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ENHANCING INDUSTRIAL POWER SYSTEMS: A CASE STUDY ON ELECTRICAL SAVINGS IMPROVEMENT WITH MICROBIAL FUEL CELL

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The object of the study is the industrial feeder system rated at 100 kVA and 150 kVA, which was integrated with an MFC system operating in parallel with the grid. This research explores the application of microbial fuel cells (MFCs) for industrial-scale power systems, focusing on their integration with medium-capacity feeders to reduce reliance on grid electricity. The central problem addressed is the scarcity of long-term, real-world demonstrations of MFCs operating in parallel with the public grid, particularly in feeders rated at 100 kVA and 150 kVA, where stable and reliable performance is critical. To overcome this gap, customized MFC panels were designed, equipped with a Delta PLC-based control system, and installed on two industrial feeders. Their operation was monitored continuously for nine months using PM-5350 power meters to capture load, grid, and MFC contributions. The results demonstrate that the MFCs consistently supplied a fraction of the feeder demand, reducing grid energy consumption by 9.68–18.48%, with an overall average saving of 12.38%. Corresponding reductions in electricity costs reached up to USD 1,034 per month. Differences in savings between the two feeders were explained by variations in load profiles, synchronization strategies, and microbial performance stability over time. A distinctive outcome of this study is the successful demonstration of reliable, long-horizon MFC operation under industrial conditions, enabled by protective interconnection schemes and automated control. The practical implications are significant: MFCs can be deployed on medium-scale feeders in manufacturing or processing industries to achieve measurable cost reductions while simultaneously contributing to renewable energy adoption and waste-to-energy initiatives. These findings strengthen the case for MFCs as a viable complement to conventional distributed generation technologies

Keywords: microbial fuel cells, industrial feeders, grid integration, energy savings, cost reduction

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1. Introduction

In modern industrial environments, the simultaneous demand for energy efficiency, sustainability, and waste minimization has made renewable and decentralized power generation a pressing necessity. Global energy consumption in manufacturing sectors continues to rise, while dependence on fossil-based grids contributes to operational vulnerability and carbon emissions. This context underlines the need for technologies capable of producing on-site renewable electricity from industrial and organic waste streams.

Microbial fuel cells (MFCs) have emerged as one of the most promising bioelectrochemical systems to meet these needs, as they enable the direct conversion of chemical energy from biodegradable substrates into electrical energy through microbial catalysis [1]. Beyond electricity generation, MFCs contribute to wastewater remediation and resource recovery, positioning them as dual-function systems for both energy and environmental management [2]. Recent advances in electrode materials – particularly porous carbon and nanocomposite-based structures – have significantly improved electron transfer efficiency and microbial adhesion, thereby enhancing system stability and energy yield [3, 4]. Such improvements demonstrate the growing technological maturity of MFCs for real-world applications.

Despite this progress, significant challenges remain unresolved in scaling MFCs beyond laboratory or pilot-scale configurations. Studies consistently report a decline in power density as reactor volume increases, primarily due to internal resistance and reduced microbial efficiency under large-scale conditions [5]. Further limitations are observed in reactor durability, electrode degradation, and cost-efficiency, all of which hinder long-term industrial deployment [6, 7]. Additionally, biological instability over extended operation remains a key technical obstacle, as microbial communities can lose electroactivity under fluctuating temperature, substrate, and load profiles [8]. These factors collectively explain why industrial adoption of MFCs has lagged behind their scientific potential.

However, ongoing research offers promising directions. Modular system architectures, where multiple small MFC units are interconnected at the electrical feeder level, can improve scalability and operational control while minimizing performance losses [9]. Moreover, simulation-based optimization platforms now allow better prediction of MFC dynamic behavior under variable loading, supporting the design of reliable grid-parallel operation [10]. Combined with life cycle and cost assessments that evaluate long-term environmental and economic benefits [11], these advances suggest that MFC integration into industrial power systems is approaching practical feasibility.

Therefore, research on the development and industrial integration of microbial fuel cell technology is highly relevant and timely. Demonstrating reliable MFC operation within medium-capacity feeders can provide industries with a viable means of reducing grid dependence, lowering electricity costs, and transforming waste into a renewable energy resource. The findings of such studies will not only validate the long-term stability of MFCs under real operating conditions but also strengthen their role as complementary technologies within sustainable industrial energy systems. Therefore, the studies on the development and industrial integration of microbial fuel cell technology are scientifically relevant.

2. Literature review and problem statement

One study [1] explored renewable coffee waste–derived porous carbon as an anode material for MFCs. It demonstrated superior conductivity and stability, confirming the potential of waste-based carbon electrodes. However, scalability remained unaddressed, as electrode uniformity and mechanical strength are difficult to control in mass fabrication.

Research [2] integrated microalgae cultivation into MFC operation, combining electricity generation, wastewater treatment, and CO_2 sequestration. Although this system achieved multifunctional environmental benefits, biological complexity hindered the simultaneous optimization of growth and electrochemical efficiency under industrial conditions.

A review [3] discussed nanofiber-based electrode materials that increase surface area and microbial adhesion, boosting power output. Nevertheless, nanofiber production is energy-intensive and costly, leaving the challenge of low-cost, scalable fabrication unresolved.

Another comprehensive review [4] summarized hybrid nanocomposites for enhanced conductivity and biocompatibility. Despite improved charge transfer, their synthesis involved toxic reagents and complex processing, discouraging large-scale application in environmentally oriented industries.

Experimental work [5] employed edible mushrooms as natural biocatalysts in laccase-based MFCs. Improved enzymatic activity was observed; however, enzyme degradation under fluctuating pH and temperature conditions resulted in unstable output – an issue that remains unaddressed due to the limited research on enzyme durability.

A scaling study [6] treated swine wastewater using large MFC reactors. Although pollutant removal and electricity generation were confirmed, internal resistance and biofilm irregularities caused performance losses. The lack of standard design protocols for large-scale electrodes remains a barrier.

Research [7] treated refinery wastewater while generating power. However, electrode corrosion and material fatigue reduced performance over time. The need for chemical-resistant and long-lasting electrodes remains unexplored, primarily due to the high costs of materials and limitations in testing.

Another investigation [8] treated aromatic hydrocarbon effluents using MFCs in series and parallel configurations. The approach improved power density and bioremediation but lacked adaptive control for fluctuating influent characteristics. The dynamic behavior of microbial communities under varying loads remains poorly understood.

An experiment [9] compared nanostructured electrodes for power density improvement. Although short-term gains were achieved, long-term operational stability was not tested, likely due to time and cost constraints of extended experiments.

A life cycle study [10] analyzed bioelectrochemical systems for hexavalent chromium removal, demonstrating both environmental and economic potential. Yet, high data uncertainty and the absence of industrial-scale validation limited confidence in its real-world applicability.

Computational modeling [11] developed a simulation platform for dual-chamber MFCs. The tool improved predictive capability but lacked experimental verification, as model parameters are difficult to validate without standardized test datasets.

Earlier reviews also contributed to foundational understanding. A seminal work [12] described MFC-based wastewater treatment mechanisms but did not quantify energy–pollutant tradeoffs, since computational tools were underdeveloped at that time. Another study [13] examined metal ions as electron acceptors in single-chamber MFCs, improving current density but leaving unresolved the problem of ion toxicity over long durations. In parallel, [14] investigated microbial electricity utilization for practical devices, yet did not address integration into power electronics because of early-stage technology maturity.

A mini-review [15] summarized MFC development for bioelectricity generation, identifying cost and power density as central bottlenecks. However, the review provided limited design guidance due to inconsistent metrics among primary studies. A related work [16] highlighted bioenergy potential but lacked quantitative comparison across feedstocks, reflecting data scarcity in diverse wastewater matrices.

Integrated approaches also emerged. Research [17] combined MFCs with complementary technologies for improved energy recovery, yet interconnection losses and maintenance complexity were not evaluated. Study [18] applied MFCs to pharmaceutical wastewater, revealing high pollutant tolerance but also low long-term biofilm stability; this issue persists because continuous pharmaceutical waste monitoring is rarely feasible. In a separate context, [19] contributed a methodological paper on cognitive association that is not directly energy-related but provided statistical modeling techniques later adapted for MFC performance prediction.

Work [20] utilized agricultural waste as substrate, showing strong electricity yield potential; still, feedstock variability caused inconsistent outcomes that remain unmodeled due to the heterogeneity of agricultural residues. Maritime-oriented analysis [21] reviewed fuel cell power systems at sea but omitted microbial variants, implying that marine MFC applications are still underexplored. A focused review [22] examined brewery wastewater treatment using MFCs and identified scaling to pilot systems as the key barrier, which persists because brewery effluent composition fluctuates seasonally.

Several studies investigated materials and electrode design. Paper [23] assessed MFCs as energy storage devices, but experimental runs were short, preventing aging analysis. Work [24] treated fermentation sludge using dual-chamber systems, confirming dual benefits in waste stabilization and power output, though long-term fouling behavior was not addressed. Research [25] discussed enzyme immobilization and electrode optimization strategies, yet their industrial cost-effectiveness remains unproven due to limited techno-economic data.

Study [26] tested pre-treated sludge for electricity generation, achieving higher output but lacking characterization of microbial evolution over time. Similarly, [27] investigated carbon fiber electrodes for waste-potato-fed MFCs and achieved enhanced activity; still, substrate variability and nutrient imbalance limited reproducibility. Another experiment [28] treated bulgur industry wastewater and confirmed pollutant reduction, though scalability beyond lab scale was not assessed due to equipment limitations.

Finally, [29] introduced modified water hyacinth biochar electrodes for pharmaceutical wastewater, highlighting low-cost fabrication potential. Yet, electrochemical stability over repeated cycles was not analyzed, primarily because such biochar materials degrade under long-term aqueous exposure.

Despite notable progress in electrode innovation, wastewater treatment integration, and bioelectricity generation, microbial fuel cell (MFC) research remains confined mainly to laboratory and pilot scales. Most studies have not demonstrated reliable performance under industrial operating conditions. All this allows to assert that it is expedient to conduct a study to address these gaps by developing and validating a microbial fuel cell system integrated with medium-capacity industrial feeders. The focus should be on evaluating scalability, durability, and predictive control to support sustainable and energy-efficient industrial operation.

3. The aim and objectives of the study

The aim of the study is to develop and empirically validate a modular, grid-parallel method for integrating microbial fuel cells (MFCs) into medium-capacity industrial feeders (100 kVA and 150 kVA) and to identify long-term performance regularities (relationships among load profile, synchronization strategy, and microbial stability) under real operating conditions; this will allow industrial users to reduce grid electricity consumption and operating costs and to adopt requirements for practical deployment.

To achieve this aim, the following objectives were accomplished:

– to design and implement MFC panels suitable for 100 kVA and 150 kVA systems;

– to conduct a nine-month grid-parallel trial and identify the relationships between feeder load characteristics, control strategies, microbial performance, and the MFC power contribution;

– to analyze the energy savings attributable to MFC integration and quantify the corresponding reductions in electricity costs on a month-by-month basis.

4. Materials and methods

The object of the study is the industrial feeder system rated at 100 kVA and 150 kVA, which was integrated with an MFC system operating in parallel with the grid.

The main hypothesis of the study states that the integration of an MFC into an industrial feeder can effectively reduce grid electricity consumption and enhance power quality. This hypothesis reflects the expectation that MFC-generated power can operate reliably alongside grid electricity to contribute measurable energy savings.

Several assumptions were made to maintain experimental consistency. It was assumed that the microbial activity inside the MFC remained sufficiently stable throughout the observation period to sustain power generation, that the industrial load profiles recorded were representative of typical daily operations, and that all measuring and protection devices functioned within their calibration limits. Environmental parameters such as temperature and humidity were also presumed to have minimal influence on the electrical performance of the MFC system.

To facilitate long-term monitoring and analysis, several simplifications were adopted. The study focused primarily on electrical performance parameters without conducting a characterization of microbial behavior.

This study employed a case study approach to evaluate the integration of microbial fuel cell (MFC) systems into industrial electrical feeders. The methodology followed a structured sequence, including system design, panel integration, control configuration, and long-term monitoring.

The conceptual operation of an integrated MFC system for industrial use is illustrated in Fig. 1, showing the bioreactor, grounding system, and chemical reactor that support energy generation.

System integration and configuration. Two industrial feeder capacities were selected for implementation: 100 kVA and 150 kVA. A dedicated MFC unit was integrated into each feeder to operate in parallel with the grid supply, enabling real-time load sharing. The integration design comprised two panels:

1) an interconnection panel, responsible for grid synchronization, electrical protection, and metering;

2) an MFC panel, which contained the control logic, measurement devices, relays, and a human-machine interface (HMI).

Component specifications include miniature circuit breakers (MCBs), molded case circuit breakers (MCCBs), relays, PLC modules, power meters, and control indicators.

Control and monitoring. Custom wiring diagrams were developed for each capacity, covering:

1) single-line distribution and load interconnection;

2) internal control and protection wiring;

3) relay-based logic for reactors and power modules.

The control system was based on a Delta DVP-series PLC communicating with current transformers, temperature sensors, and contactors. An HMI was used for operator interaction and system supervision.

Experimental conditions. Both MFC-integrated feeders were operated continuously for nine months under standard industrial load profiles. Energy parameters were recorded via PM-5350 digital power meters and data acquisition modules integrated in the panels. Recorded variables included feeder load, grid-supplied energy, and MFC-supplemented energy.

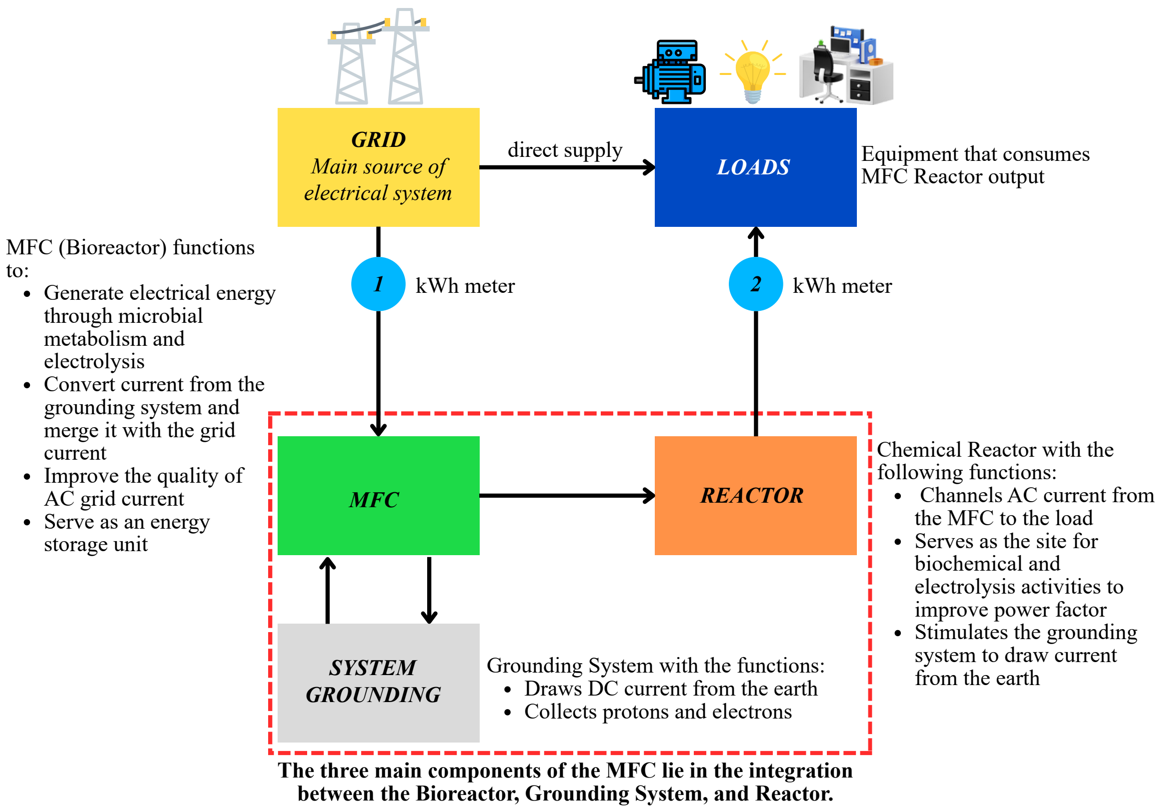

Fig. 1. Integrated schematic of the microbial fuel cell (MFC) system

Validation and data processing. Data were logged monthly using HMI to ensure adequate coverage of peak and off-peak conditions. The adequacy of the setup was validated through cross-checking panel measurements with independent meters during commissioning. The collected data were then prepared for subsequent analysis of energy savings and cost impacts, which are reported in Section 5.

5. Experimental results of microbial fuel cell integration for energy efficiency in industrial applications

5. 1. Design and implementation of microbial fuel cell system

To achieve the first objective, two industrial feeder systems rated at 100 kVA and 150 kVA were selected for integration with microbial fuel cell (MFC) units. The MFCs were configured to operate in parallel with the existing grid supply, enabling real-time load sharing and supplemental energy generation. The integration design consisted of two main panels:

– interconnection panel, responsible for grid synchronization, electrical protection, and metering;

– MFC Panel, containing the programmable logic controller (PLC), relays, measurement devices, human-machine interface (HMI), and associated control circuitry.

The control system was based on a Delta DVP-series PLC that communicated with current transformers, temperature sensors, and contactors. At the same time, the HMI interface allowed operators to monitor and configure system operation. The schematic of the integrated MFC system within the industrial feeder arrangement is illustrated in Fig. 1 of this paper, showing the bioreactor, grounding system, and chemical reactor interconnected with the electrical infrastructure.

The wiring diagram illustrates the 100 kVA and 150 kVA systems, including their interconnections with the load and the upper and lower sections of the MFC panel. Fig. 4 presents the wiring diagram of the 100 kVA MFC system Fig. 2, *a* shows the single-line diagram of a dual-transformer power configuration, where each transformer (Trafo 1 and Trafo 2) is connected to its respective MFC, air circuit breaker (ACB), and capacitor bank. The transformers step down the incoming high-voltage supply for MFC operation, with the MFC units serving as bio-electrochemical generators. The ACBs provide system protection, while capacitor banks improve power factor and stabilize voltage. Both systems receive dual utility inputs (Grid 1 and Grid 2) with interconnection panels for synchronization, enabling load sharing and redundancy. Overall monitoring, grounding, and protection are managed by the Continuous Power Organic Earth (CPOE), also known as the grounding system, to ensure reliable operation.

The 100 kVA feeder configuration is illustrated in Fig. 2, *b*, where the grid, MFC modules, and reactors are connected to supply industrial loads. A simplified wiring, where the upper section integrates protection devices (MCBs, MCCBs, relays, and fuses) and automation components (PLC, HMI, sensors), while the lower section manages three MFC units (M1–M3) and eight reactors (R1–R8). Power and control circuits are separated through busbars, terminal blocks, and dedicated 24 VDC lines, ensuring safe operation, modularity, and clear signal routing between reactor modules and the control panel. On the other hand, the simplified wiring diagram of the 150 kVA MFC Panel is shown in Fig. 3.

The wiring configuration of the upper section and the interconnection with the load in the 150 kVA system follow the same design principles as those implemented in the 100 kVA configuration, ensuring consistency in protection, control, and monitoring functions. As seen in Fig. 3, the different form of the 100kVA system is at the lower section of the system, where the 150 kVA configuration accommodates six MFC units (M1–M6) instead of three, to handle the higher power demand and maintain balanced power distribution across the reactor array. This expansion in the number of MFC modules enhances the system's capacity without altering the established control architecture, enabling scalability while preserving the integrity and reliability of the original design. The layout of the lower MFC panel for the 150 kVA configuration is illustrated in Fig. 3.

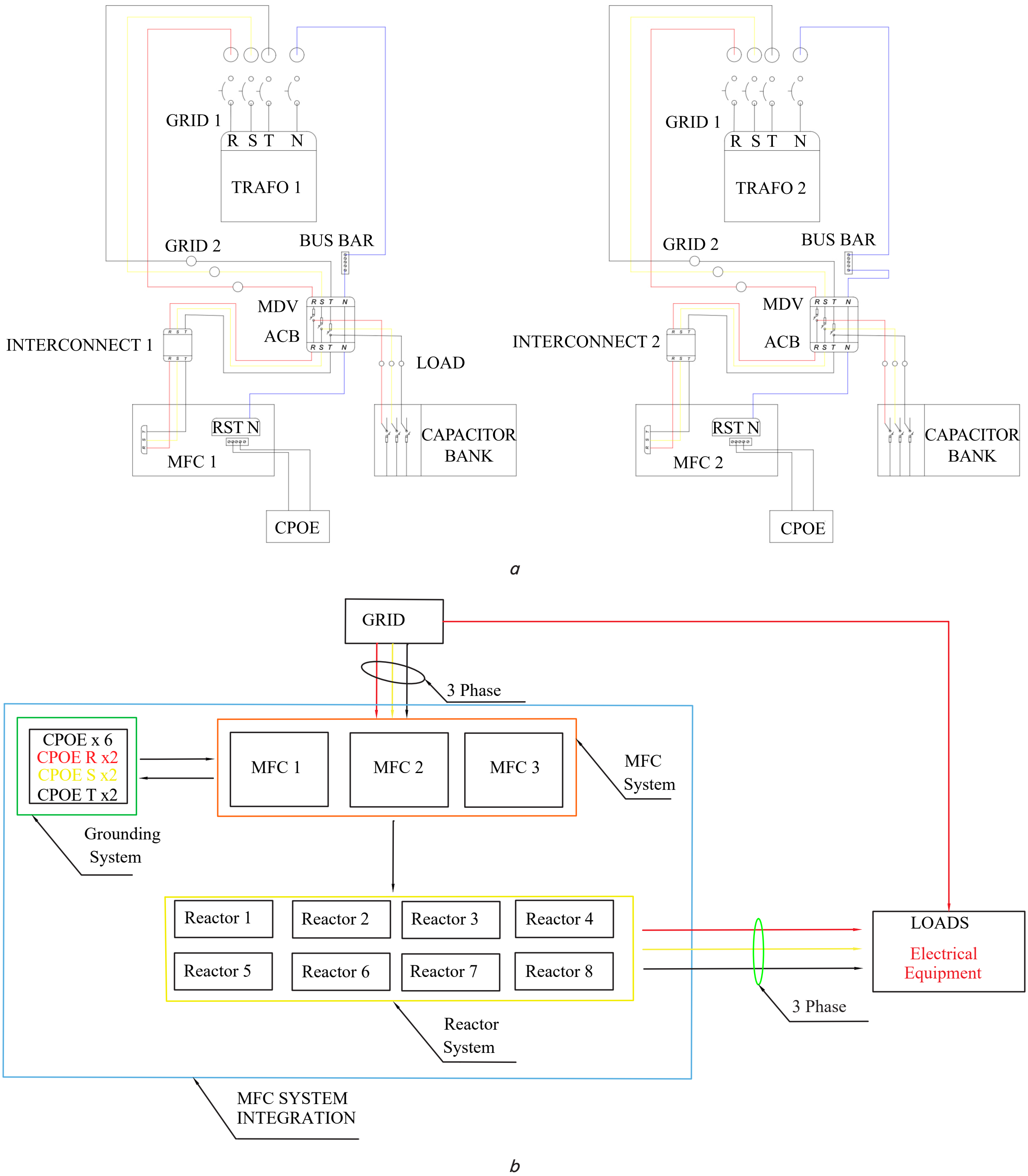

Fig. 2. Simplified wiring diagram of: *a* — interconnection with load; *b* — microbial fuel cell 100 kVA panel

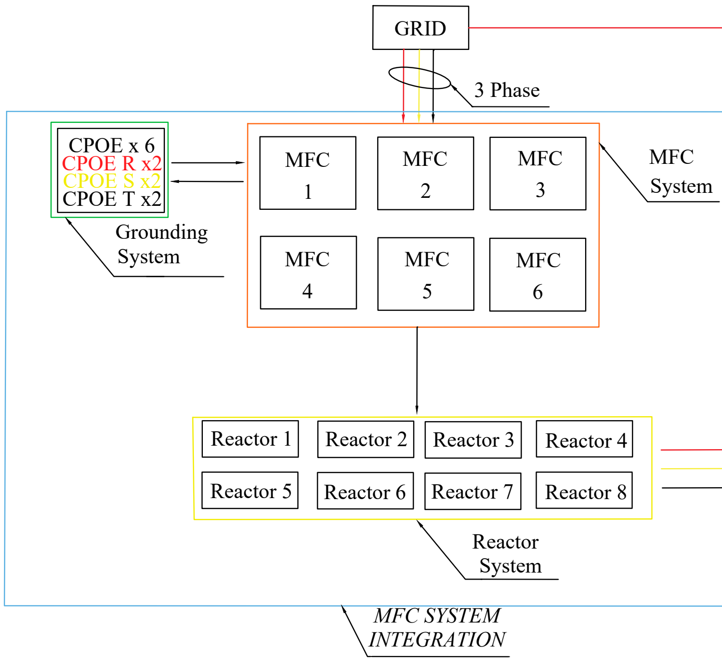

Fig. 3. Simplified wiring diagram of 150 kVA microbial fuel cell panel

5. 2. Long-term monitoring of load and grid

Based on the early investigation, the experimental results were obtained from the implementation of microbial fuel cell (MFC) systems with capacities of 100 kVA and 150 kVA. However, it should be noted that the case study is in the office sector.

The data are presented through comparative graphs that depict the electrical load, grid consumption, and resulting energy savings over a nine-month observation period. Fig. 4 illustrates the monthly energy performance of the 100 kVA MFC system, highlighting variations in load demand, grid energy usage, and energy savings during both off-peak and peak periods.

In Fig. 4, *a*, the off-peak period performance is presented. On the other hand, Fig. 4, *b* shows the peak load performance. The corresponding peak grid consumption, depicted by the orange line, and energy savings by the green dashed line.

Similar to the 100 kVA system, Fig. 5 presents a monthly comparison of total load, grid energy consumption, and energy saving percentages for both off-peak and peak periods under the 150 kVA microbial fuel cell (MFC) system.

In Fig. 5, *a*, presents the off-peak period is presented. On the other hand, Fig. 5, *b* presents the peak period performance, where the solid purple line indicates the peak load. At the same time, the grid consumption and energy savings are represented by the orange and green lines, respectively.

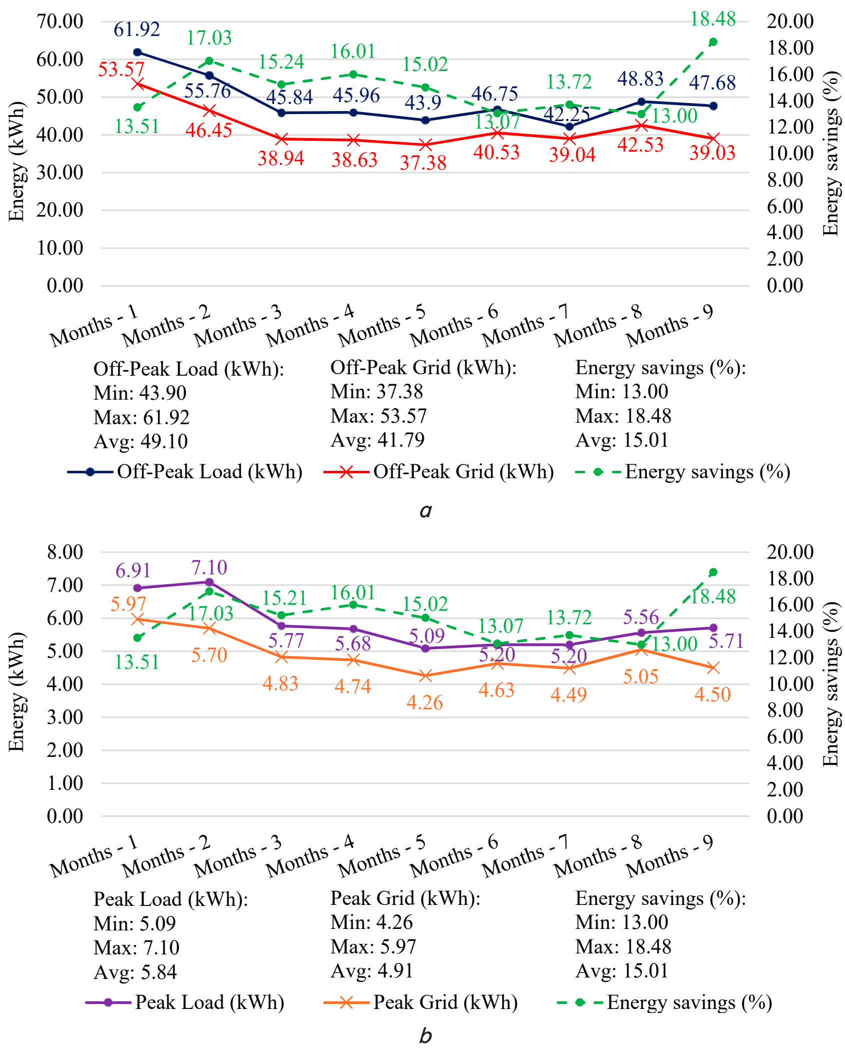

Fig. 4. Monthly comparison of load, grid consumption, and energy savings for the 100 kVA microbial fuel cell system: *a* – off-peak; *b* – peak

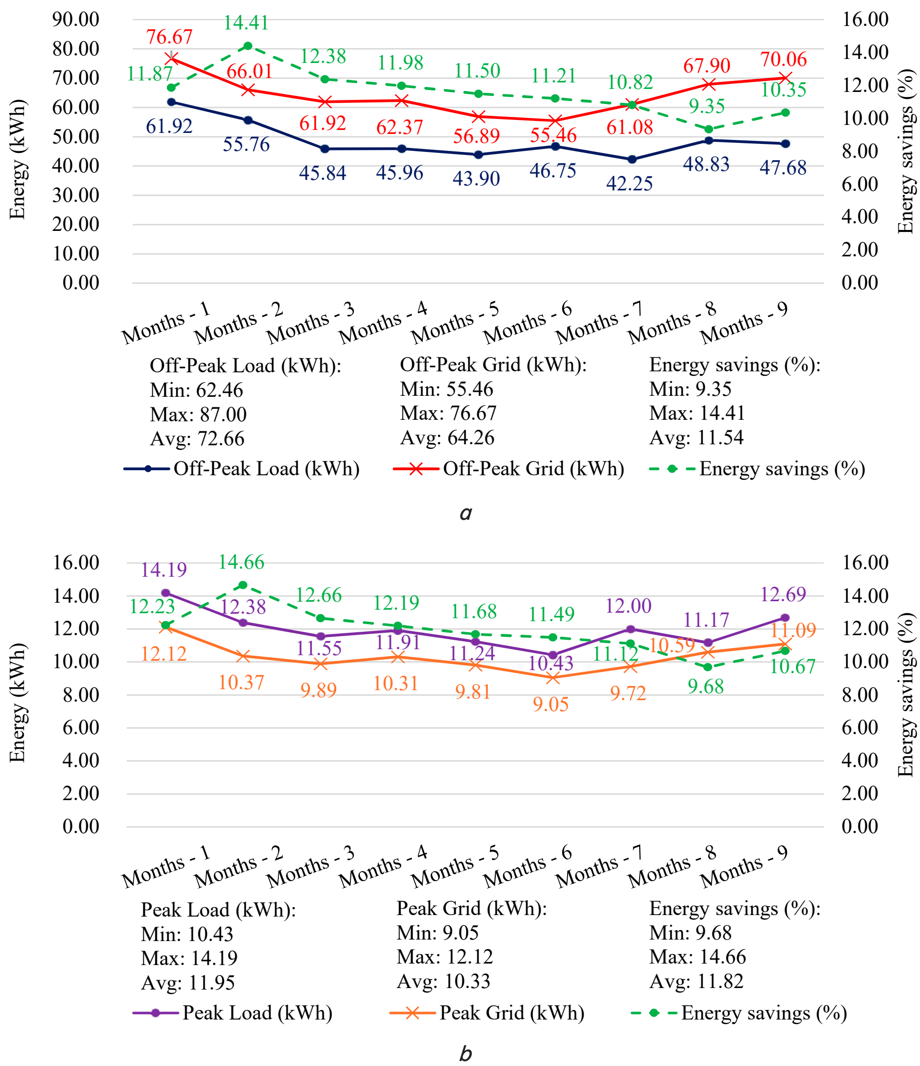

Fig. 5. Monthly comparison of load, grid consumption, and energy savings for the 150 *kVA* microbial fuel cell system: *a* — off-peak; *b* — peak

The results in Table 1 indicate that both the 100 kVA and 150 kVA MFC-integrated systems achieved consistent monthly savings in operational costs by reducing grid electricity consumption. For the 100 kVA system, savings ranged from 12.97% to 17.17%, with the highest cost reduction observed in month-2, reflecting stable MFC performance across varying load conditions. The 150 kVA system demonstrated a similar trend, achieving savings between 9.81% and 14.77%, with peak performance also in month-2.

6. Discussion of the interconnection of microbial fuel cell systems

As shown in Fig. 2, 3, the developed configuration successfully established a stable and safe electrical interconnection between the MFC modules, the grounding system, and the industrial feeders. The interconnection panel ensured proper synchronization and protection through the inclusion of circuit breakers, relays, and monitoring devices. In contrast, the MFC panel incorporated a PLC-based control system that automated start-up, switching, and protection functions. The use of PM-5350 power meters enabled precise real-time monitoring of energy flow between the grid, MFC, and load. This architecture validated the technical feasibility of integrating bioelectrochemical power sources into medium-capacity feeders without requiring significant modification of existing infrastructure. The apparent modularity observed in the panel arrangement also confirms that the system can be scaled between 100 kVA and 150 kVA capacities while maintaining the same core design.

5. 3. Energy savings and electricity cost reductions

Table 1 presents a comparative analysis of the operational costs for two configurations of the electrical system with microbial fuel cell integration: the 100 kVA and 150 kVA systems. The data cover a period of nine months and include four key parameters for each month: total load cost, grid cost with MFC, total savings, and monthly savings percentage. This comparison provides insights into the cost efficiency of each system in reducing grid dependency and operational expenditures.

Table 1

Cost savings analysis

Month	100 kVA MFC				150 kVA MFC			
	Total load cost	Grid cost (with MFC)	Total savings	Savings (%)	Total load cost	Grid cost (with MFC)	Total savings	Savings (%)
Month-1	$5,291.89	$4,576.58	$715.31	13.52%	$7,925.78	$6,943.81	$981.97	12.39%
Month-2	$4,861.24	$4,026.64	$834.60	17.17%	$7,005.37	$5,971.39	$1,033.99	14.77%
Month-3	$3,990.02	$3,380.90	$609.12	15.27%	$6,441.60	$5,618.71	$822.88	12.77%
Month-4	$3,988.43	$3,348.91	$639.52	16.03%	$6,495.40	$5,698.24	$797.16	12.27%
Month-5	$3,773.19	$3,203.96	$569.22	15.08%	$5,940.66	$5,242.33	$698.33	11.75%
Month-6	$3,993.50	$3,475.32	$518.17	12.97%	$5,171.74	$5,054.19	$663.55	12.83%
Month-7	$3,883.04	$3,350.54	$532.50	13.71%	$6,240.19	$5,538.54	$701.65	11.24%
Month-8	$4,217.65	$3,667.69	$549.96	13.04%	$6,801.89	$6,134.51	$667.38	9.81%
Month-9	$4,117.88	$3,351.35	$766.53	18.61%	$7,114.66	$6,346.67	$768.00	10.75%

On the other hand, the savings reported in Table 1, supported by the performance curves in Fig. 4, 5, highlight consistent reductions in grid dependency under both peak and off-peak conditions. These outcomes can be explained by the ability of the MFCs to continuously supplement the load, thereby lowering the share of energy drawn from the grid. In particular, the 100 kVA system achieved higher relative efficiency, with savings ranging from 12.97% to 18.61%, while the 150 kVA system, although slightly lower in percentage terms (9.81%–14.77%), delivered greater absolute monetary savings due to its larger load profile. This distinction reflects the influence of system scale on the balance between relative efficiency and absolute financial benefit.

For MFC 100 kVA, in Fig. 4, *a*, the off-peak load values range from 41.935 kWh to 61.915 kWh, with an average of 49.098 kWh. In comparison, the off-peak grid consumption ranges from 31.390 kWh to 53.566 kWh, averaging 41.787 kWh. The energy savings achieved during off-peak periods vary from 13.00% to 18.48%, with a consistent average of 15.01%. Fig. 4, *b*, the peak load ranges from 5.001 kWh to 7.097 kWh, with an average of 5.853 kWh. The corresponding peak grid consumption spans from 4.197 kWh to 5.965 kWh, with an average value of 4.907 kWh. Energy savings in the peak period range from 13.00% to 18.48%, with a mean value of 15.01%, demonstrating a stable reduction in grid energy usage even under lower demand conditions.

Taken together, these results confirm the 100 kVA MFC system's consistent performance in reducing grid dependency across both peak and off-peak operational periods. The system continually maintained energy savings above 13%, with minimal variance between different months, despite variations in load from as low as 41.935 kWh to as high as 61.915 kWh in the off-peak period. This highlights the system's strong operational reliability and practical applicability in hybrid energy configurations aimed at enhancing efficiency and sustainability.

For the MFC 150 kVA, in Fig. 5, *a*, the off-peak load ranges from 62.464 kWh to 86.997 kWh, with an average value of 72.660 kWh. Correspondingly, the off-peak grid energy consumption varies between 55.462 kWh and 76.073 kWh, with an average of 64.263 kWh. The resulting energy savings percentages fluctuate from 9.68% to 14.66%, yielding a mean value of 11.82%. Fig. 5, *b*, the recorded peak load values range from 10.43 kWh to 14.19 kWh, with an average of 11.95 kWh. The corresponding grid energy consumption spans from 9.05 kWh to 12.12 kWh, averaging 10.33 kWh. Similar to the off-peak results, the peak-period energy savings range from 9.68% to 14.66%, with a consistent average of 11.82%, indicating stable performance across different operational conditions.

Collectively, these datasets confirm the 150 kVA MFC system's consistent capability in reducing grid energy demand across a wide range of load levels. The system continuously achieved energy savings exceeding 9.68% in both peak and off-peak periods, with average values maintained at 11.82%. This consistent efficiency demonstrates that even under varying load conditions from as low as 62.464 kWh to as high as 86.997 kWh during off-peak hours, the system reliably offsets a significant portion of the grid supply.

The 100 kVA system demonstrated a higher average energy savings of 15.01%, with variations ranging from 13.00% to 18.48%. In contrast, the 150 kVA system exhibited more consistent performance, achieving savings between 9.68% and 14.68%, with an average of 11.82%. Although its percentage savings were slightly lower, the 150 kVA system achieved a greater absolute reduction in grid energy consumption due to its higher load profile – averaging 72.660 kWh during off-peak and 11.950 kWh during peak periods – compared to 49.098 kWh and 5.853 kWh, respectively, for the 100 kVA system. This indicates that the larger system, while relatively less efficient in percentage terms, provides a greater overall impact in offsetting grid demand. The superior performance of the 150 kVA system can be attributed to its higher load-handling capacity, reduced internal losses, and more stable microbial fuel utilization, making it particularly suitable for large-scale or highly variable energy applications in hybrid infrastructures. Conversely, the 100 kVA system, with its higher relative efficiency, is better suited for small- to medium-scale deployments where maximizing energy savings per unit of load is the primary objective, especially in facilities with lower or more stable energy demands.

From Table 1, over a span of nine months, the 100 kVA system consistently achieves notable reductions in energy expenditures, with monthly savings ranging from $518.17 to $834.60 and percentage savings between 12.97% and 18.61%. The peak percentage saving of 18.61% in Month-9 signifies not only cost efficiency but also the stability of MFC performance across varying operational loads. Despite operating at a smaller scale, the 100 kVA system proves to be highly effective in optimizing energy consumption relative to its load profile, making it a cost-effective solution particularly for medium-sized facilities aiming to reduce grid dependency. On the other hand, the 150 kVA system demonstrates superior performance in absolute savings, with monthly reductions ranging from $663.55 to $1,033.99, reflecting its capacity to offset a greater portion of grid-based energy use due to higher energy demands. Although its percentage savings are slightly lower, ranging from 9.81% to 14.77% this is primarily attributed to the naturally higher total load costs in larger systems. The highest financial and percentage savings are observed in Month-2, indicating optimal synergy between load conditions and MFC contribution during that period.

Overall, the comparison underscores the scalability and practicality of MFC integration. The 100 kVA configuration excels in efficiency when measured as a proportion of cost savings, ideal for systems with moderate energy usage. Meanwhile, the 150 kVA system offers more substantial absolute cost reductions, making it well-suited for high-demand environments where every percentage point of savings translates into larger monetary returns. These results affirm the MFC's versatility and economic viability as a sustainable energy solution across different system sizes.

Compared to previous studies that mainly demonstrated MFC feasibility at laboratory or pilot scales with limited stability [6, 7, 25], the results here confirm long-term operational reliability under real industrial conditions. Unlike short-duration trials in wastewater-based MFCs [8–11], the continuous nine-month monitoring in this study demonstrates that MFC systems can sustain meaningful energy contributions without major performance deterioration. This represents a significant step toward bridging the gap between academic prototypes and industrial deployment, extending the relevance of earlier findings by providing quantitative cost savings in actual feeder systems.

The proposed method's peculiar feature is its modular design of feeder-integrated panels, ensuring stable synchronization, protection, and monitoring. The PLC-based control scheme provided reliable automation, while the reactor arrangement allowed scalability from 100 kVA to 150 kVA without altering the core architecture. This modularity distinguishes the study from conventional distributed generation systems, which often require extensive reconfiguration when scaled [19, 22].

However, several limitations must be acknowledged. First, the reproducibility of results is constrained by the microbial performance of the reactors, which may vary depending on substrate quality and operational conditions. Second, the study was conducted under specific industrial load profiles, and the outcomes may differ in environments with higher variability or less predictable demand. Third, while savings were consistent, the overall contribution of MFCs remains supplementary rather than primary, highlighting limitations in absolute power density relative to alternative technologies such as photovoltaic systems or conventional fuel cells [17, 23, 28].

A disadvantage of this study is the absence of a detailed life cycle cost assessment, which would better quantify the long-term economic tradeoffs, including maintenance and microbial replacement costs. This could be addressed in future work by incorporating life cycle analysis (LCA) frameworks, as suggested in recent works on bioelectrochemical systems [27].

Future development in the near term will concentrate on a more detailed evaluation of system behavior under industrial conditions. This includes investigating the influence of different soils, reactor configurations, and MFC modules on overall performance; analyzing the power conversion efficiency of each principal component within the integrated panels; and studying the impact of various load types on the savings. In addition, further work will involve the validation of active and reactive power contributions using more reliable instrumentation, such as Power Quality Analyzers (PQA), over extended monitoring periods. These steps will provide clearer technical insights and strengthen the practical foundation for future scaling. Overcoming these challenges would significantly expand the applicability of MFCs as a complementary renewable energy technology in industrial power systems.

7. Conclusion

1. The design and implementation of 100 kVA and 150 kVA MFC panels proved technically feasible and stable under industrial operating conditions. This confirms that the developed configuration overcomes scalability and control challenges commonly reported in laboratory-scale studies, providing a practical framework for real industrial integration.

2. Long-term operation demonstrated consistent MFC performance, with average monthly energy savings of 12.38% and peak values reaching 18.48% for the 100 kVA system and 14.66% for the 150 kVA system. These results verify that MFCs can sustain continuous energy contribution in grid-connected industrial feeders, maintaining operational stability far beyond previously reported short-term experiments.

3. Economic evaluation indicated tangible cost benefits, with monthly savings ranging from USD 518.17–834.60 for the 100 kVA system and USD 663.55–1,033.99 for the 150 kVA system. Although smaller systems achieved higher relative efficiency, the larger configuration provided greater total savings, highlighting its more substantial financial advantage for high-demand facilities. These findings confirm that MFC integration delivers measurable economic and sustainability gains under real industrial conditions.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that support the findings of this study are available upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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