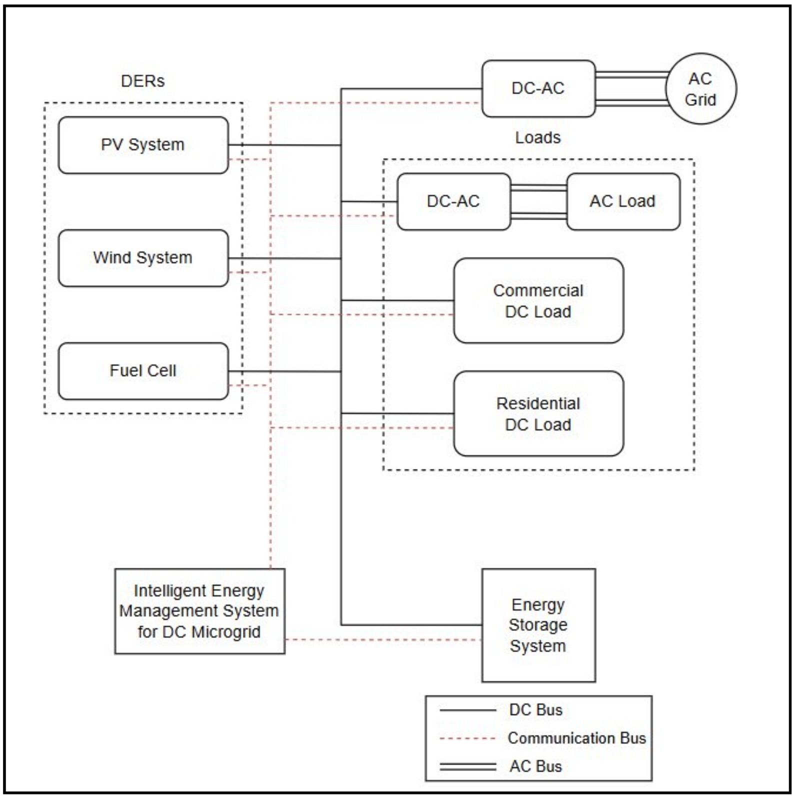

Fig. 1. Structural diagram of DCMG operation

Based on the work [4], microgrids can be divided into two basic types: Alternating Current Microgrids (ACMG) and Direct Current Microgrids (DCMG). In recent years, interest in DCMG has grown significantly due to increased demand for direct current systems, particularly for charging electric vehicles and operating rechargeable batteries. DCMGs are considered a more promising option than ACMGs due to their simpler management and operation, higher reliability, better controllability, lower losses during power transmission, and easier equipment integration. Unlike ACMG, Direct Current (DC) systems do not have problems related to maintaining frequency and power quality parameters, which reduces the risk of emergency shutdowns or network disruptions.

DCMG primarily uses renewable energy sources, which helps reduce CO_2 emissions and improve the environmental performance of the power system. Improving the efficiency of converters and power transmission systems at DCMG reduces losses and simplifies the integration of power sources. Distributed Energy Resources (DER), such as photovoltaic panels, wind turbines, and fuel cells connected to local loads, provide a stable and reliable supply of electricity. Photovoltaic panels generate direct current, are easily integrated into DCMG, and have low operating costs, while wind energy, although alternating current, can provide a continuous supply through converters. A structural diagram of DCMG is shown in Figure 1.

Battery Storage Systems (BSS) at DCMG play a key role in providing energy during the absence of renewable sources and backup power for critical loads [5]. Modern lithium-ion batteries have high energy density and fast response times, allowing them to meet the dynamic needs of DCMG, although their initial cost remains high.

DCMG also integrates effectively with electric vehicles, providing fast and reliable charging, as well as the ability for bidirectional energy exchange between vehicles and the grid (V2G and G2V). In addition, most household and commercial devices operate on direct current, making DCMG effective for powering home electronics, lighting, and charging stations, as well as telecommunications and data centers, where stability and security of power supply are critical.

Multi-Microgrid (MMG) connected to the external network is presented in [6]. Energy flows in MMG are controlled at two levels:

1) at the level of a separate microgrid to balance Diesel Generator (DG) power and local loads within each Microgrid;

2) at the MMG level to coordinate energy exchange between Microgrids and ensure energy operations between the Distribution Network (DN) and Microgrid.

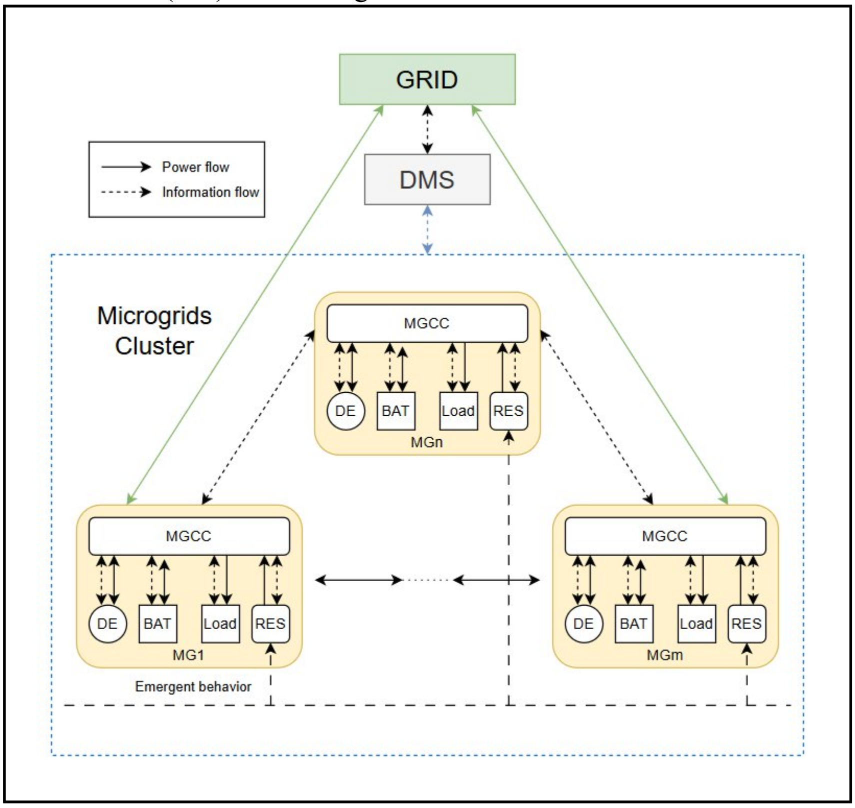

Fig. 2. SoS architecture for energy flow management in the MMG system

Each Microgrid is an autonomous, geographically distributed system that integrates Renewable Energy Sources (RES), Energy Storage (ES) systems, and DG to meet local needs [7]. Energy management at the individual microgrid level aims to compensate for temporary fluctuations in RES generation and load consumption by leveraging the advantages of ES, DG, and the complementary characteristics of different RES [8]. In this context, optimization under uncertainty is a reasonable approach.

System of Systems (SoS) architecture for managing energy flows. Each Microgrid functions as a centralized autonomous system thanks to a central controller known as the Microgrid Central Controller (MGCC). The MGCC generates and sends the schedule for the next day to local DG and load controllers, and adjusts this schedule based on feedback from local controllers (Figure 2).

The Multi-Microgrid system has a hierarchical decentralized SoS structure [9]. Individual Microgrids are managed and operated independently, and they can be connected to the MMG. An MMG-level controller known as a Distribution Management System (DMS) is used to coordinate energy exchange between the involved Microgrids and conduct energy trading with the DN. Energy management at the MMG level interacts with the DN and coordinates the participation of Microgrids in the system [10].

In other words, each MGCC involved receives the optimal solution for energy management within the Microgrid, taking into account the energy exchange and trading request from the DMS. At the same time, the DMS evaluates the effectiveness and optimality of energy management decisions for the entire MMG based on data received from the MGCC.

4. Results and discussion

When considering energy management architectures, a Microgrid does not provide for the use of an ontological model. This creates a methodological gap, since without a formalized semantic description of the system elements and their interactions, it is impossible to ensure full consistency of the processes of collecting, processing, and further using information. That is why there is a need to develop an architecture that will integrate an ontological model as the basis for forming a unified Microgrid information space.

Computable ontologies are a formal way of representing knowledge that allows semantic relationships between different data elements to be defined and provides computer systems with a deeper understanding of the context of information. When applied to a Microgrid, ontology is a key tool that unifies the interpretation of data collection, classification, and processing processes. It provides a formal model that defines what data should be obtained, how it should be structured, and how it should be used for decision-making.

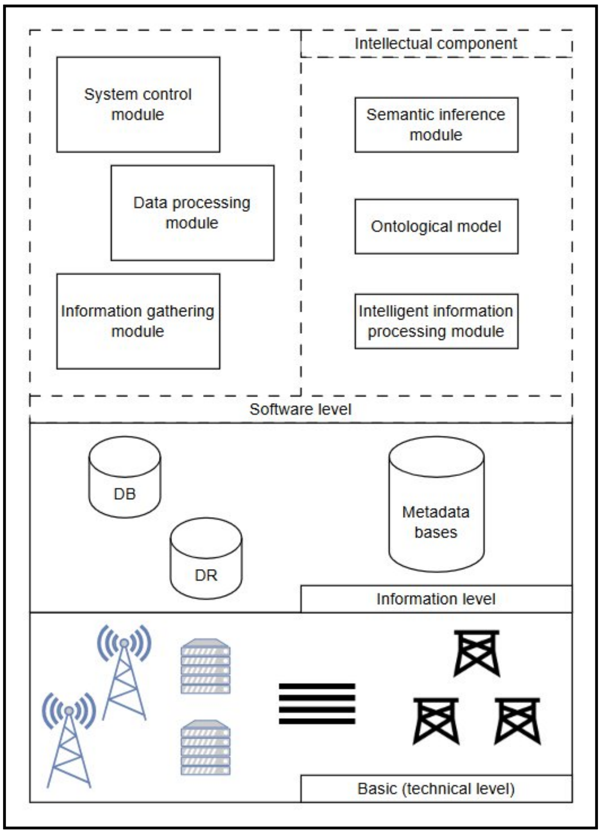

Fig. 3 Architecture of the Microgrid power management system

The ontological approach allows standardizing the presentation of information, ensuring compatibility between system components, simplifying integration with external platforms, and increasing the transparency of control logic for engineers and administrators. An ontological model of the information collection and processing system in Microgrid, aimed at optimizing control processes, is presented in [11]. The use of such a model ensures the formalization of parameters and interrelationships, allowing the system to be viewed as a clearly defined structure with formally described properties.

An ontology is a systematic representation of a subject area based on raw data stored in a relevant database. Such data includes information about energy production and consumption, equipment status, current energy costs, and other relevant parameters.

The implementation of the proposed control system architecture aims to optimize electricity distribution, use intelligent algorithms to improve network efficiency and reliability, and automate monitoring and control processes.

The system is built on a multi-level structure that ensures a clear distribution of functions and interaction between components, as shown in Figure 3.

It comprises three main levels:

1. The basic level, which includes base stations, power generators, data storage servers, and power transmission lines. If necessary, a separate communication level can be added, and some of the basic level components will be integrated into it.
2. The information level, which contains a database and information repository, ensures the preservation, organization, and structured presentation of all system resources and indicators.
3. The software level is shown in Figure 4, which is a key component of the control system architecture, as it provides interaction between information resources and intelligent analysis modules. The software level is represented by a set of software tools that implement a range of functional services for data processing, decision-making, and support of management processes in Microgrid. The set is shown in Figure 4 and includes:

- Management service that coordinates the operation of all software modules;
- A data processing service that performs preliminary filtering and normalization of data;
- A resource collection service that integrates data from generators, energy storage systems (ES), and consumers;
- Knowledge base containing formalized rules and an ontological model;
- An intelligent information processing service that performs in-depth data analysis based on an ontological model, establishes logical relationships between Microgrid elements, and makes decisions based on the intelligent component.

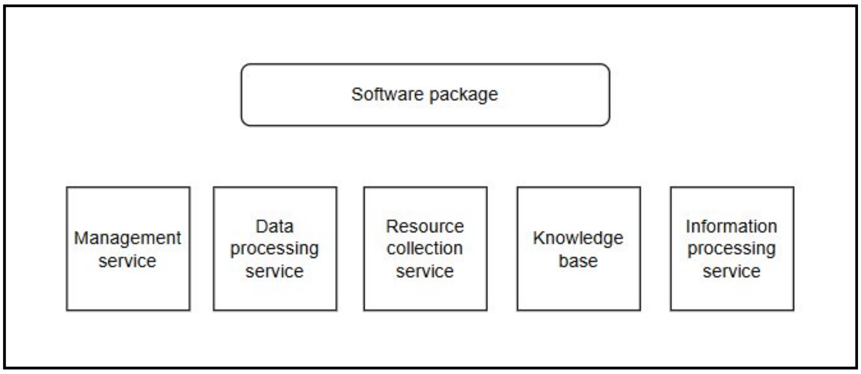

Fig. 4. Software level of architecture

Intelligent software modules, such as an ontological model, a semantic inference module, and an intelligent information processing module, provide in-depth data analysis and enable decision-making in conditions of uncertainty. The software suite acts as an integrating link between the information and intellectual levels, ensuring a systematic, structured, and formalized approach to electricity management in a Microgrid.

The proposed level architecture reflects the logical structure of the system, includes key elements of its functioning, and allows for formalized analysis of component interactions. Unlike an unsystematic list of components, the level model provides a clear definition of the role of each element and their interrelationships, increasing the efficiency of planning, optimization, and management of energy flows.

5. Conclusion

This paper presents a control system architecture for microgrid networks, structured according to a hierarchical principle and designed to support complex processes of monitoring, analysis, and distribution of electricity. The proposed solution combines information resources, software services, and intelligent modules into a single coordinated structure that ensures systematic management.

A review of existing architectures has shown that despite the large number of approaches to management in power systems, most of them do not take into account the need for deep structuring and formalization of data. This complicates the integration of heterogeneous Microgrid components and creates barriers to the development of intelligent management functions. To address these limitations, the proposed architecture also provides for the use of an ontological model as a tool for semantic data consistency, which enhances the performance of the information and software levels.

The proposed architecture provides: a clear separation of functions between the basic, information, software, and intellectual levels; the ability to centrally collect, pre-process, and structurally analyze data; and support for intelligent decisions to optimize Microgrid operation.

Level architecture is an effective approach for building modern Microgrid management systems, ensuring transparency of interaction between elements, ease of modernization, and the possibility of implementing advanced decision-making mechanisms. The ontological component, although not a key element, enhances the system's capabilities for formalized data analysis and ensures data consistency.

Further research should focus on improving intelligent optimization modules, testing the architecture in real-world energy scenarios, and expanding its capabilities for operation in microgrids. This will improve management efficiency, reduce energy losses, and lay the foundation for the deployment of more sustainable and autonomous energy supply systems.

References

1. Olivares D. E., Lara J. D., Caizares C. A., Kazerani M. Stochasticpredictive energy management system for isolated microgrids. *IEEE Transactions on Smart Grid*. 2015. Vol. 6, pp. 2681–2693. DOI: 10.1109/TSG.2015.2469631

2. Ouammi A., Dagdougui H., Dessaint L., Sacile R. Coordinated Model Predictive-Based Power Flows Control in a Cooperative Network of Smart Microgrids. *IEEE Transactions on Smart Grid*. 2015. Vol. 6, no. 5, pp. 2233-2244. DOI: 10.1109/TSG.2015.2396294

3. Isuru Sampath L. P. M., Krishnan A., Chaudhari K., Gooi H. B., Ukil A. A control architecture for optimal power sharing among interconnected microgrids. *IEEE Power & Energy Society General Meeting*. 2017. Chicago, IL, USA, pp. 1-5. DOI: 10.1109/PESGM.2017.8274333

4. Shah T., Ansari Z. A. An Overview of Intelligent Energy Management System for DC Microgrid: System and Communication Architecture and Application in Power Distribution System. *IEEE 13th International Conference on Industrial and Information Systems (ICIIS)*. 2018. Rupnagar, India, 2018, pp. 1-4. DOI: 10.1109/ICIINFS.2018.8721384

5. Hossain E., Perez R., Bayindir R. Implementation of Hybrid Energy Storage Systems to Compensate Microgrid Instability in the Presence of Constant Power Loads. International Journal of Renewable Energy Research. 2017. 2(7), 1-13. DOI: https://doi.org/10.20508/ijrer.v7i2.5622.g7054

6. Hatziargyriou N. Microgrids: Architectures and Control. Hoboken, NJ, USA: Wiley. 2014. https://ieeexplore.ieee.org/servlet/opac?bknumber=6685216

7. Zhang C., Xu Y., Dong Z. Y., Ma J. Robust Operation of Microgrids via Two-Stage Coordinated Energy Storage and Direct Load Control. *IEEE Transactions on Power Systems*. 2017. Vol. 32, no. 4, pp. 2858-2868. DOI: 10.1109/TPWRS.2016.2627583

8. Khodaei A., Bahramirad S., Shahidehpour M. Microgrid Planning Under Uncertainty. *IEEE Transactions on Power Systems*. 2015. Vol. 30, no. 5, pp. 2417-2425. DOI: 10.1109/TPWRS.2014.2361094

9. Marvasti A. K., Fu Y., DorMohammadi S., Rais-Rohani M. Optimal Operation of Active Distribution Grids: A System of Systems Framework. *IEEE Transactions on Smart Grid*. 2014. Vol. 5, no. 3, pp. 1228-1237. 10.1109/TSG.2013.2282867

10. Zhao B., Wang X., Lin D., Calvin M. M., Morgan J. C., Qin R. Energy Management of Multiple Microgrids Based on a System of Systems Architecture. *IEEE Transactions on Power Systems*. 2018. Vol. 33, no. 6, pp. 6410-6421. DOI: 10.1109/TPWRS.2018.2840055

11. Stepanov G., Novogrudska R. Interoperability Solutions for Enhanced Energy Network Efficiency: Models, Management, and Integration. *In: Ilchenko M., Uryvsky L., Globa L. (eds) Advanced Smart Information and Communication Technology and Systems. MCT 2024. Lecture Notes in Networks and Systems*. 2025. Vol 1470. Springer, Cham. DOI: https://doi.org/10.1007/978-3-031-94799-5_4