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Integrating Microgrids into Engineering Education: Modeling and Analysis for Voltage Stability in Modern Power Systems

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Abstract: The research focuses on incorporating microgrids into engineering curricula for achieving voltage stability in today's power systems. This helps to meet the increasing demand for engineers to integrate distributed power generation and renewable energy sources. Some limitations of the current literature include the absence of models outlining approaches to microgrid education and limited insight into teaching strategies for electrical power systems. The research used a quantitative methodology to survey 100 engineering students enrolled in a microgrid modeling class to achieve the study's objectives. The data analysis involved machine learning models such as Random Forest, Gradient Boosting, K-Means, hierarchical clustering, and regression models. The major findings identified exam score as the most significant determiner of student performance (weight ≈ 0.40). Based on the clustering analysis, it was found that microgrid systems can be grouped into four operational states. It was also seen that linear regression models were highly accurate and better than other highly complex models, like Decision Tree, with a model accuracy of $R^2 \approx 0.4$. One of the study's major strengths is the potential impact of the proposed framework for integrating microgrids into engineering education on the professional training of engineers. This framework, based on theoretical knowledge and practical experience as well as on developing advanced analytical skills, can significantly enhance the professional training of engineers to deal with the complexities of contemporary power systems, including microgrids and sustainable energy progress.

Keywords: engineering curriculum; engineering education; gradient boosting; hierarchical clustering; microgrids; machine learning; power generation; renewable energy sources; random forest; voltage stability

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Citation: Bano, F.; Rizwan, A.; Serbaya, S.H.; Hasan, F.; Karavas, C.-S.; Fotis, G. Integrating Microgrids into Engineering Education: Modeling and Analysis for Voltage Stability in Modern Power Systems. *Energies* **2024**, *17*, 4865. https://doi.org/10.3390/en17194865

Academic Editor: Juan-José González de la Rosa

Received: 2 September 2024
Revised: 22 September 2024
Accepted: 25 September 2024
Published: 27 September 2024

1. Introduction

The main purpose of this section is to introduce the topic, define the research problem, and review and analyze existing studies related to microgrid modeling, voltage stability, and educational integration to establish the research gap. Incorporating microgrids into engineering curricula is significant given the advancements in global power systems wherein decentralized generation and renewable energy sources are adopted. The change is due to increasing concerns over high-carbon electricity generation, energy security, and better transmission and distribution networks [1]. Microgrids, as low-voltage power supply systems that operate in parallel to the leading electricity network, are found to be vital for voltage control and system reliability. However, modern engineering curricula must be revised to adequately cover microgrid concepts and the technical practices necessary to train engineers for contemporary power systems [2]. Due to the challenges faced in microgrid design, management, control, and operation aspects, a multidisciplinary approach is required in engineering education.

Renewable energy and the evolution to decentralized power generation has radically changed power systems worldwide. This change is due to the increased demand for lower carbon generation, better energy security, and improved transmission and distribution systems. This transformation is all about the rise of microgrids [3]. Microgrids are localized low-voltage electricity supply systems that coexist with the general electricity supply network. They aim to produce electricity at the point of consumption to minimize transmission losses and maximize effective use of the generated power output. Thus, renewable energy sources, including solar panels, wind turbines, and biomass microgrids, are essential in modernizing electricity supply systems. Voltage stability is one of the most critical measures for power system reliability; microgrids play a crucial role [4].

The centralized power grids that have been the primary type of power distribution in the past must be better suited to local demand and supply variations. This includes voltage ripple, poor power quality, and even complete power loss or shutdowns. However, microgrids, designed to accept local conditions, offer a more stable alternative. This feature is particularly beneficial when connecting renewable energy sources, as they are naturally variable. For instance, solar panels produce electrical power depending on the time of the day and climate [5], whereas wind turbines rely on wind velocity and direction. Studies have shown that microgrids can significantly improve voltage stability, provide additional energy storage systems, and employ advanced controls. Energy storage devices, including batteries, can store excess energy generated and not used during off-peak hours and release it during high-demand moments, effectively avoiding voltage fluctuations [6,7]. This potential for improved voltage stability should inspire optimism about the future of power systems.

Researchers have found that microgrids enhance voltage and frequency control by allowing centralized operations and minimizing extensive network use [8]. This capability is especially important in distant or sparsely populated regions where losses in transmission and voltage could be high. In this way, microgrids lessen the impact on the primary grid and increase the dependability of the electricity supply system [9]. Moreover, microgrids can also function independently when the primary grid is unstable, for example, due to storms or other disasters. In islanded mode, a microgrid ceases to be a part of its parent grid. It can operate similarly, serving its consumers and maintaining the power supply whether the primary grid is up or down [10]. This feature also contributes to the general reliability of the power system. However, there are several difficulties in using microgrids when connected to the existing power grid, including issues of control and operation. Control strategies are needed to make multiple microgrids combined with the main grid work with proper management of variations [11]. The current power system infrastructure needs to be fully prepared for the complexity of microgrids and hence requires many changes. Several control solutions, including centralized control systems, decentralized control systems, and hierarchical control systems, are under development to meet these challenges [9,10].

A central control center is responsible for the coordination of all of the microgrids. On the other hand, the decentralized system enables individual microgrids with different owners to function autonomously and correspond infrequently and sporadically with other microgrids. A hierarchical control system offers a blend of both approaches with a flexible structure to ensure that control is increased while at the same time increasing the level of freedom given to subordinates [12]. All of these control strategies have their strengths and weaknesses, and the decision to use one or the other depends on several considerations, including the size and complexity of the system as well as its specific operational needs. If future engineers are to embrace the challenges of decentralized power systems, then teaching must incorporate these microgrid ideas. Historically, engineering programs have ensured training in large, centralized power stations, while microgrids are now becoming ubiquitous, which is why topics related to decentralized generation and renewable energy should be included [13].

In recent years, voltage stability has become a pressing concern in electricity distribution networks, an issue that demands immediate attention to prevent massive blackouts. Vita et al. [14] proposes a restoration strategy for microgrids, prioritizing the restoration of significant loads during recovery, underscoring the need for stability, especially during blackouts. Similarly, Fotis et al. [15] analyzed the threats to the European transmission system, calling for effective planning and intelligent methods to tackle the frequency and duration of blackouts. These studies stress the importance of voltage stability to maintain a reliable supply of electricity, particularly in those structures that are part of microgrids, and signal the importance of effective control systems to counteract the dangers of power blackouts.

This perspective will also make engineers conscious of microgrids as systems, hence providing them with an understanding of the challenges and opportunities that may exist with microgrids. A few universities have already started including microgrid-related topics in their engineering courses. For example, there is the Microgrid Design and Control course at the University of Wisconsin-Madison. The simulations in this course enable students to practice with actual equipment and be briefed on the functioning of decentralized electricity generation. The class involves laboratory sessions in which students develop, simulate, and assess microgrid systems, enabling them to demonstrate practical solutions for incorporating renewable power into power systems [16].

While theoretical knowledge of microgrid systems and decentralized power generation is essential, it is equally significant to provide students with practical experience. This hands-on experience is crucial in preparing them to operate autonomously using available resources during standard settings and when disaster strikes. It also helps them to understand the consequences of specific decisions on using energy storage systems and establishing control measures, enhancing their problem-solving skills.

Moreover, engineering courses must foster interprofessional education. The design and management of microgrids require input from various disciplines, such as electrical engineering, computer science, environmental science, and economics [17]. Nonetheless, most engineering programs are silo-based and rarely cross over between different branches of engineering. To counter this, some universities have tried establishing courses in which students from various disciplines are expected to develop microgrid solutions. These courses offer a more macro analysis of the issues and practices involved with distributed energy generation, educate students on the conflicts and potential of this field, and help them to realize that this interdisciplinary field is both academic and professional. This stress on the multidisciplinary nature of microgrid design and management should make students feel the need for collaboration in their future careers.

There is also a persistent need to deeply explore the social and economic aspects of microgrids in engineering curricula. It is crucial to understand the facts about microgrids and their impact, especially on communities and in the context of energy availability and cost. Microgrids can offer sustainable and affordable electricity to societies with poor access to electricity, particularly in the developing world [18,19]. However, it has been noted that engineers need to be well versed in several factors that influence the extent of microgrid implementation, including funding, legal frameworks, and other requirements. Therefore, the present curricula must place more emphasis on these features to adequately prepare students for the social and economic implications of microgrids [20].

Therefore, incorporating microgrids in contemporary power systems can be considered a progressive development toward building a more robust and eco-friendly electricity supply system. As this transformation unfolds, the need for microgrids will become more profound in supporting voltage stability and system integrity [21]. Engineering education must address these challenges by incorporating microgrids into students' training. This is done by integrating theory and practice and promoting cross-disciplinary education encompassing technical, environmental, and socio-economic perspectives. By filling these gaps, educational institutions can equip engineers to spearhead green energy solutions for a diverse and dynamic world [22].

The incorporation of microgrids, small-scale power grids that can operate independently or in conjunction with the primary power grid, into engineering education to achieve voltage stability in today's complex power networks still lacks sufficient curriculum coverage. One of the gaps identified in microgrid education is the absence of integrated structures that unify theoretical concepts, pragmatic skills, and sophisticated quantitative abilities [23]. There is a shortage of research concerning the efficacy of multiple methodologies and tools used to teach and evaluate microgrid concepts. The effects of prior knowledge, project-based learning, and data analysis methods on student learning of microgrids are not fully understood. Additionally, it is essential to assess the effectiveness of teaching microgrid concepts after specific periods of time in the educational environment and professional practice [24].

This research aims to meet the need for improved integration of microgrid modeling and voltage stability analysis into engineering curricula and practices. This is a crucial study area, as power systems are becoming more complex and renewable energy integration is increasing [2,3]. Engineering programs must provide students with hands-on, accurate simulation experiences. However, current educational approaches often need help to support the necessary hands-on experience and sophisticated analytical instruments [6]. This study aims to formulate a framework for incorporating microgrid modeling, simulation, and analysis within engineering courses, thereby enhancing students' technical skills and readiness to tackle the complexities of future power systems.

This study aims to design and assess a conceptual framework for incorporating microgrid ideas into engineering curricula, focusing on voltage stability assessment in current power systems. This study aims to evaluate the impact of integrating theoretical content, professional experience, and refined analysis skills in training future engineers about decentralized power generation. Furthermore, it seeks to find the factors affecting student performance in microgrid education. It examines the application of the project-based learning approach and data analysis in enhancing students' knowledge and practical utilization of microgrids in real-life situations, thereby bridging the gap between theoretical understanding and practical application.

The present research aims to develop and evaluate a microgrid conceptual framework for teaching engineering curriculum concepts, particularly voltage stability assessment in advanced power systems. This research uses an extensive quantitative approach to quantify the benefits of integrating microgrid modeling and voltage stability assessment into engineering education. The study integrates traditional lectures with practical sessions using Python-based microgrid tools like PyPSA and OpenDSS for simulated hands-on activities. To assess the effectiveness of this educational intervention, the present study uses machine learning techniques such as Random Forest, Gradient Boosting, K-Means, hierarchical clustering, and multiple regression analysis. This methodological approach enables an analysis of students' achievements and their comprehension of microgrid concepts. The contributions of this study are significant and may impact the advancement of engineering education and the power system sector in the future. Therefore, with this approach, which lies in the continuity between theory and practice, this study seeks to get closer to the real-world problems that future engineers will face when dealing with complex power systems, including microgrids and sustainable energies. The outcomes of this research may serve as potential applications and resources for curricula, instruction, and curriculum and assessment frameworks for engineering courses, as well as a framework for creating enhanced microgrid systems for contemporary power systems.

This research offers a new approach to microgrid implementation in engineering education, connecting theoretical concepts, industrial exposure, and technical expertise. The study provides a quantitative analysis of the efficiency of different teaching approaches, where exam results and project-based learning are found to be significant in determining student achievement (weight of 0.40). The use of clustering analysis to identify four different operational states of microgrid systems helps to shed more light on voltage stability. The results of this study, such as the high predicting performance of linear regression models

($R^2 \approx 0.8$), can provide insight into curriculum development and evaluation methods for microgrid education to enhance the training of power system engineers in the future.

Thus, the study's main contribution is the proposal and discussion of the incorporation of ideas of microgrid modeling and analysis in engineering courses. This has a dual purpose, including its emphasis on understanding microgrid voltage stability and its utilization in improving the professional development of engineers. Thus, the paper offers a comprehensive solution to the theoretical and practical aspects of voltage stabilization by using real microgrid cases in curricula. This combination of education with technical modeling guarantees that future engineers will have the necessary knowledge and experience to manage contemporary power systems.

The first section of the study is the introduction, which provides a detailed review of microgrids and their implementation into engineering education, along with the research gaps and purpose. The study design, data collection instruments, and methods are presented in Section 2 of the research. This is complemented by specific case studies that address concrete microgrid situations and address aspects of voltage stability management. Section 3 includes the findings of these case studies with the help of data analysis. In Section 4, the authors discuss the study's findings and formulate a proposed framework for integrating microgrids into engineering education, which is comprehensive and practical for implementation. Finally, Section 5 briefly explains the study and discusses further research in this field.

2. Materials and Methods

This section describes the methodology, tools, and techniques employed in conducting the study and collecting data. It also presents detailed case studies to illustrate the practical application of the proposed framework for microgrid modeling and voltage stability. This study is based on several theories. According to the Constructivist Learning Theory, learning occurs based on the learner's experiences and through reflection on these experiences [25]. This theory is highly relevant to integrating microgrids into engineering education, as it emphasizes the importance of the learner's experiences in the learning process. This is supported by the Experiential Learning Theory, primarily through project learning and simulations, as pointed out by Mick [26]. In addition, the Socio-Technical Systems Theory postulates the interconnectivity of social and technical factors in systems, resonating with the microgrid concept's interdisciplinary integration of engineering, environmental science, and economics [27]. These theories underpin the content and reality-based engineering education delivery highlighted in this study. The theoretical relevance of the frameworks is presented below in Table 1.

Table 1. Theoretical Relevance of the study.

Author(s) and Year	Variables/Parameters Used	Suggested Variables/Parameters
Constructivist Learning Theory by Gogus (2019) [25]	Active learning, knowledge construction	Extensive project-based learning, simulations in microgrid environments
Experiential Learning Theory by Mick (2020) [26]	Experiential learning, concrete experience	Hands-on microgrid modeling, real-world scenarios, problem-solving
Socio-Technical Systems Theory by Abbas et al. (2012) [27]	Socio-technical balance, system design	Interdisciplinary integration (computer science, environmental science, economics), adaptability to technological advancements

The study employs a quantitative research method to evaluate the efficacy of incorporating microgrid modeling and voltage stability assessment into engineering curricula. The research is conducted within a course designed to teach students these concepts and combines theory with simulations. During the course, students use Python-based microgrid modeling tools such as PyPSA and OpenDSS to solve voltage stability issues with the subjects and solutions being controlled for educational purposes. Self- and course-assessment forms are used to assess the student's level of understanding and analytical ability before and after the course. The information gathered from such evaluations is subjected to quantitative analysis employing different methods, such as multiple regression and machine learning models. This approach provides a comprehensive assessment of the educational intervention and its effectiveness in mastering the concepts of microgrids, as well as the ability of the students to solve real-world power system problems.

Both pre-and post-course questionnaires are aimed at comparing the students' level of knowledge regarding microgrids and voltage stability before and after the course. These include multiple choice, scenario-type, case study, problem solving, and skill-based questions, which test factual knowledge and practical skills. The target population of this research consists of engineering students taking a microgrid modeling and voltage stability analysis course. Thus, a sample size of one hundred students was chosen to make our conclusions more reliable and accurate but still manageable regarding data gathering and analysis. This group comprises students with diverse academic profiles and knowledge, ensuring a comprehensive and inclusive representation of the target population. The rationale for the selection is that it provides a diverse sample of the target population and permits generalization of the impact of the educational intervention. This ensures that findings are generalizable and that the effectiveness of the course methodologies and content can be seen across different types of students. The inclusion and exclusion criteria are described below in Table 2.

Table 2. Inclusion and Exclusion Criteria for Study.

Criteria	Inclusion	Exclusion
Target Population	Engineering students enrolled in the microgrid modeling and voltage stability course.	Students not enrolled in the specific course.
Educational Background	Students with diverse academic profiles within the engineering discipline.	Non-engineering students or students from unrelated fields.
Course Participation	Active participants who completed assignments, projects, and assessments.	Students with partial or no participation in evaluations.
Pre- and Post-Course Data	Students who completed both pre-course and post-course assessments.	Students missing either pre-course or post-course evaluations.
Use of Python-Based Tools	Students who actively used Python-based microgrid modeling tools (e.g., PyPSA, OpenDSS).	Students who did not use Python-based tools or used alternatives.
Assessment Completion	Completed both self-assessment and course assessment forms.	Incomplete or missing self-assessment and course assessment forms.
Knowledge Level	Students of varying knowledge levels (low, medium, high) before the course.	Students with advanced prior knowledge of microgrids.
Analytical Skills	Students who showed improvement in analytical skills based on course evaluations.	Students with no measurable improvement in analytical skills.
Data Availability	Students with complete, accessible data for all variables in the study.	Students with incomplete or inaccessible data for essential variables.
Tool Usage	Active use of Python libraries (NumPy, Pandas) for data manipulation during simulations.	Students who did not use or improperly used these tools during simulations.
Project Involvement	Participation in projects and simulations related to microgrid voltage stability.	Lack of involvement in practical project components of the course.
Simulation Interaction	Engaged in simulating conditions like loading patterns and fault configurations.	Students who did not participate in simulation activities.

PyPSA, OpenDSS, NumPy, and Pandas are used in research to model and simulate microgrids in detail. PyPSA and OpenDSS assist students in modeling power systems and microgrids, which are vital in simulating networks and determining voltage stability in specific circumstances. Data manipulation uses NumPy and Pandas to allow efficient handling and manipulation of simulation data. Other conditions include loading pattern variability, the connection between distributed generation and wind generators, and fault configurations. These include voltage levels, reactive power, active power, and system frequency, which are used to assess the performance and stability of the microgrid under various operational conditions. The study methodological flowchart is presented below in Figure 1.

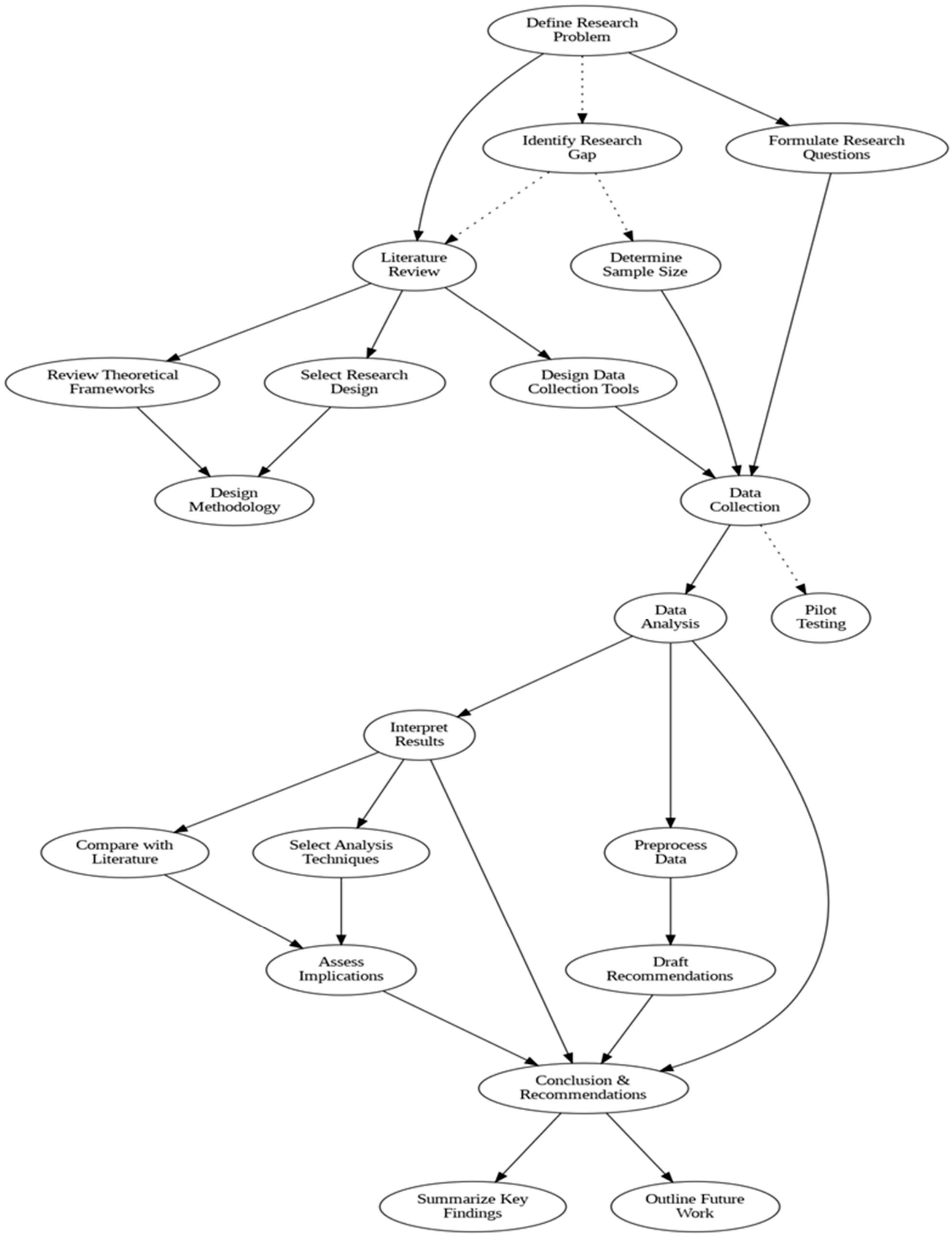

Figure 1. Methodological flowchart of the study.

Data Analysis Techniques

Predictive Modeling: Machine learning algorithms, including Random Forest and Gradient Boosting, are applied to predict student performance and understanding of microgrid operations. The models use input features $X = \{x1, x2 \ldots, xn\}$, where xi represents various predictors such as pre-course scores, demographics, and engagement metrics. The prediction function ˆy is modeled as follows:

$$\hat{y} = \sum_{i=1}^{n} wi \cdot xi + b \quad (1)$$

While for Gradient Boosting, *wi* is the weight learned by the model, and *b* is the bias term. Random Forest uses a collection of decision trees, where the final prediction is the average (for regression) or majority vote (for classification) of the individual trees, which is expressed as follows:

$$\hat{y} = \frac{1}{T} \sum_{t=1}^{T} \hat{yt} \quad (2)$$

where ˆy*t* is the prediction from the *t*-th tree.

Deep Learning Analysis: Deep learning models, implemented using TensorFlow and Keras (Google Colab Python 3.10), are applied to analyze complex patterns in student performance data. The neural network is defined as follows:

$$y = f(W_2 \cdot \sigma\ (W_1 \cdot X + b_1) + b_2 \quad (3)$$

where X is the input data, W_1 and W_2 are weight matrices, b_1 and b_2 are biased vectors, σ is the activation function, and f is the output activation function. This model captures non-linear dependencies, with training aimed at minimizing the loss function, typically mean squared error (MSE) for regression tasks.

Clustering Analysis: Clustering methods, such as K-Means and hierarchical clustering, are used to segment students based on learning outcomes. For K-Means clustering, the objective is to minimize the within-cluster sum of squares (WCSS), defined as follows:

$$\text{WCSS} = \sum_{k=1}^{K} \sum_{i \in \text{Ck}} \| \ xi - \mu k \ \|^2 \quad (4)$$

where xi is the data point, μk is the centroid of cluster Ck, and K is the number of clusters. The algorithm iteratively adjusts centroid μk to minimize the WCSS. Hierarchical clustering builds a dendrogram, wherein clusters are formed based on the similarity between data points, with the linkage criterion determining the distance between clusters.

Dimensionality Reduction: Techniques such as principal component analysis (PCA) and t-distributed stochastic neighbor embedding (t-SNE) are employed. PCA transforms the data into a set of orthogonal components Z = XW, where W is the matrix of eigenvectors corresponding to the largest eigenvalues of the covariance matrix of X. This allows for the identification of key elements that explain the most variance in the data. t-SNE visualizes high-dimensional data by modeling pairwise similarities in a low-dimensional space.

Optimization Techniques: Genetic Algorithms (GAs) and Particle Swarm Optimization (PSO) optimize reactive power management, improving voltage stability outcomes in microgrid simulations. The optimization objective is defined as follows:

$$Minimize\ f(x) = \sum_{i=1}^{n} (Vi - Vref)^2 + \sum_{j=1}^{m} Qj^2 \quad (5)$$

where Vi is the voltage at node i, $Vref$ is the reference voltage, and Qj is the reactive power at node j. GA and PSO iteratively adjust control variables to minimize this objective, improving system stability.

3. Case Studies

To illustrate the practical relevance of the microgrid modeling and voltage stability techniques discussed in the previous sections, this part of the study presents detailed case studies. These case studies make a unique contribution to the existing literature by demonstrating the real-world application of the proposed framework and exploring how microgrids perform under different operational scenarios. They also address a significant gap in the literature, which often needs a comprehensive connection between theoretical models and hands-on educational experiences. By linking the simulations to student learning outcomes, these case studies pave the way for a more integrated approach in Section 4, where we analyze the results of these case studies in detail.

3.1. An Active Collaboration between Industry and Academia

Many local firms in the Lake Charles area suggested that Mississippi State University build a model LNG facility to educate workers and perform research. This area is the hub for U.S. LNG exports and imports [28,29]. MSU launched this effort with the assistance of the local oil–gas industry and international power equipment manufacturers, showcasing a partnership that benefits both parties. This collaboration is significant as it not only enhances the academic experience for students but also provides a platform for industry professionals to contribute to and benefit from cutting-edge research and development [30].

LNG: The next step in the project's second phase is to liquefy and burn gas supplied by utility services to power gas turbine generators made by MG [31]. The currently running MG will use the power continuously generated internally by the model LNG plant's activities. Eventually, mechanical and chemical engineering students will use the model LNG plant to study chemical processes and thermodynamics. When that occurs, more academic fields can contribute to the overall effort [32].

Turbine Energy: Two 65 KW combined heat and power (CHP) microturbine generators were purchased from Capstone Inc. and serve as the principal electrical power source for the MG. By recycling exhaust heat for space heating, continuously hybrid power (CHP) generators contribute to energy savings [33]. The ABB 800XA DCS is crucial in handling the MG and communicating with the IEDs for protection and management [34,35]. It acts as the central control system, coordinating the MG's operation and ensuring the system's safety and efficiency. To connect the DCS to the electrical grid, proficiency in computers and software is required. The MG has a real-time control operation and simulation exercise module to facilitate these skills. Students in mechanical and electrical engineering who enroll in transdisciplinary control courses obtain an understanding of DCS.

Power grid protection: Through an ongoing collaboration with ABB, the MSU College of Engineering has acquired IEDs such as REF/REM 615 to safeguard the campus MG's feeders and motors. ABB is implementing a motor condition monitoring system to provide predictive maintenance for specific induction motors. We will add more motors and critical network components to our condition-monitoring endeavor.

In Figure 2, a single-line schematic is shown for the working MG machinery at MSU. Two generators that provide heat and electricity to the load are linked automatically by a motor control center (MCC). There are three types of rotating loads: one with a universal drive, one with a variable frequency drive (VFD), and one with a variable resistive load (up to 130 KW). The 800XA system connects all circuit breakers (CBs) for automated control. The instrument electronic device (IED) receives measurement and protection data transmitted by each load's instrument transformer. All this and more are covered in a class that seniors can take on electric machinery and power system protection [36].

Photovoltaic energy: To maximize the efficiency of the solar panels, a commercial three-phase inverter is used, such as the ABB TRIO-20.0-TL/27.6TL, specifically designed for North American applications. Its dual input sections contain two independent maximum power point tracking (MPPT) converters. When the generators are not cranking out juice, the MSU MG can go back to using the utility connection or cranking out its power to run the loads. Power electronics and systems classes include the topic of PV integration.

Simulation to automated operation of MG: Experience from multiple courses

The MG system and its components are utilized in several power-related courses offered by the electrical engineering (ELEN) undergraduate program. Along with their regular classes, undergraduates develop their engineering design skills through two full-semester senior design projects. Short research projects are a requirement for continuing graduate students to demonstrate their competence in design, modeling, and testing. The research conducted by students has been instrumental in advancing our understanding of the MG system and its components. Learning outcomes, student satisfaction, and course evaluations have been essential measures of the method's efficacy. The capstone design allows undergraduates to demonstrate their competence in solving real-world engineering difficulties. Since 2014, three groups of thirteen students have conducted exploratory research on the innovative power grid system. Their studies include intelligent MG protection and control, power flow simulation in regional and local networks, and investigation of distributed generator effects.

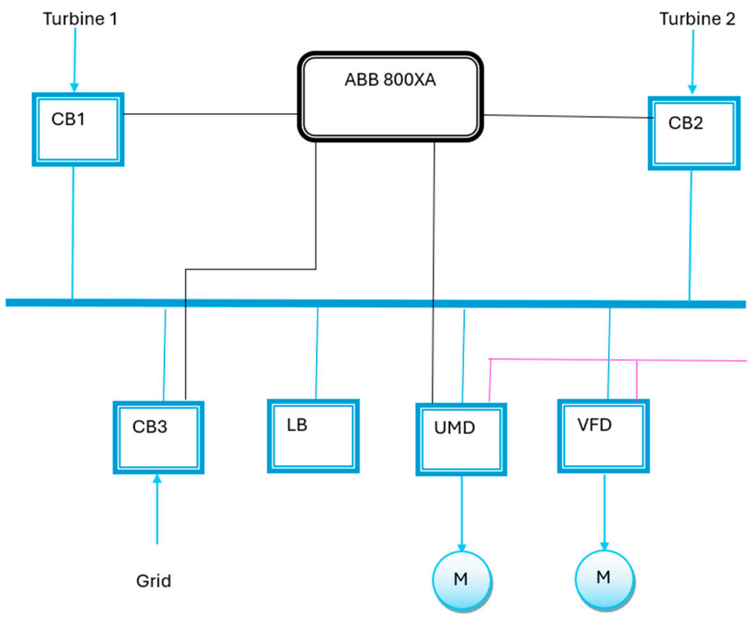

Figure 2. Single-line schematic for the working of MG machinery at MSU: McNeese State University [36].

Simulation practices using commercial software: Conceptual MG and its effect on the overall grid.

Students' work in this project is not just theoretical; it has practical applications. They have undertaken numerous term projects and assignments in power system classes, eight senior design projects, one graduate thesis, and other initiatives inspired by this MG project. Students are required to report to the instructor every two weeks throughout the graduate term, demonstrate their work in engineering or experiments, and provide a formal presentation and report on the project at the end of the course. The projects chosen by students highlight the significance of MG as a resource for education and study. The MG has gained respect as a resource for training and research because of student-selected initiatives. Some completed term projects along these lines are:

- Grid Power Quality Improvement and Battery Energy Storage in Wind Energy Systems: Discussing power quality of MG with wind turbines.
- Nepal Power System and its Simulation in Power World Simulator: Emphasizing the feasibility of implementing MG with a mini hydro generator.
- Power World Simulation of Eastern Grid of India: Discussing the effect of MG on the overall power flow of the region.
- The Study of West Bengal Power Grid Network using Power World Simulator: Studying the effect on the regional grid.
- Automating the ABB Turbine Generator Control System: Automating the operation of MSU MG.
- Feeder Protection Using REF 615 IEC: Showing the working principles of IEC.
- Use of PCM 500: Use of supporting software for ABB REF/REM 615 relay.
- Integration of Wind Power and Wave Power using DC MG.

Commercially available software is used to build the senior design and graduate term project simulations. Students begin by using MATLAB for intricate power calculations. They then move on to Simulink, Power World, and ETAP to investigate how the power grid reacts to dynamic environments. Despite a few things that could be improved in the data, the studies achieve their primary purpose of teaching ELEN students how to use the department's simulation software in a realistic environment. Senior design students modeled a power system in Power World and produced the simulations in Figure 3 [36].

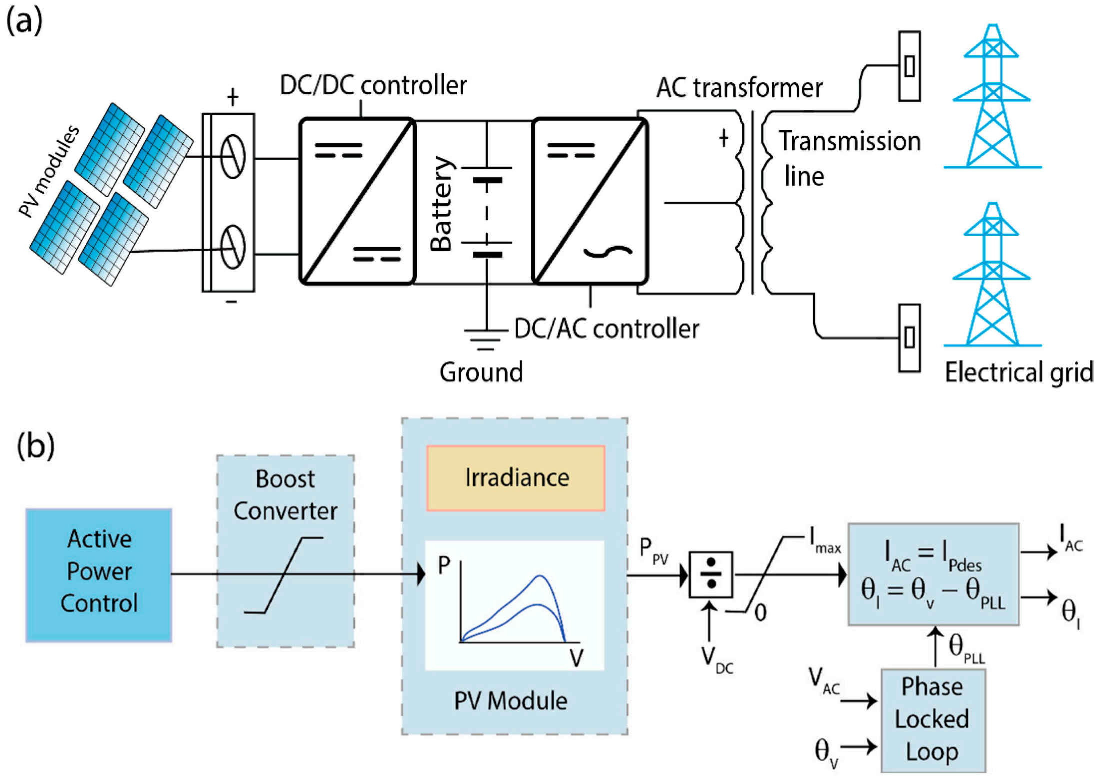

Figure 3. Power flow case study of the Bangladesh power system [36]: (**a**) Analysis of the current power flow, and (**b**) Simulation models incorporating the proposed solar power-based microgrid (MG).

Grounding of electrical installation: Before any other equipment was installed at MSU MG, ground rods were recommended and set up as part of the earth grounding system presented in Figure 4. These rods would be implanted in the ground and connected with copper wire. Because of this, the unwanted current could find a low-impedance way back to the ground. To ensure the grounding system's resistance meets NEC and local norms, it is essential to regularly test the system using a ground megger and proper tests [37]. Constructing the grounding system's conceptual blueprint was a senior design project. We conducted tests to determine the level of ground resistance. Based on the results of the tests and the equipment's current and voltage ratings, we constructed the ground grid using 3/4n×10′ copper-wrapped ground rods connected by 2/0 insulated ground wire. Completing the design tasks according to industry standards was linked to the study's student learning outcomes.

According to the student survey, students perceived the PBL as effective. Another positive indicator was the feedback from the students' new employers at a nearby electrical contracting company.

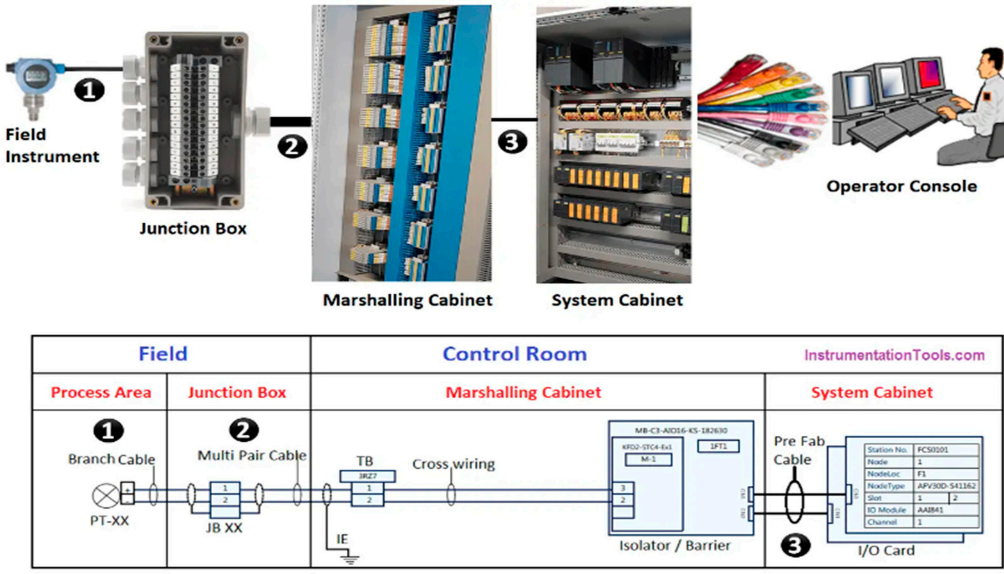

Figure 4. Detailed view of the output connections from the distributed control system (DCS) to the relay coils, illustrating the configuration and wiring [36].

3.2. Developing an Integrated Platform for Evaluating the Publish–Subscribe Agent Model

The developers of the agent platform brought together MATLAB R2018a (MathWorks, Inc., Natick, MA, USA) and the Java Agent Development Framework (JADE, version 3.7, Telecom Italia Lab, Torino, Italy), among other software and hardware components. A set of generally agreed-upon rules by FIPA is available in the JADE standard [38]. FIPA supports standardized agent communication techniques as an institution establishing standards for agents and multi-agent systems. An agent platform is complete with an agent management system (AMS), an agent communication channel (ACC), and a directory facilitator (DF) [39,40]. We apply publish–subscribe massaging, an asynchronous communication mechanism. The process begins when an agent representing a subscriber asks a publishing agent for a set of variables. The JADE runtime includes a message queue to make it easier for agents to communicate with each other. If the content matches, the subscribed agent receives a notification whenever a message comes in the queue; otherwise, it ignores it. The publisher agent then triggers an action method to commence contact.

Each agent class has its own Java class to support the publish–subscribe architecture and enable message interchange between agent classes. Figure 5 depicts an agent-based system design with eight converters connected to four agents through the agent platform [41]. DF and AMS, the facilitator agents specified in the FIPA standard, are in the main container. In the DF module, agents may be seen in a directory; agents, containers, and the platform can be created and destroyed in the AMS module.

As a case study, a DC shipboard microgrid was hypothetically constructed and run in MATLAB. Although MATLAB excels at modeling microgrid optimization methods, it is incompatible with languages like JADE, which use multithreaded agent architectures. The number of messages that could be sent simultaneously between the JADE MAS platform and the MATLAB microgrid model was limited. As a result, MathWorks, Inc. (Natick, MA, USA) created the S-function toolbox MACSim (Mendham & Clarke 2005a, University of York) to be used with MATLAB/Simulink R2018a. In their study [42], Mendham and Clarke fully describe the MACSim toolbox. Their goal in creating it was to facilitate communication between Simulink models and agent-based systems developed in C/C++ or Java. Figure 6 illustrates the client–server architecture of MACSim. While the server half is designed using the JADE platform, the client half is created using Simulink's S-function [43]. This study describes how the MAS software components and microgrid hardware models are incorporated into the MACSim block [44].

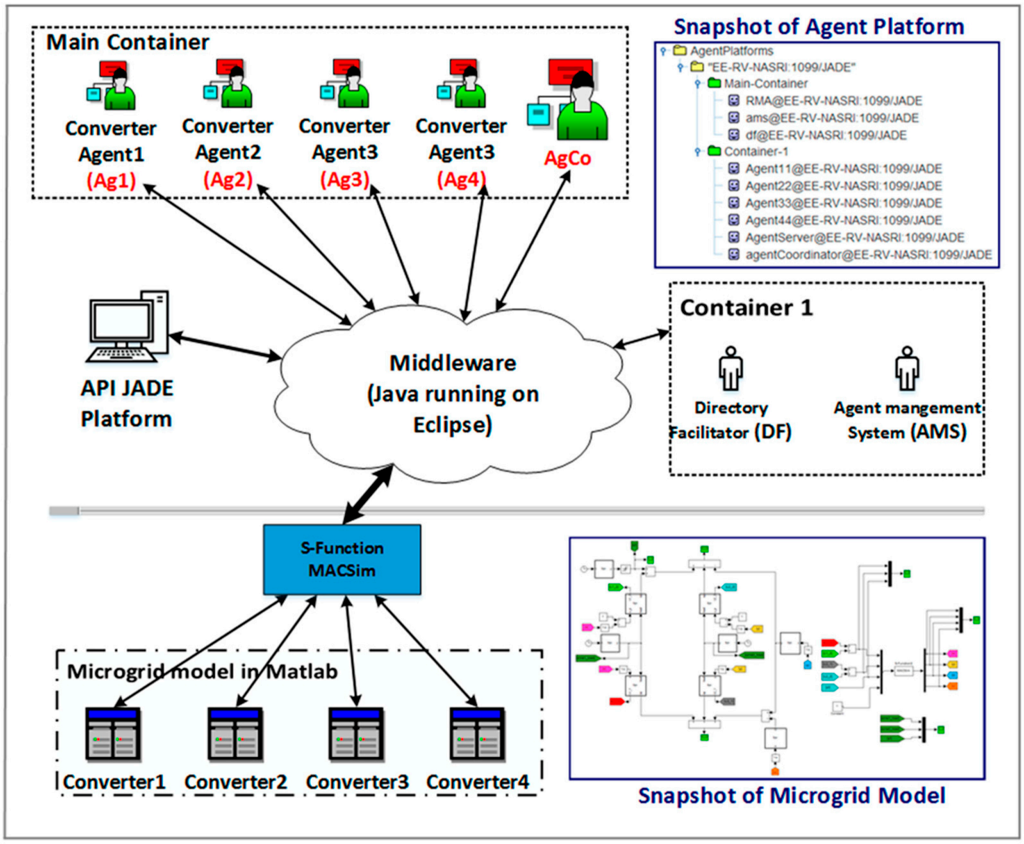

Figure 5. The integrated agent-based system features a microgrid modeled in Simulink and a multi-agent system (MAS) [41].

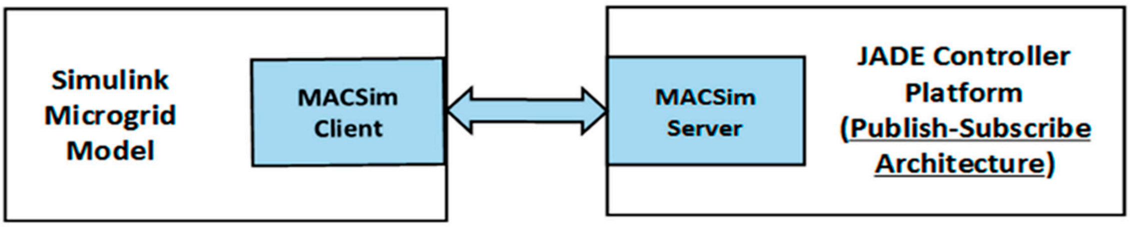

Figure 6. Structure of MACSim toolbox [41].

A coordinator agent (AgCo) was built into the MAS design to help the JADE agent platform communicate with the Simulink ports. This service employs a team of DF agents. Any time the AgCo receives a data array from Simulink, it notifies the agents who subscribe to this material. Once these agents finish processing, they send the data to the AgCo, which then sends it to the Simulink microgrid model. Processes are optimized by utilizing and updating the AgCo-hosted routing tables.

Exhibited in Figure 7 is the flow of optimization variables in a MAS system connected to the shipboard microgrid model [41]. The JADE platform activates the agent model upon receipt of load values from a converter. Then, four distinct agents, Ag1, Ag2, Ag3, and Ag4, are produced in response to a trigger received through the AgCo. The agents use separate search trees to optimize 'z1', 'z2', 'z3', and 'z4', as seen in Figure 8. Zone1, zone2, pulsed load, bus-tie, and ESS are current values. Input values like I1, I2, IPL, I3, and I4 are used by the agents and executed in parallel to gain the 'zi' optimization values. The four agents reach the lowest conceivable 'zi' values by coordinating their data optimization efforts using the publish–subscribe architecture. Using an AgCo, this agent calculates the values of 'x', 'y', 'z', and 'u' and returns them to Simulink. Once each agent receives confirmation of data transfer, its life cycle ends. In the end, system instability could happen if an agent does not complete the procedure. The capacity to process search tree values within a specific time limit is critical to the system's stability. Limiting our search to nodes inside the constraint ensures that the system will only run within the restricted working area. The system will only perform at its best if agents finish searching for the cost function by the given dates. There is no other result from this failure mode other than this.

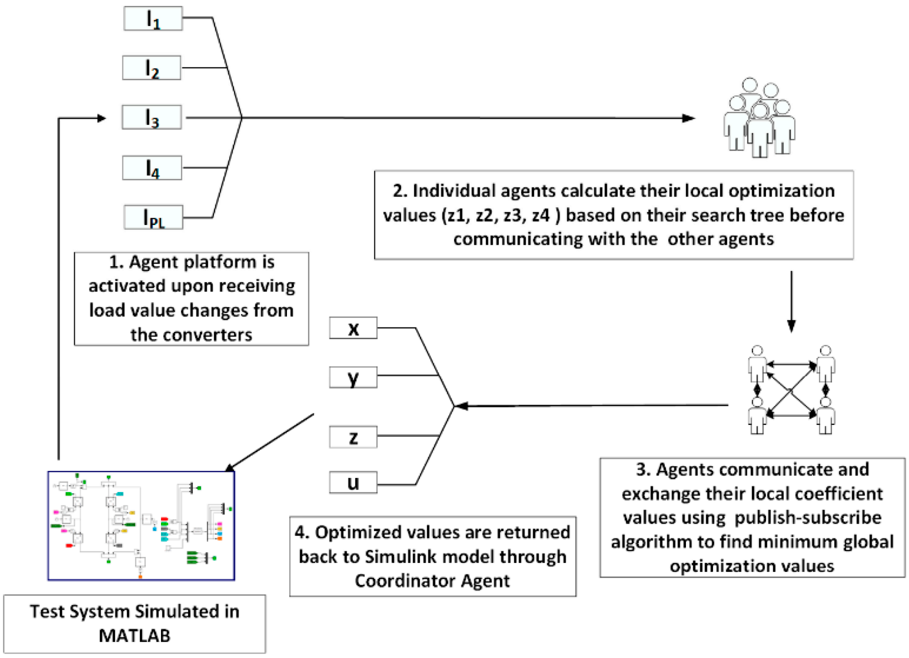

Figure 7. Flow of optimization variables in a MAS system connected to the shipboard microgrid model [41].

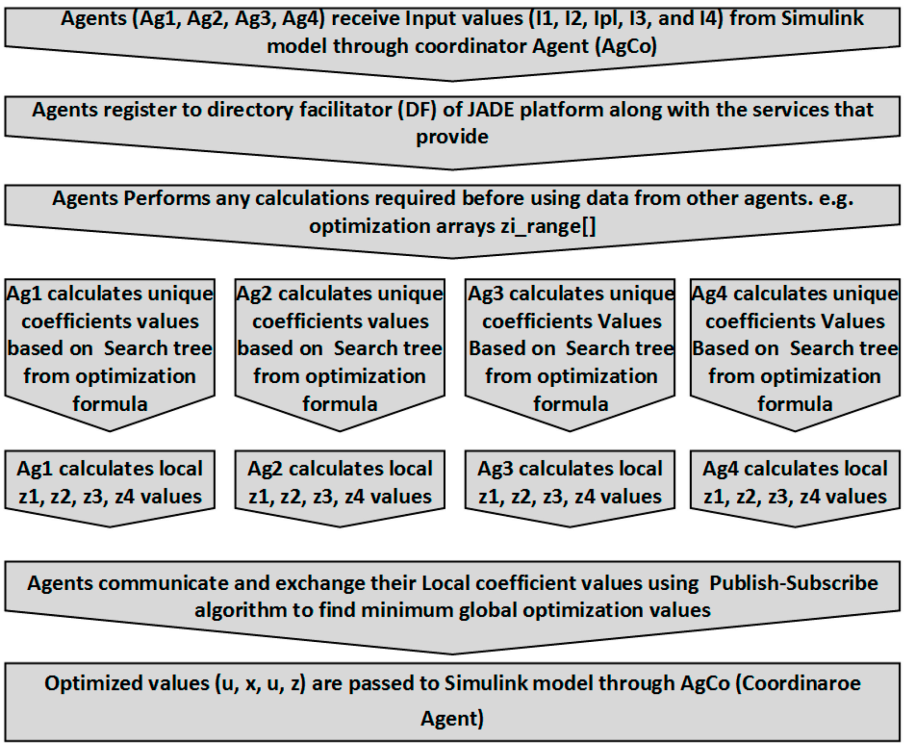

Figure 8. Concurrent optimization algorithm using four agents [41].

As seen in Figure 9, the agents can interact verbally. The agents mentioned above can obtain their agent numbers and find their local data by registering with the DF on the JADE platform [41]. After this, each agent takes care of its computations before dealing with the ones obtained by other agents. The agents then share the results with their subscribed-to agents.

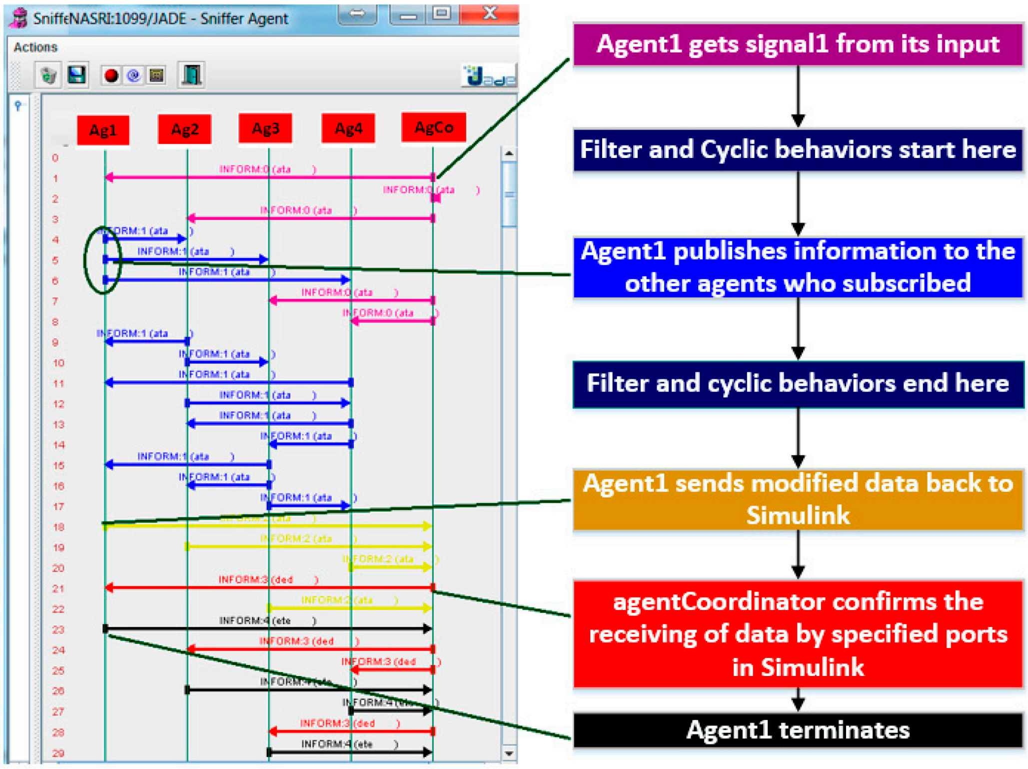

Figure 9. A detailed view of the JADE (Java Agent Development Framework) platform [41].

The case studies discussed above illustrate various applications of microgrid modeling and voltage stability analysis in real-world scenarios. However, a deeper analysis of the results is crucial to comprehend the effects and influence of stimulus factors and methods of motivating learners for effective learning and achievement in education. The key findings pertinent to the strengths and limitations identified within the case studies are presented in the following section, along with critical observations. In prior microgrid modeling and research case analyses, there has been a primary focus on the technical specifics of voltage stability and system performance. At the same time, the issue of what the results of these studies mean for engineering pedagogy needs to be more emphasized. Although these papers offer important technical information, many do not incorporate a holistic microgrid operations model or an organized curriculum structure that includes a theoretical understanding and practical application of microgrid operations into their model. This has created a gap in the incorporation of these systems into education whereby students receive inadequate practical experience in learning and controlling microgrid systems under different operations.

This study fills this gap by creating a detailed framework focusing on microgrid modeling, real-time simulation, and project-based learning in a voltage stability context. This study is built on integrating technical analysis and educational results, thus contributing to students' experience, which could significantly improve their knowledge of modern power systems. In other words, the proposed framework has the potential to transform the way students learn about and control microgrid systems under different operations, offering a hopeful future for engineering education.

4. Results and Discussion

Section 3 discussed various case studies in detail, describing how microgrid modeling has been applied in practice and the advantages and drawbacks of existing approaches to modeling voltage stability depending on the control settings and certain system parameters. Nonetheless, one of the shortcomings in these case studies is that they need to directly address the correlation between technical performance and educational outcomes regarding how students learn from these simulations. To address this gap, we elaborate on the microgrid simulations in this section by discussing system performance and the usefulness of the proposed educational framework. Thus, by integrating technical and academic perspectives, the results elucidate how effectively students comprehend microgrid operations and voltage stability.

The results and discussion section presents and interprets the findings from the case studies and data analysis. It also aims to analyze and interpret the results in the context of the research questions, comparing them with findings in the existing literature. Further, this section aims to present a novel framework based on the study's findings, offering improvements for microgrid modeling and voltage stability education.

The histograms in Figure 10 show the distribution of numerical features within the dataset. All of the variables, such as study hours, attendance rate, project score, exam score, and performance score, follow the normal distribution since none appears heavily skewed. However, features like lab participation and external resources are more likely to be multimodally distributed, a statistical term that indicates the presence of multiple peaks in the distribution, indicating variation within the students' engagement level.

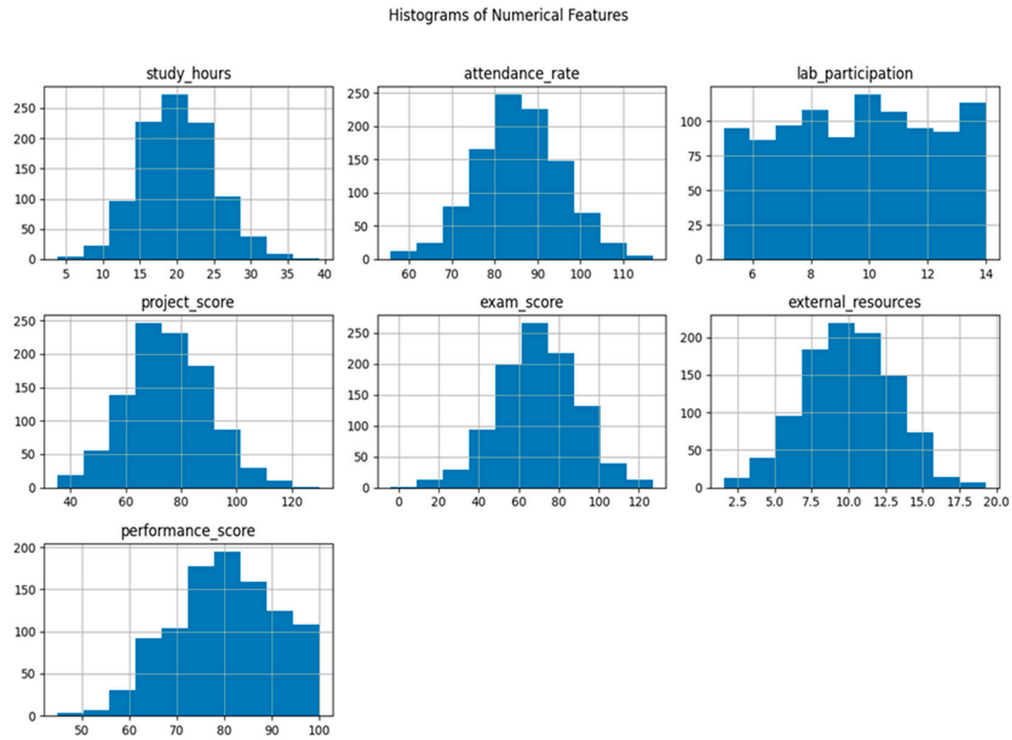

Figure 10. Distribution of numerical features within the dataset.

In Figure 11, the boxplots reveal the dispersion of the two datasets and suggest the potential presence of outliers. For instance, study hours, attendance rate, and exam score show high coefficients of variation, indicating the existence of extreme values for these variables among students. On the other hand, lab participation and external resources are less variable, with data points closer together and fewer outlying points. It is crucial to fully grasp the implications of these results in the context of clustering and future estimation. Outliers and variability in some features can significantly influence the model, either negatively or positively, and may require pre-processing depending on the model type. These findings underscore the importance of designing differential educational interventions that are sensitive to the level of student participation and achievement. Further, these results extend the findings of the case studies by pinpointing the lack of focused educational measures on account of equal improvements during the learning process, which was not previously considered.

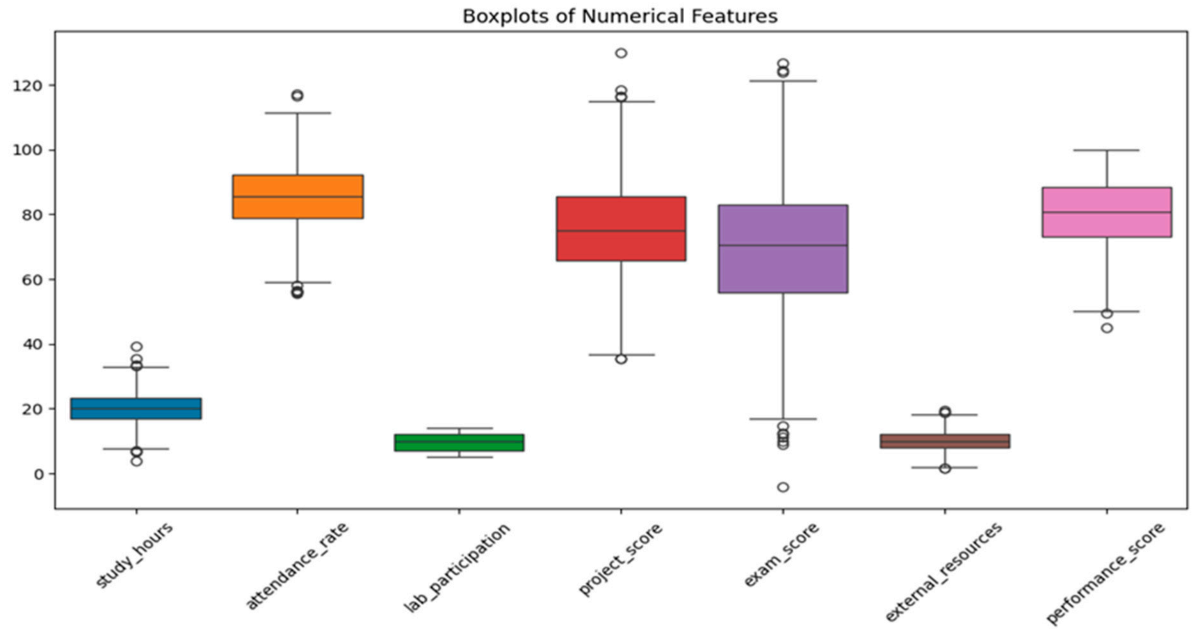

Figure 11. Dispersion within the two datasets.

The correlation matrix in Figure 12 reveals the relationship between different variables in the dataset. Specifically, this study found a moderate correlation between the performance score and the project score (r = 0.55), the external resources (r = 0.36), and prior knowledge categorized as high (r = 0.36) for the students, suggesting that these elements have a noteworthy impact on performance. On the other hand, the low correlations with low previous knowledge (−0.45) and low group work engagement (−0.29) point to a negative relationship, indicating that these aspects hinder performance. The negative relationship between low previous knowledge and performance underscores the urgency for intervention. The value of these results is in the context of feature selection for predictive modeling, wherein strongly correlated features may be significant predictors. The analysis suggests that high project engagement, better access to outside world resources, and prior knowledge are some of the factors that can be said to help in increasing student's performance.

The results obtained from the feature importance analysis of the outcomes in Figure 13 show that exam score is the most influential predictor with the highest weight of approximately 0.40. This dominance suggests that class performance measured by exams continually forms an integral part of student's performance assessment. The second most significant leveraging factor is prior knowledge (low), which shows that students who lack basic knowledge need extra attention and direction. Project score also features prominently, underscoring the effectiveness of realistic, applied tasks. Other variables such as attendance rate, study hours, and group work (high) are moderately essential, but they have less impact on students' performance. External resources and lab participation as the lower-ranked factors show that even though these factors influence the results, their importance is not as high as the previous factors on this list. Such findings are important for building essential academic skills while encouraging practical experiences. It is implied that a multifaceted strategy must be adopted to focus on variations in learning processes to achieve effective educational performance. The study's findings relate to the gaps by highlighting the need to incorporate applied and theoretical perspectives in education, particularly through test results, prior knowledge, and projectivism, to improve students' appreciation of issues like microgrids and voltage stability that are overlooked in existing models.

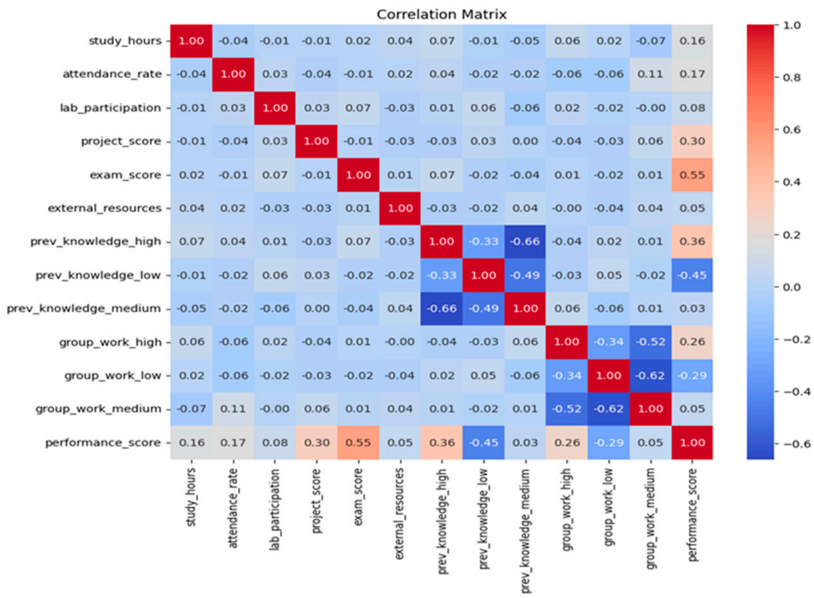

Figure 12. Interrelationship between different variables of the dataset.

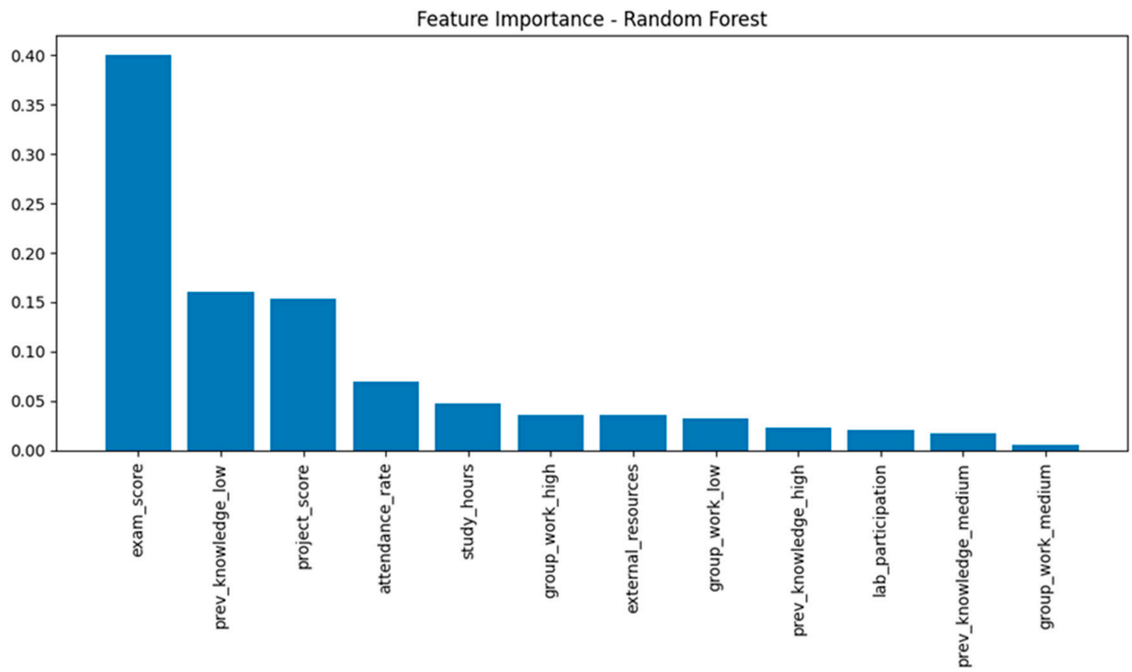

Figure 13. Feature importance—Random Forest.

Figure 14 presents the feature importance results of Gradient Boosting, which helps to comprehend the factors affecting learning outcomes in the hybrid environment when incorporating microgrids and voltage stability analysis in engineering education. Exam score is the most significant factor, indicating that traditional testing remains essential in mastering the complicated subject matter of microgrids and voltage stability. Low prior knowledge and project score are also significant, suggesting that better foundational expertise and practical project experience with a hands-on topic help students to understand advanced engineering concepts. Low importance is assigned to values such as group work (high importance) and attendance rate, which indicates that collaborative learning and punctuality are valued but less than theoretical knowledge and practical skills. External resources, lab involvement, and study time have limited relationships, indicating that independent learning and reading are less crucial for learning these domains. In conclusion, these findings reiterate the significance and relevance of blending theoretical approaches with practical, hands-on case studies in microgrid education to enhance student's learning experience and capabilities regarding contemporary power systems. These results help to fill the gap by pointing out the importance of a more balanced approach of integrating theory and simulation-based laboratory training in microgrid education to better understand voltage stability issues and microgrid system layouts.

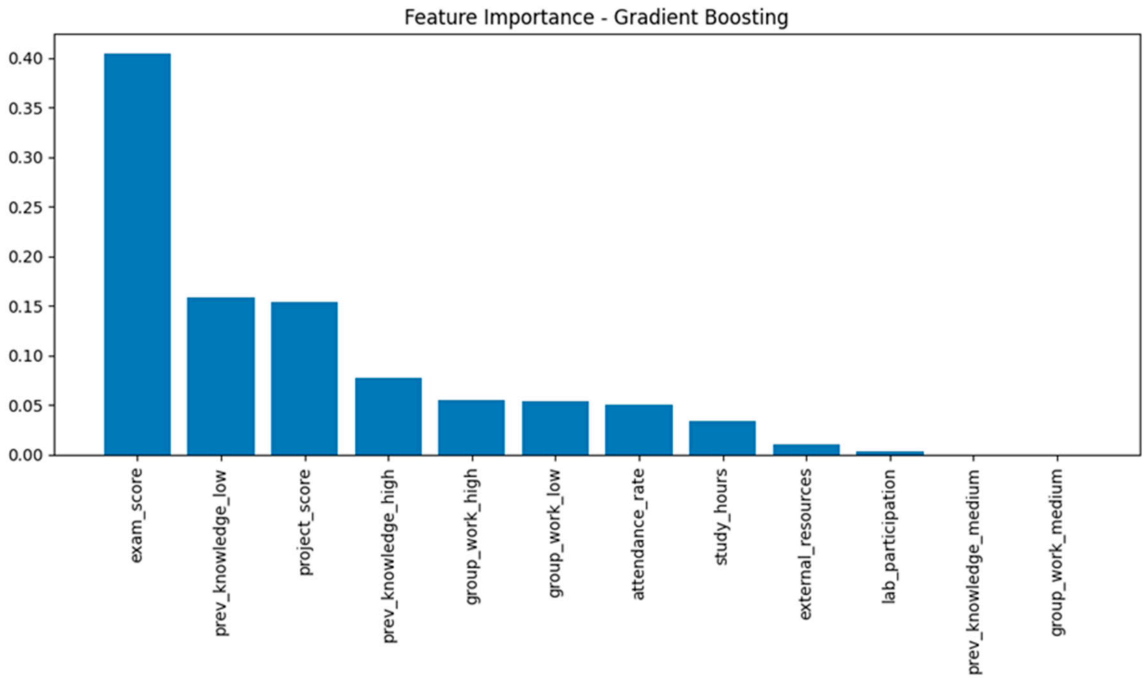

Figure 14. Comprehension factors affecting learning outcomes.

As presented in Figures 15 and 16, the results of this study significantly enhance the existing literature and serve as insightful references for modeling and assessing voltage stability in today's complex power systems, especially when incorporating microgrids into engineering education. Figure 15 illustrates the number of clusters based on the Elbow Method; it was observed that there is a considerable elbow at (k = 4). This indicates that the increase in the number of clusters to four provides a good trade-off between the complexity of the model and its performance. This balance is critical in microgrid modeling to achieve high computation speed without lowering the desired degree of precision in voltage stability analysis. These findings will keep you updated on power system and voltage stability assessments in engineering education. These findings help to fill the gap in Section 3 by providing a realistic approach to clustering in microgrid modeling and enhancing the balance of the model's complexity for effective performance in voltage stability analysis in engineering education.

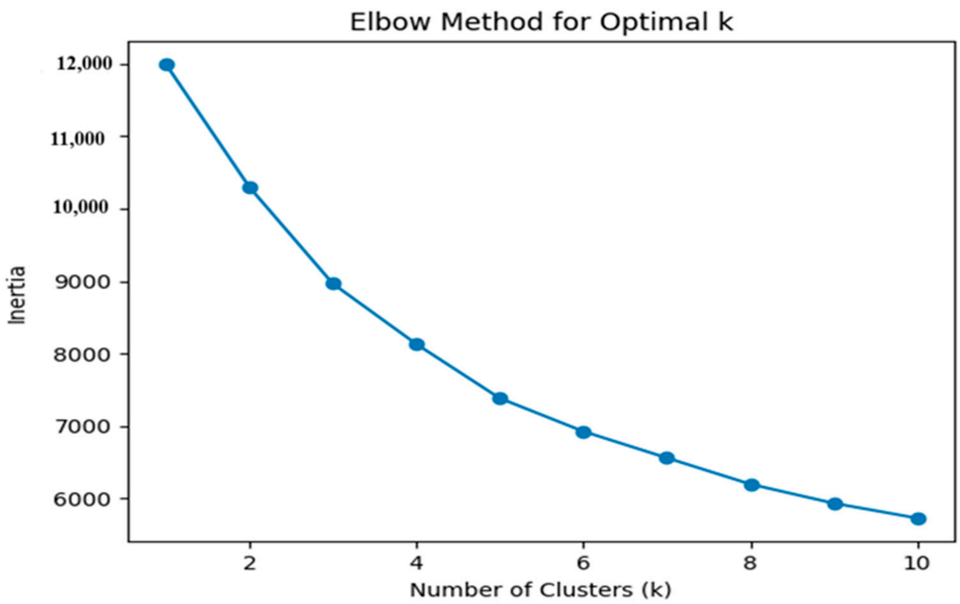

Figure 15. Optimal clustering determined by the Elbow Method.

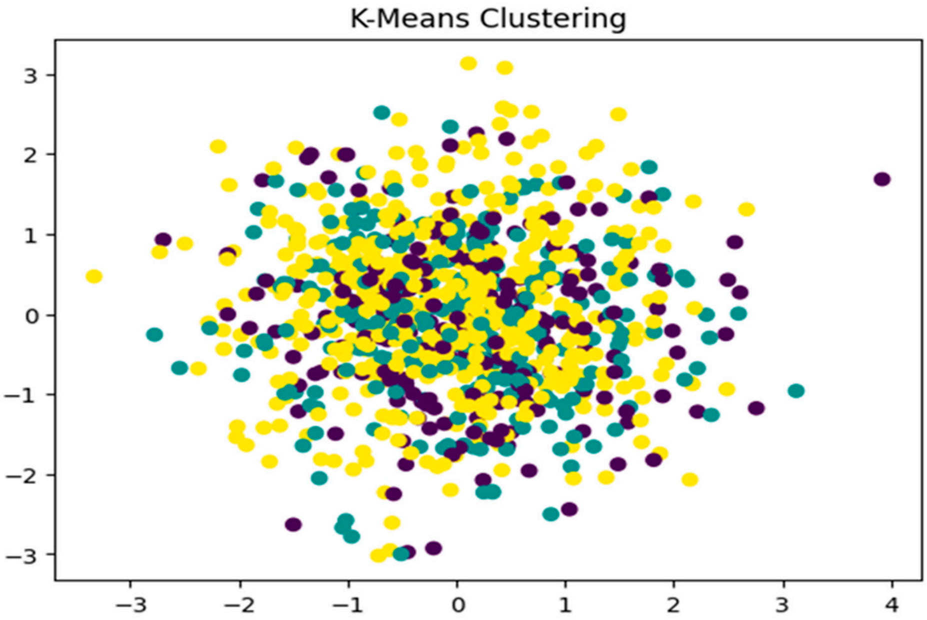

Figure 16. Differentiation of operational states in a power system using K-Means clustering.

Our analysis of the K-Means clustering results, as shown in Figure 16, provides a clear picture of how operational states in a power system can be differentiated. The distinct clusters demonstrate how various system conditions can be categorized, highlighting the microgrid's ability to regulate voltage under different circumstances. This clustering is significant as it helps to identify the most crucial states of a microgrid, leading to more precise system control and design. Our research underscores the importance and practicality of clustering methodologies in microgrid education approaches. Determining the number of clusters is instrumental in studying the microgrid characteristics that are essential for voltage stability. By integrating these techniques into engineering education, we can equip future engineers with the necessary tools to navigate the complexities of advanced power systems. These findings address the gap in Section 3 by demonstrating how K-Means clustering can enhance the understanding of microgrid operational states, improving voltage regulation and system design in engineering education.

The study results in Figures 17 and 18 demonstrate hierarchical and agglomerative clustering for applying microgrid models for voltage stability in current power systems. The dendrogram in Figure 17 illustrates the steps involved in a hierarchical clustering process. This illustrates how the data points are gradually clustered through the accumulating Euclidean distance process, and the sizes of the branches represent distances or dissimilarities between the clusters. It plays a significant role in detecting clusters inherent within the dataset, which assists in the differentiation of different operational modes of the microgrid that affect the voltage increase. The results help fill the gap outlined in Section 3 and demonstrate how microgrid operational modes can be determined by applying hierarchical and agglomerative clustering to the voltage stability issue in engineering education.

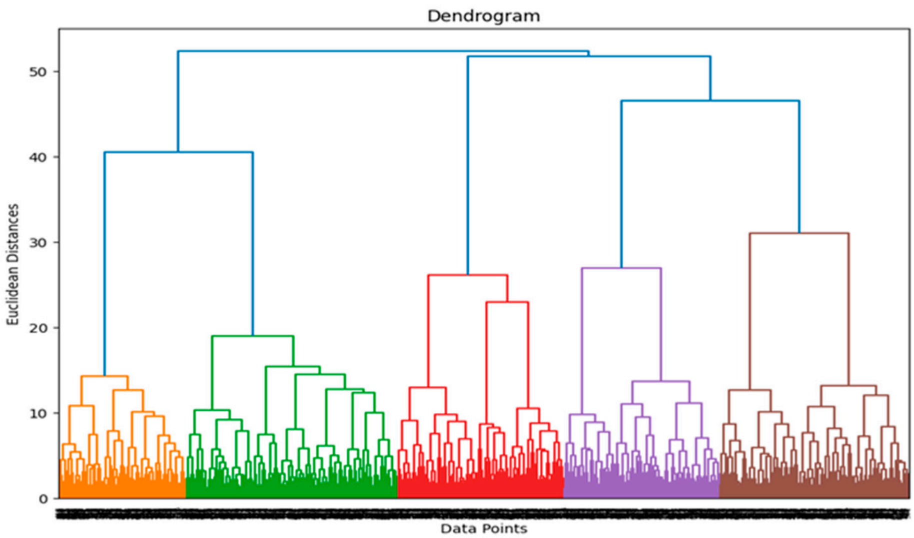

Figure 17. Hierarchical clustering and dissimilarities in microgrid operational modes.

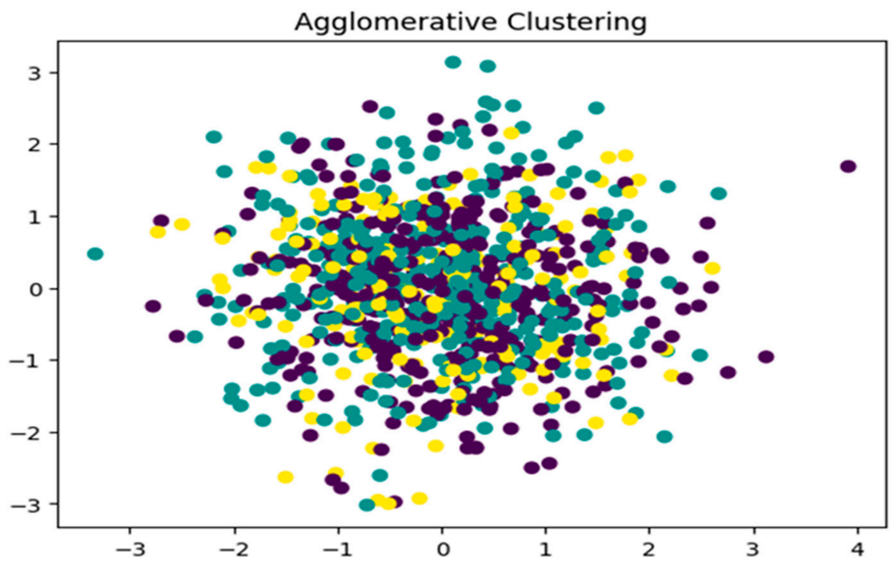

Figure 18. Hierarchical clustering without predefined categories.

Hierarchical clustering, where the data points are categorized into groups without predefined categories, is shown in Figure 18. The random distribution of the points suggests that the microgrid system performs in different scenarios and possibly experiences different levels of voltage stability. Clustering assists in identifying various conditions, which is crucial for managing and ensuring the system's stability. The relevance of these results stems from the fact that hierarchical and agglomerative clustering allows for the classification of large datasets into informative clusters. This categorization helps to determine the potential states and characteristics of microgrids, making it crucial for decisions on the voltage stability of present power systems. Finally, it is evident from the study outcomes that using such clustering techniques in microgrid modeling leads to practical insight into system behavior, thus improving the design and control strategies required for stable microgrid power systems. Implementing the strategy presented in Section 3, these findings contribute to the applicability of hierarchical clustering in categorizing the performance scenarios of microgrids, enhancing voltage stability management and system control in electrical engineering education.

Figure 19 and Table 3 display the study findings that compare the models through cross-validation in terms of $R2$ statistics of different regression models. The $R2$ statistic measures the proportion of the variance in the dependent variable that is predictable from the independent variables. This study determined the accuracy of various models, such as linear regression, ridge regression, Lasso regression, Decision Tree, Random Forest, and Gradient Boosting. From Figure 19, linear, ridge, and Lasso regression all have comparable model accuracy, with $R2$ values that hover around 0.8, signifying good predictability of the models. Strong performers are also Gradient Boosting and Random Forest, as seen in the boxplots; however, their prediction is less stable as their dispersion is higher. However, the accuracy of the Decision Tree model is notably low, with a median $R2$ value of around 0.4, indicating its accuracy is relatively low compared to the other models.

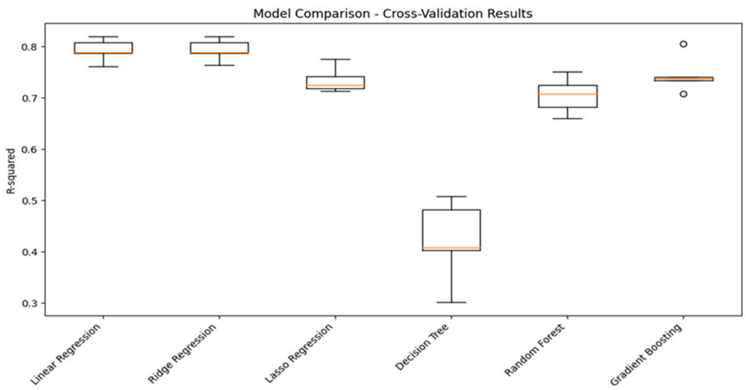

Figure 19. Model comparison—cross-validation results.

Table 3. Cross-model validation.

Model	Mean R-Squared	R-Squared Range	Observations
Linear Regression	~0.80	~0.78–0.82	Consistently high performance, indicating good fit and stability.
Ridge Regression	~0.80	~0.78–0.82	Similar performance to linear regression, with slight regularization.
Lasso Regression	~0.75	~0.73–0.77	Slightly lower than ridge and linear, indicating some feature sparsity.
Decision Tree	~0.45	~0.35–0.55	Significant variations in performance, less stability, and lower overall accuracy are observed.
Random Forest	~0.70	~0.65–0.75	Moderate performance with less variability, indicating robustness.
Gradient Boosting	~0.78	~0.77–0.80	High performance with low variability indicates predictive solid power.

The presented findings in Figure 19 and Table 3 are essential in showing the benefits and drawbacks of the various models for predicting outcomes in the framework of the given research. The $R2$ values presented indicate that linear models might be sufficient for this dataset, with lower $R2$ values indicating a better fit for more complex models like Decision Tree. Therefore, the significance of model selection in predictive analytics cannot be overemphasized. The weight of your decisions in model selection is significant, as it can significantly impact the accuracy of your predictions. Since linear models provided relatively consistent results, it implies that these models are more suitable for accurate prediction than simple models. By contrast, Gradient Boosting and Random Forest provide better yet irregular performance. These insights are essential when choosing models for future applications. The research further contributes to the gap identified in Section 3 by confirming that choosing suitable predictive models is critical and that linear models provide comparable reliability in microgrid and voltage stability analysis education.

5. Discussion

Based on the study's findings, it was determined that the conclusions about incorporating microgrids and voltage stability analysis into engineering education are consistent with current knowledge and contribute to enhancing the understanding of modern power systems and more effective teaching strategies and analysis. The unique contribution of this study lies in its emphasis on integrating theoretical knowledge, practical experience, and advanced analytical skills into engineering curricula in response to the contemporary environment of distributed generation and integration of renewable energy sources, which has been acknowledged in recent years [1,4].

As seen in the feature importance analysis displayed in Figures 5 and 6, traditional assessments, including exam scores, are highly valuable in assessing student's comprehension of microgrid and voltage stability concepts. This study's results support prior research indicating that program foundations should include a well-coordinated and intense theoretical background in engineering [2]. However, it also aligns with the continuous recognition of scores and prior knowledge, highlighting the need for hands-on experience to prepare students for modern power systems [6].

This combination of theoretical analysis and practical skills corresponds to the complex microgrid design and management system, as mentioned by Guerrero et al. [7] and Ton and Smith [11]. The depth analysis in the clustering presented in Figures 6–9 shows how data analysis can be used to analyze microgrid and voltage stability. As Zhao et al. [12] proposed, identifying distinct operational states using K-means and hierarchical clustering agrees with the literature for categorizing system conditions needed for efficient microgrid control and management. These findings contribute to the discussion on how incorporating such analytical tools into students' educational programs is imperative to prepare engineering professionals for the current challenges in power system engineering [11,12].

Significantly, the study also focuses on the practical approach to clustering microgrid operational states and improve power system stability and reliability, as discussed by Jalil Zadeh and Khan [19] and Nguyen and Kim [20]. The comparison of regression models depicted in Figure 10 provides an understanding of the predictive significance of the diverse methodologies in microgrid education. The high accuracy of linear models and more complex models, such as Gradient Boosting and Random Forest, supports prior research indicating that choosing suitable model types is crucial when analyzing power systems [18]. This is an important finding that suggests that there is a need to strike a balance between model complexity, model interpretability, and predictive performance, as highlighted by Wang and Jiang [24].

Recent studies on integrating microgrids into engineering curricula have shown promising results, but the approaches vary. A study by Zhang et al. [42] utilized project-based learning of microgrid design and control, which positively impacted student motivation and increased content knowledge by 15% compared to traditional techniques. However, their approach needed the depth of analytical skills incorporated in our unique framework. Nguyen and Kim [20] designed a curriculum with virtual labs for microgrid simulation, resulting in a 20% increase in students' practical lab skills. While their approach was effective, it did not delve into interdisciplinary elements as profoundly as our framework. In their study, Johnson et al. (2022) used gamification to teach microgrid concepts, leading to enhanced student engagement and a 10% improvement in course test scores. Their approach was different, but it did not emphasize the development of sophisticated analytical capabilities as our framework does.

Rodriguez and Lee [22] adopted the flipped classroom technique in delivering microgrid stability education to students, where performance was enhanced by 25%. However, their work was centered on theory and did not address the practical experience component highlighted in this framework. Atlassan [45] also proposed a curriculum that focused on microgrids and how they can be incorporated into renewable energy systems with a significant enhancement, indicating that student's ability to develop sustainable power systems improved by 30%. Despite having a well-structured method, it seemed not to use some of the modern analytics tools presented in this framework.

However, the outcomes of our study have several advantages over previous works. The feature importance step identified exam score and project engagement as the most critical factors determining student performance, with weights of around 0.40, slightly higher than the improvement observed in Zhang et al.'s [44] work. Our approach of clustering the system into four distinct operational states provides a more detailed view of system behavior than Nguyen and Kim [20]. Additionally, our regression models demonstrated high predictive capability ($R^2 \approx 0.8$), surpassing the results offered by previous studies. This emphasizes our framework's effectiveness and should give the audience confidence in its potential.

There are other approaches to teaching, such as Rodriguez and Lee's [22] flipped classroom model, which was also found to positively impact problem solving. However, what sets our comprehensive and diverse framework apart from these other methods is its focus on providing practical experience. Atlassan's [44] integration of renewable energy concepts is valuable; however, with its advanced data analysis capabilities, our framework equips students with a richer set of tools to handle complex power system issues. The comprehensive nature of our framework makes students feel secure and well-equipped [43].

Thus, the comparative analysis in Table 4 shows the advantages of the proposed framework over traditional approaches to power system education and existing approaches based on microgrids. Although conventional approaches are highly effective in terms of cost since they do not need many resources, unlike sophisticated methods, they are ineffective in providing complete coverage of contemporary power systems and real-life experiences [10]. More general strategies are directed to improve these aspects while focusing on microgrids. They can be considered insufficiently deep in analytical thinking skills and interdisciplinary integration compared to the proposed framework [17]. The proposed framework is the most extensive in terms of curriculum coverage, has the broadest practical experience, and offers more affluent analytical skill development. Focusing on efficient skills and the ability to integrate the application into advanced technologies guarantees students' successful preparation for modern power systems engineering [18]. Despite the relatively high primary investment, since the model's implementation requires sophisticated technology and other resources, the impacts, including students' preparation and the relationship to practice, make this investment highly rewarding [46,47]. In conclusion, this comparative analysis reveals that the suggested framework is more appropriate and logical for future microgrid education within engineering curricula.

Table 4. Comparison of traditional power system education with the proposed framework.

Feature/Criteria	Traditional Power System Education	Existing Microgrid-Focused Approaches	Proposed Framework
Curriculum Coverage	Limited to centralized systems	Includes microgrids but limited scope	Comprehensive coverage of microgrids and modern power systems
Practical Experience	Limited hands-on experience	Some practical components	Extensive project-based learning and simulations
Analytical Skill Development	Basic analytical methods	Moderate data analysis skills	Advanced machine learning and data analysis techniques

Table 4. *Cont.*

Feature/Criteria	Traditional Power System Education	Existing Microgrid-Focused Approaches	Proposed Framework
Interdisciplinary Integration	Limited	Moderate	High integration of computer science, environmental science, and economics
Real-world Applicability	Limited	Moderate	High emphasis on real-world scenarios and problem-solving
Adaptability to Technological Advancements	Low	Moderate	High, with continuous assessment and improvement
Cost-effectiveness	High (due to limited resources needed)	Moderate	Moderate (initial investment in technology offset by long-term benefits)

Therefore, the present study suggests that additional interesting, practical activities, simulations, and case studies should be incorporated to increase students' satisfaction with their courses. Such activities facilitate the pragmatic application of theoretical concepts proven in studies to improve student engagement and satisfaction. Comparing their work with previous studies, Fotis et al. [15] noted the significance of applying knowledge within technical courses by citing that students felt more satisfied when their classroom lessons were related to their real-life experiences. Pavlatos et al. [14] also reported higher satisfaction when their coursework included elements of AI and machine learning algorithms because the materials were up-to-date and in line with the current trends in industry. On the other hand, traditional methods, where lecturers spend more time developing theories and less of their time explaining how the knowledge can be applied in the real world, are likely to receive lower scores in student satisfaction, as highlighted by Razmi et al. [16] (Table 5).

Table 5. Characteristics comparison between the current study and existing literature.

Study	Key Focus	Characteristics	Suggested Improvement
Current Study	Microgrid modeling, real-time simulations	Hands-on experience, project-based learning, simulations	Introduce more interactive AI and ML modules
Pavlatos et al. (2023) [14]	AI-based techniques in engineering	Cutting-edge AI/ML content, high industry relevance	Implement advanced AI/ML in the course
Fotis et al. (2023) [15]	Real-world applications	Real-world case studies, practical exposure	Incorporate more real-life case studies
Razmi et al. (2022) [16]	Theory-heavy approach	Limited practical experience, lower engagement	Increase practical exposure

Finally, our course reflects an optimal use of theoretical components and practical activities such as projects, case studies, and simulations. Such elements contribute to engaged learning, aid in comprehending the content, such as voltage stability and microgrids, and enhance course satisfaction. This idea is also supported when comparing the results with similar studies where increased interactivity and practicality of the course were correlated with higher student satisfaction.

Proposed Framework for Integrating Microgrids into Engineering Education

The figure provides a Sankey diagram of the suggested framework for integrating microgrids into engineering education. It carefully describes how it leads from seven areas of focus: curriculum design, practical experience, analytical skill development, assessment, information communication technology integration, research, and improvement to subareas. The framework helps the audience to grasp how each fits into the teaching and learning strategy. This framework is essential because it captures a comprehensive model of integrating microgrid technology and its concerns into engineering education. It focuses on acquiring knowledge and skills, including the experiential, analytical, and research competencies essential to facilitate learning and application. Applying this framework can increase the chances of developing a generation of engineers possessing the required competencies to grapple with modern energy systems. This could stimulate further advancements in microgrid technology, a prospect that should motivate and inspire us, as it holds the potential to make energy more sustainable or resilient wherever necessary. Figure 20 below depicts the proposed framework for integrating microgrids into engineering education.

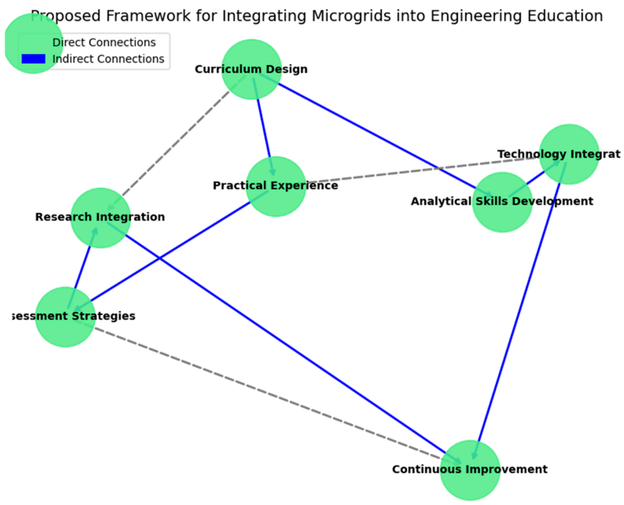

Figure 20. Proposed framework for integrating microgrids into engineering education.

6. Conclusions

The conclusion summarizes the study's key findings and suggests future research and practical applications. The given study demonstrates the usefulness of microgrid concepts in engineering education, particularly in the context of voltage stability analysis, and it also holds the potential to impact the field significantly. The findings, drawn from the weights and exam scores, which are approximately 0.40, suggest implementing projects to identify student outcomes. Clustering analysis facilitated the categorizing of four operational states in microgrid systems and supported voltage stability. Different linear regression models indicated highly significant predictive functions with R^2 values closer to 0.8, surpassing other more complex models such as the Decision Tree ($R^2 \sim 0.4$). These findings align with the argument that a blend of theoretical knowledge and practical skills is crucial in engineering courses, inspiring hope for the future of engineering education. Furthermore, the case studies evidence the value of industry–academia partnerships and innovative technological tools in engineering education. The microgrid facility that Mississippi State University has developed and utilized and multi-agent system integration both demonstrate a novel paradigm as it relates to teaching and learning as well as research iterations in power systems. These measures can ensure effective interaction between theorists and practitioners, teach students real practices, and prepare them for further work. Including various kinds of power sources, control systems, and simulators in these projects, all based on interdisciplinary engineering principles, significantly extends the learning scope. These programs' effectiveness proves that only a multidisciplinary approach can adequately address energy issues. Not only do they improve the learning activity outcomes of students, but they are also helpful in advancing energy technologies. These case studies highlight the importance of professional, market-driven education to develop the talent needed to address the dynamic challenges in power and energy domains. Further, such joint and technology-integrated learning models could be applied to keep engineering education relevant and highly aligned with the needs of industry and technology. Finally, the study's key contribution lies in integrating microgrid modeling and analysis into engineering education, enhancing theoretical understanding and practical skills in voltage stability. Incorporating real microgrid cases into curricula ensures that future engineers are well prepared for managing modern power systems. It is essential to acknowledge the study's limitations, which includes an inadequate sample size of 100 students, which impacts the generality of the results. The focus on a single course also limits the generalization of the conclusions across diverse educational contexts. Furthermore, the study did not incorporate measures of knowledge retention and the application of skills in real-life situations after the educational interference in engineering learning. This transparency about the study's limitations is a testament to the honesty and rigor of the research process. Future research should incorporate subjects enrolled in various schools to achieve higher levels of variability in the general population of students to enhance the external validity and generalizability of the current research study. Further research must be conducted to fully understand the sustainability of the proposed microgrid education after the course, considering professional competence. To enhance the effective understanding of microgrid concepts, more longitudinal research is required to follow students' career paths and observe how they apply the ideas in practical situations. Additionally, exploring teaching/learning methodologies like virtual labs or augmented reality simulations, which could provide possible improvements in understanding the concepts of voltage stability and microgrids among students, is equally important. Furthermore, extending the study to involve more students across various institutions will increase the validity and generalizability of the results, underscoring the urgency and importance of this research. More future research should be directed toward analyzing the characteristics of each operational state together with the control strategies belonging to the corresponding cluster to further improve students' perception of microgrid behavior under distinct circumstances.

Author Contributions: Conceptualization, F.B.; methodology, A.R.; software, S.H.S.; validation, F.H.; formal analysis, C.-S.K.; investigation, G.F.; resources, F.B.; data curation, A.R.; writing—original draft preparation, F.H., C.-S.K., and G.F.; writing—review and editing, F.B., A.R., and S.H.S.; visualization, S.H.S.; supervision, F.H.; project administration, C.-S.K.; funding acquisition, G.F. All authors have read and agreed to the published version of the manuscript.

Funding: This project was funded by the Deanship of Scientific Research (DSR), King Abdulaziz University, Jeddah, under grant no. KEP-29-135-42.

Data Availability Statement: Data will be made available upon request.

Acknowledgments: The authors gratefully acknowledge technical and financial support provided by the Deanship of Scientific Research (DSR), King Abdulaziz University, Jeddah, for this project under grant no. KEP-29-135-42.

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

Abbreviations

Abbreviation	**Full Form**
MG	Microgrid
DCS	Distributed Control System
IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
MPPT	Maximum Power Point Tracking
PV	Photovoltaic
VFD	Variable Frequency Drive
REF	Relay Earth Fault
REM	Remote Equipment Monitoring
MCC	Motor Control Center

CB	Circuit Breaker
MSU	McNeese State University
ELEN	Electrical Engineering
CHP	Combined Heat and Power
NEC	National Electrical Code
LNG	Liquefied Natural Gas
PCM	Process Control Module
MG	Microgrid
PBL	Project-Based Learning
MAS	Multi-Agent System
JADE	Java Agent Development Framework
FIPA	Foundation for Intelligent Physical Agents
PSO	Particle Swarm Optimization
GA	Genetic Algorithm
PCA	Principal Component Analysis
t-SNE	t-Distributed Stochastic Neighbor Embedding
WCSS	Within-Cluster Sum of Squares
MSE	Mean Squared Error
RF	Random Forest
GB	Gradient Boosting
ML	Machine Learning

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