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Development of Energy Management System for Microgrid System Considering Demand Response Program for Clean and Economic Operation

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ABSTRACT
Micro-grids are small-scale localized energy systems operating independently or in conjunction with the main power grid. A micro-grid system (MGS) is made up of various energy sources like solar panels, wind turbines, fuel cells, along with storage units, control mechanisms, and a network of radial load feeders, all designed to enhance the economic efficiency of the micro-grid system. A fundamental microgrid system experiences hourly fluctuations in load demand. To manage this variability, utilities implement time-of-use (TOU) pricing, which establishes different electricity prices at various times based on the demand curve. This pricing structure incentivizes consumers to adjust their energy usage according to price signals, promoting efficiency and better alignment with supply conditions throughout the day. The primary goal of this work is to develop a demand response (DR) model aimed at maximizing benefits for microgrid customers. This model assesses the utility and elasticity of different customer segments, considering their varied behaviors during peak and off-peak periods. A hybrid of the Moth flame optimization and JAYA (MFOJAYA) algorithm is applied to minimize the overall costs of the microgrid system, comparing outcomes with and without the DR program. The analysis incorporates various cost factors, including fuel costs, pollution fines, operating and maintenance expenses, and depreciation costs, ensuring a thorough evaluation of the system's economic viability. The implementation of a DR-based energy management microgrid system led to a notable reduction in overall generation costs, decreasing from $880 to $868, along with a reduction in pollutants, as supported by numerical data. Additionally, the peak demand was reduced by 8.3%, dropping from 180 kW to 165 kW. The proposed optimization method is highlighted as superior through central tendency analysis, further demonstrating its effectiveness in enhancing the system’s performance and efficiency compared to existing approaches in the literature.

1. INTRODUCTION
Renewable energy sources within micro-grids have experienced significant growth in the past few years. In recent years, micro-grids, comprising decentralized energy sources like micro-turbines, wind turbines, fuel cells, photovoltaic panels, storage units, and interconnected radial load feeders, have surged in popularity [1]. The increased alertness to ecological and energy challenges (high costs) has led to clamoring for energy independence, energy efficiency, and minimal energy cost. A micro-grid can typically be categorized into two main types: AC and DC. The AC micro-grid is the predominant form, wherein all distributed power sources and loads link to a shared AC bus via power electronic interfaces [2].

A micro-grid is created by combining different electrical energy sources, loads, and an energy storage system, capable of operating either connected to the primary grid or independently in an isolated manner [3]. RESs are sources that can be replenished naturally and constantly, such as wind, sunlight, water, geothermal, and biomass. As described by the U.S. Department of Energy, a micro-grid is a system of interconnected energy consumers and distributed energy resources (DERs) with clearly defined electrical boundaries. It operates as a cohesive and manageable unit within the grid, having the capability to connect to or disconnect from the grid, allowing for operation in either grid-connected or islanded modes [4]. The benefits of integrating renewable energy sources

(RESs) into the micro-grid include lowering operational expenses, enhancing returns for investors, reducing greenhouse gas emissions, and decreasing expenditure on grid-purchased power [5].

Micro-grid technology offers an effective means to implement large-scale grid-connected generation of renewable energy in a practical manner. Efficient utilization of distributed energy resources within a Micro-grid relies on the crucial role of Energy Management Systems (EMS), ensuring smart, secure, reliable, and well-coordinated operation [6]. Certain power system operation techniques regulate power generation according to the predicted network load. Occasionally, direct regulation of loads occurs; for example, during peak periods when generation is insufficient, demand-side management algorithms may reduce the load. Generally, power generation is distributed to align with demand. Currently, numerous independent system operators (ISOs) and utility companies, such as the California ISO (CAISO), ISO New England (ISO-NE), and Pacific Gas & Electric (PG&E), have initiated diverse market-oriented demand response (DR) initiatives.

The adoption of DR programs has the potential to yield advantages for both end-users and utility providers. ISO statistics indicate that the United States experienced a reduction in system peak demand ranging from 1.4% to 4.1% during summer peak periods in 2006 as a result of implementing demand response (DR) measures. In the literature, demand response (DR) has been classified into price-based and incentive-based programs. Nevertheless, incentive-based demand response (DR) initiatives, such as direct load control (DLC), interruptible/curtailable service (I/C), emergency demand-response program (EDRP), capacity market program (CAP), and ancillary services (A/S) markets, are aimed at encouraging reduced electricity consumption during periods of high wholesale market prices or when system reliability is at risk. Incentive-based demand response (DR) programs are widely favored and account for 93% of peak load reduction in the United States of America [7]. As the share of renewable energy on the power grid rises, the task of synchronizing with network demand grows increasingly intricate [8]. This research addresses the issue of the microgrid energy generation costs, and the system's penalized emission expenses. The focus is on implementing an Energy Management System (EMS) in micro-grids, utilizing incentive-based demand response to optimize energy usage costs. The goal is to develop a micro-grid model that achieves the most economically efficient cost from Renewable Energy Sources (RESs). An optimal control technique for autonomous micro-grids with RESs is introduced to establish the best operational schedule, minimizing power generation costs, consumers' energy consumption and system's penalized emission expenses. The overarching objective is to maximize profit, minimize energy consumption and system's penalized emission expenses in micro-grids system incorporated with RESs and Distributed Generators (DGs). The economic benefits of RES such as wind and solar energy will be maximized, and an optimal generation schedule for these sources was determined. The research also considers micro-grids with gasoline generators, wind turbines, and solar-based DGs, aiming to minimize the cost of diesel generators. A model for an energy management system was developed to pinpoint the most efficient operating parameters for the micro-grid, prioritizing assistance to the demand side to decrease distributed generation, consumer expenses and system's penalized emission expenses [9].

2.0 Hybrid MFOJAYA algorithm

Essentially, Jaya operates as a greedy search engine, aiming to move away from the worst solution as defined by the fitness function and towards the optimal value with each iteration. This characteristic of Jaya is encapsulated in the Hybrid MFO-JAYA equation, which integrates it with the food-seeking behavior of the crow search algorithm. By combining the crow's search strategy with Jaya's pursuit of optimal fitness values, a new algorithm, known as hybrid MFO-JAYA, is formed. The algorithm evaluates the fitness function for each particle in the memory matrix, identifying the best and worst outcomes through iterative refinement for further calculations. Hybrid MFOJAYA has been successfully applied to various benchmark functions, both unimodal and multi-modal, and has been utilized by researchers to address reactive power planning issues in Indian test systems. Additionally, the MFOJAYA algorithm has been implemented to solve dynamic economic emission dispatch problems on small to medium-scale test systems comprising 3 to 15 fossil fuel generating units, considering objective functions of linear and nonlinear, convex, and non-convex nature. In this research, the proposed MFOJAYA algorithm will be employed to tackle the micro-grid energy management problem based on demand response (DR) [10].

2.1 Objective function

In this research, the micro-grid to be established is characterized by a combination of Distributed Generator (DG), Wind Energy, PV, Storage system, and loads. The primary components of the micro-grid include a Hybrid of DG, Wind Energy, PV, Storage system, and loads. While operating a micro-grid, the primary costs come from running the distributed power supply, fuel expenses, and buying electricity from the urban power grid. However, once the micro-grid attains energy balance, it can sell surplus power to the conventional grid. Additionally, the micro-grid system will actively participate in demand response, adjusting its power usage according to market conditions in the electric supply market. It will leverage demand response to manage electricity prices [11].

Building upon this analysis, this research focuses on developing an optimization model for micro-grid operation that incorporates demand response pricing and incentives. The goal of the model is to reduce the operational expenses of the micro-grid. This is achieved through an objective function that covers distributed generation expenses, energy storage operation expenses, electricity expenses, and diesel expenses. Below is the optimization model aimed at minimizing the overall cost of operating the micro-grid [12].

$$F = \min C_{op} = \oint_0^T \left[\sum_{t=1}^{n} C_1 P_1 + \frac{P_{fuel}V}{60} + C_{bat,dep} + C_{B-grid}\right] \quad (1)$$

$$C_{B-grid} = \begin{cases} K_b P_{grid} & , P_{grid} > 0 \\ K_s P_{grid} & , P_{grid} < 0 \end{cases} \quad (2)$$

In this context, C_{op} represents the operational cost of the micro-grid system in Dollar, while T denotes the time period in minutes. C_i stands for the operational cost of distributed generation systems in Dollar per kilowatt ($/kW), P_{fuel} represents the diesel price in Dollar per cubic meter ($/m³), V is the diesel consumption in cubic meters per hour (Nm³/h), P_i signifies the output of the distributed generation during the response period in kilowatts (kW), and $C_{bat\ dep}$ denotes the charge/discharge depreciation cost of the energy storage system in Dollar per kilowatt-hour ($/kWh). Furthermore, C_{B-grid} represents the electricity cost of the micro-grid in Dollar per kilowatt-hour ($/kWh), K_b is the purchase price in Dollar per kilowatt-hour ($/kWh), K_s is the selling price of the micro-grid in Dollar per kilowatt-hour ($/kWh), and P_{grid} is the power exchanged between the conventional power grid and the micro-grid in kilowatts (kW) [13].

2.2 Constraints

2.2.1 Response load constraints

According to the micro-grid model outlined in this document, the user-side assets participating in the Demand Response initiative primarily consist of distributed generations (DGs) and responsive loads. The primary limitations affecting DGs include the power restrictions of the distributed generation unit and constraints related to responsive loads, notably concerning load reduction and transfer time.

2.2.2 Output Constraint of distributed generations (DGs) While Distributed Generators are in operation, the unit's output power is limited by the equipment model. The generator set's maximum and minimum power levels are established, and the actual output power must fall within this specified range [14].

$P_{GDs}^{min}(t) < P_{GDs}(t) < P_{GDs}^{max}$ 3) $P_{DGs}(t)$ represent the output of DGs in kilowatts (kW), while $P^{max}_{GDs}(t)$ and $P^{min}_{GDs}(t)$ denote the maximum and minimum values of DGs' output power in kW.

2.2.3 Interruptible Load Constraint

As per the Demand Response approach, the interruptible load is subject to potential interruptions at any given moment, with no specific limitations on its overall power consumption [15].

$$P_{IL}^{min}(t) < P_{IL}(t) < P_{IL}^{max}(t) \quad (4)$$

Where $P_{IL}(t)$ represents the real power of the interruptible load, measured in kilowatts (kW); $P_{IL}^{min}(t)$ and $P_{IL}^{max}(t)$ denote the minimum and maximum power levels of the interruptible load, also measured in kilowatts (kW).

2.2.4 Adjustable load constraint

The adjustable load can be decreased based on the scheduling strategy during the demand response implementation, with the limitation that the reduction in load cannot surpass the permissible reduction limit [16].

$$\mu_{CUT}(t)p_{CUT}^{\min}(t) < P_{CUT}(t) < \mu_{CUT}(t)p_{CUT}^{\min} \quad (5)$$

$P_{CUT}^{max}(t)$ and $P_{CUT}^{min}(t)$ represent the maximum and minimum boundaries for reducing the load that can be curtailed, measured in kilowatts (kW); $\mu_{CUT}(t)$ signifies the state of the load at a specific time t, where $\mu_{CUT}(t) = 1$ signifies that the load has been curtailed, while $\mu_{CUT}(t) = 0$ indicates that the load remains unchanged; $P_{CUT}(t)$ denotes the amount of curtailable load reduction at time t, measured in kW.

2.2.5 Transferable Load Constraint

Transferable load refers to a load that has no fixed constraints on its power usage and can be relocated based on a predetermined scheduling approach during a specific timeframe. During the scheduling procedure, this load can be shifted during a less busy period, but it must be relocated within a defined time limit.

$$.\boldsymbol{T}_{tr}^{\alpha} \leq T_{tr} \leq \boldsymbol{T}_{tr}^{\beta} \quad (6)$$

The initiation time of the transfer, denoted as T_{tr}^{α} represents the beginning hour, while T_{tr}^{β} denotes the concluding hour. The user's electricity customs dictate the commencement and conclusion times of the transferable load [17].

2.2.6 System power balance constraint

During micro-grid operation, it is essential for the power supply and demand within the system to maintain a specific equilibrium, primarily seen in the correlation between input and output power levels [18]. The system's power balance is depicted as follows.

$$P_{loss} + P_{core} + P_{load} = \sum_{k=1}^{N} P_{k-i}(t) + P_{grid}(t) + P_{storage}(t) \quad (7)$$

Pi(t) represents the active power consumption of the load, primarily indicating the adjustable load within the system, measured in kilowatts (kW). P_{core} denotes the essential load power in kW. P_{laod} signifies the adjustable load power engaged in Demand Response within the system, measured in kW. P_{loss} refers to the power lost during the transportation of electric energy, measured in kW. $P_{grid}(t)$ indicates the power drawn by the system from the grid, measured in kW. $P_{storage}(t)$ represents the power used for charging and discharging in Energy Storage (ES), measured in kW.

2.2.7 ES constraint

The duration a battery can operate is crucial for Energy Storage functionality. During the operation of the Energy Storage (ES) system, there are strict limitations on the battery's charging and discharging capacities. Prolonged operation outside the specified power range can hasten battery deterioration. Therefore, the energy storage system must adhere to constraints on maximum charge/discharge power and charge status to enhance battery longevity and reduce maintenance expenses [19].

$$|p_{storage}(t)| \leq \begin{cases} P_{dis-max}\ p_{storage}(t) > 0 \\ p_{ch-max}\ p_{storage}(t) < 0 \end{cases} \quad (8)$$

Where $P_{dis-max}$ represents the peak discharge power and P_{ch-max} denotes the maximum charging power in kilowatts (kW); SOC_{max} and SOC_{min} denote the upper and lower thresholds of the remaining battery capacity.

3.0 Literature Review

In this subsection, the examination of comparable studies found in the existing body of literature is undertaken. The purpose of this review is to gauge the extent and thoroughness of research conducted in the field. Additionally, it seeks to highlight any limitations associated with these studies, with the goal of pinpointing areas where further research is needed.

[20] emphasized the emergence of micro-grids as a response to the demand for advanced energy systems. The development of these next-generation systems is driven by the potential advantages they offer, including loss compensation and the ability to enhance efficiency and reliability in transmission and distribution networks. The innovative concept of micro-grids extends its benefits to various aspects, such as overall structure and diverse topologies. The authors propose an original methodology to facilitate the design of micro-grids, culminating in the creation and analysis of a Simulink model. Micro-grids represent a promising future configuration for power systems, presenting clear economic advantages and environmental friendliness compared to conventional large power systems. However, the evolution of micro-grid concepts necessitates addressing economic, commercial, and technical challenges. Particularly valuable in underserved areas, micro-grids can complement existing utility networks to enhance power supply reliability and quality. Notably, the control of micro-grids is simplified, featuring a plug-and-play mechanism that eliminates the need for on-site engineers. While existing research predominantly focuses on micro-grid control, the protection of micro-grids remains largely theoretical and requires further exploration.

[21] conducted an analysis highlighting the advantageous features of distributed generation, such as reduced costs, heightened energy efficiency, and minimized pollution. However, they noted a challenge when considering distributed generation within a high-voltage power grid, emphasizing its lack of controllability. The authors proposed a solution in the form of a smart grid, which encompasses distributed generators, loads, energy storage, and protective control devices. This intelligent grid operates as a self-sufficient and manageable network that encompasses all aspects of power production, transportation, delivery, and energy consumption systems. It effectively addresses the inconsistency between large power grids and distributed generation, fostering the development of distributed generation capabilities. The authors specifically advocated for the implementation of smart micro-grids, describing them as technologies grounded in new energy generation and power electronics. The small-scale power systems enable the incorporation of multiple dispersed generators, harness the benefits of different generation units working together, improve efficiency in resource usage, and lessen the negative effects that a single distributed power source could have on the entire power grid. By employing thoughtful energy management, intelligent micro-grids not only guarantee the safe functioning of power distribution systems but also allow for adaptable control over dispersed generators, thereby optimizing the use of renewable and environmentally friendly energy sources. As a result, the authors argue that smart micro-grids are an essential element within the larger framework of smart grid technology. [22] investigated the application of a recently created Crow Search Algorithm (CSA) with the aim of reducing the operational expenses linked to various renewable energy sources within both minor and major Micro-grids (MGs). The micro-grid systems considered in the analysis had fitness functions that were both unimodal and multimodal. The results showed that CSA outperformed both multiple metaheuristic algorithms and conventional techniques in reducing the production costs of these micro-grid systems. [23] conducted an analysis that highlighted the incorporation of the conventional grid (CG) to address the increasing demand complexity. This integration entails utilizing communication technologies such as advanced metering equipped with sensors, demand response (DR), energy storage systems (ESS), and incorporating renewable energy sources (RES). Micro-grids, known for their low or medium-voltage distribution systems and resilient functioning, enable power exchange between the main grid, locally distributed generators (DGs), and consumers through intelligent energy management techniques. Introducing micro-grids and their operations succinctly, along with a subsequent examination of various energy management approaches, the authors underscored the importance of an energy

management system (EMS) in micro-grid control strategies. The EMS plays a crucial role in balancing energy resources (CG, DG, ESS, and RES) against available loads, all while optimizing utility profits.

[24] explored the dynamic of load demand in fundamental microgrid systems, which exhibit hourly fluctuations. Utilities respond by setting varying electricity prices based on the load demand, a practice known as time-of-use (TOU) pricing. The study delved into the multifaceted impacts of microgrid participation, electricity pricing, and renewable energy sources. However, the main objective was to develop a demand-response (DR) model that optimizes benefits for energy retailers, specifically microgrid customers. These demand models consider customer behaviour during both peak and off-peak periods, assessing utility and elasticity.

[25] conducted an analysis on addressing the complex challenges posed by escalating energy needs. They discovered that traditional power grids have been improved by incorporating advanced communication technologies like advanced metering with sensors, demand response mechanisms, energy storage systems, and the integration of electric vehicles. To ensure a localized balance of energy and improve reliability, the concept of micro-grids has been suggested. These micro-grids operate as distribution systems at low or medium voltages, demonstrating resilience and effectively managing power exchange among the main grid, locally distributed generators, and consumers through intelligent energy management techniques. The energy management system (EMS) within the micro-grid's control strategy is crucial for maintaining balance among available energy resources (main grid, distributed generators, and energy storage systems) and loads, while also contributing to the utility's overall profit. Furthermore, the study offers a comprehensive overview of micro-grid architecture, various classifications, component parts, communication technologies, implementation standards, and essential ancillary services necessary for the smooth operation of micro-grids. Moreover, the research emphasizes the vital role of energy management in various applications within the micro-grid framework, including forecasting, demand response, data management, and control structures.

[26] claimed that the increasing adoption of renewable energy (RE) in micro-grids (MGs) is seen as a promising solution to address various social and environmental challenges, driven by the rising demand for electric power. However, the complexity and intermittency of such integration can pose threats to the stability and security of power systems. Therefore, the utilization of an optimal control strategy becomes essential to guarantee the efficiency, dependability, and excellence of the electricity supplied. Moreover, effective policy formulation for micro-grid (MG) integration can improve MG operations, yet instances of power outages may undermine these measures and pose risks to the power grid. Micro-grids are considered suitable elements for decentralized power systems because of their capacity to rapidly restore such systems following physical or cyber-attacks and establish dependable protection mechanisms. The energy management system (EMS) within a micro-grid plays a crucial role in managing controllable distributed energy resources and loads in real-time, facilitating the creation of a well-suited short-term schedule to accomplish specified goals.

4.0 Methodology

For the objectives of this research work to be accomplished, the following procedures was applied sequentially.

1. Modelling of an islanded micro-grid system with hybrid renewable energy technologies, such as Deisel Generator, Wind Energy, Photovoltaic (PV) and Energy storage system.

Steps:

i. Obtaining and sorting out load data of wind power renewable energy present in the islanded Micro-grid system.
ii. Obtaining and sorting out load data of solar power renewable energy present in the islanded micro-grid system.

iii. Obtaining and sorting out load data of Deisel generator present in the islanded Micro-grid system.
iv. Obtaining and sorting solar irradiance and temperature of solar system.
v. Selecting good, rated power PV panels.
vi. Selecting the most appropriate size wind turbine to be applied
vii. Selecting the optimum energy storage system to be applied.

2. Formulation of an EMS scheme for the Hybrid Distributed Generator (DG), Wind Energy, PV, and Energy Storage system using a hybrid MFO-JAYA algorithm to achieve the optimal economic cost.

Steps:

i. Design an EMS model through integrating Diesel Generator, Wind Energy, PV, and Energy storage system in islanded mode.
ii. Optimizing the designed model using MFOJAYA algorithm Optimization technique.
iii. Optimizing the model designed through Nested integer linear programming.

3. Implement the EMS in MATLAB/Simulink and carry out a comparative analysis of generating cost and peak demand of the system with those obtained in [10].

4.1 Solar PV System

The mathematical description of PV cell has been studied over decades [27]. The electrical circuit representation of the PV cell model, consisting of a photocurrent, diode, parallel resistor (leakage current), and a series resistor; is shown in Figure 1. Based on PV cell circuit and Kirchhoff's circuit laws, the PV current can be modelled as in the following equation (11).

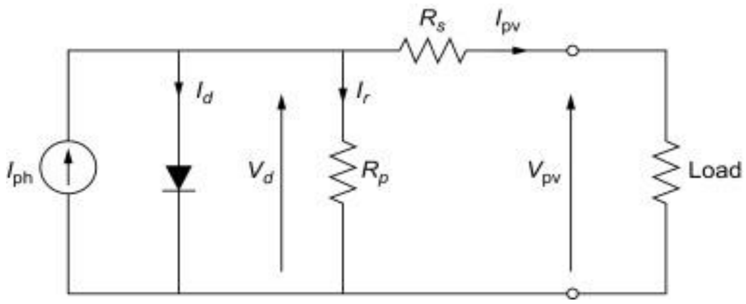

Figure 1: PV Model Electrical equivalent circuit

$$I_{pv} = I_{ph} - I_d - I_p = I_{ph} - I_0\left(e^{\frac{V_{pv}+R_sI_{pv}}{n_sV_tQ_d}} - 1\right) \quad (11)$$

Where; V_{pv} = PV- module Voltage, I_{pv}= PV Module Current, I_{pv}= Light current in (A), I_{pv} = Diode reverse saturation current, Q_d= Diode idealistic factor, R_p= Shun Resistance, R_s= series resistance, n_s= number of cells, $V_t = \frac{KT_c}{q}$ is the thermal voltage (V), k is Boltzmann's constant, T_c is the cell temperature, and q is the charge of an electron respectively.

4.1.1 SunPower SPR-330E-WHT-D PV module

In this work, the parameters of a SunPower SPR-330E-WHT-D PV module are used for simulation. The solar cell is modelled and simulated using MATLAB software. The simulation is based on the datasheet of the SunPower SPR-330E-WHT-D module. The parameters of this solar module are given in Table 1

Table 1: SunPower SPR-330E-WHT-D PV module Electrical Characteristic

Parameters	Values
Maximum Power (P_{max})	330.303W
Voltage at P_{max} (V_{mp})	64V
Current at P_{max} (I_{mp})	5.49A
Open-circuit voltage (V_{oc})	85.3V
Short-circuit current (I_{sc})	5.87A

In this work, the programme was run with a population size of 50 to 80 and 1000 iterations over 30 trials, and all optimization techniques were used uniformly. The test system used is a low voltage microgrid comprising several Distributed Generation (DG) units. These include a photovoltaic (PV) unit, wind unit, direct-methanol fuel cell (FC) unit, natural gas-based gas turbine (GT,) and three other distinct electricity-producing generating units (G1, G2, and G3). The focus of the study is on minimizing the total system cost by utilizing various demand response (DR) strategies and employing the proposed MFOJAYA optimization algorithm. This approach is applied to optimize the power output and operational costs. The expected power outputs from the renewable energy sources (RES) for each unit are visualized for a typical day, as shown in Figure 2, which illustrates how renewable energy units contribute to the overall energy production in the microgrid. Figure 2 shows the flowchart of the scheme used in this work.

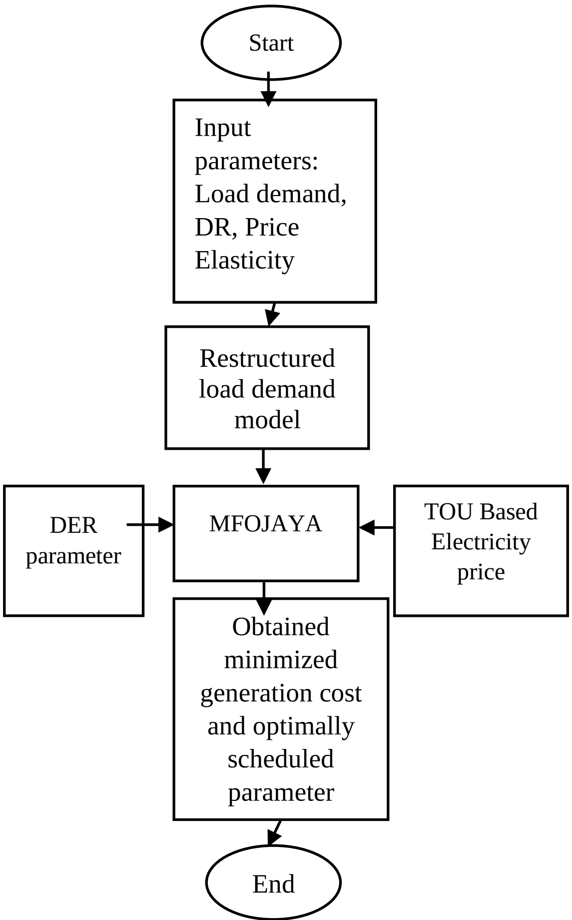

Figure 2: Flowchart of developed work

5.0 Results and Discussion

The total power demand for the microgrid is 2.2660 MW, which is distributed across a 24-hour period. This power demand pattern is illustrated in Figure 3, showcasing how the load varies throughout the day. The demand fluctuates based on the time of day, reflecting typical consumption cycles within the microgrid. This 24-hour load profile is essential for optimizing the generation schedule of the DG units and implementing the demand response strategies to minimize operational costs while ensuring reliable power supply.

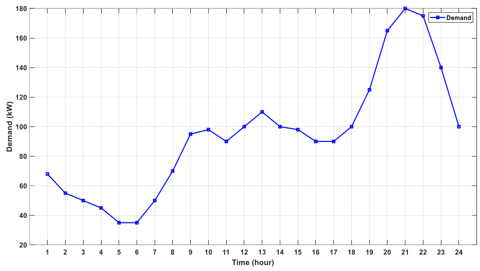

Figure 3: System Load Demand

The live electricity market pricing, as shown in Figure 4, fluctuates in response to the dynamic load demand of the system. This variability in pricing reflects the real-time conditions of the electricity market, where prices tend to rise during peak demand periods and fall during off-peak times. Such fluctuations are influenced by several factors that includes Supply and Demand Balance, Time-of-Use (TOU) Pricing, Renewable Energy Integration and Market Conditions. This pricing structure is crucial for optimizing the operation of the microgrid, as it helps in scheduling generation and demand response (DR) programs to minimize operational costs and enhance economic efficiency. The integration of the MFOJAYA optimization algorithm in this context seeks to take advantage of low-priced periods while avoiding high-cost intervals, thus optimizing the overall cost of electricity generation in the microgrid.

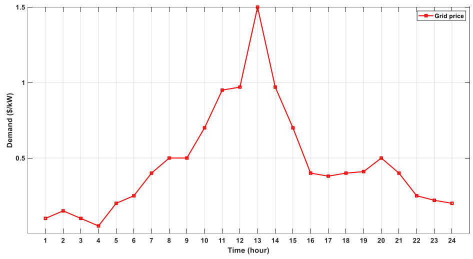

Figure 4: Electricity Market Pricing

5.1. Without Demand Response

The section is divided into two categories: compulsive analysis and comprehensive analysis. In the compulsive analysis section, we often replicate and build upon the analyses the paper aimed to perform. This type of analysis focuses on three scenarios: operating the microgrid system in islanded mode, connecting it to the grid, and functioning without renewable energy sources. For a more detailed analysis, we considered two additional scenarios: one where the grid plays a passive role (only selling energy to the microgrid) and another where the fixed power market price method was applied. Using the proposed hybrid MFOJAYA method, equation (2.34) was minimized across four different scenarios (two compulsive, two comprehensive) for all load demand patters. Table 2 presents the minimized generation cost for each case.

5.1.2 With Demand Response

Scenario 4 is not considered in this section because the previous section has already shown that the fixed price-based electricity market strategy and the FP-based pricing strategy do not help in achieving a minimized or balanced solution between generation costs and emissions. Given that 40% of microgrid users participated in the demand response (DR) program, the remaining three scenarios were evaluated. In the first assessment, incentive values ranging from $0.05 to $0.50 were analyzed to determine the incentive costs for consumers participating in the DR program. Figure 5 illustrates the total incentive costs for different incentive levels, revealing a consistent increase in costs as the incentive values rise.

Next, the power generation cost and total cost were evaluated for each incentive value within the $0.05 to $0.50 range. The generation cost includes the cost of purchasing and selling power from the grid, as well as the cost of Distributed Energy Resources (DERs). The total cost is the sum of the generation cost, and the incentive cost provided as a benefit to consumers.

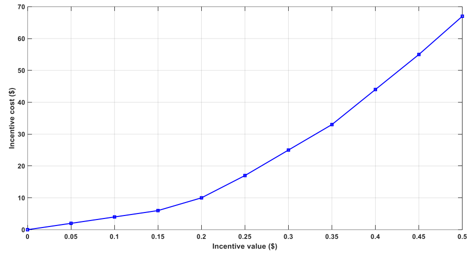

Figure 5: Incentive costs to be paid to customers with respect to change in incentive values

Figure 6 presents the generation cost and total cost of active power production after optimization using the proposed MFOJAYA algorithm. The chart indicates that the overall system cost decreases until the incentive value reaches $0.15, after which the cost begins to rise. However, as the incentive value increases, the generation cost consistently decreases. The incentive value of $0.15 is considered optimal for further analysis, as it reduces the overall system cost to as low as $871.9796. At this optimal incentive value, $6.0666 must be paid as incentive costs to consumers. Therefore, the optimal reduced power generation cost for the microgrid system using the demand response algorithm is $865.913.

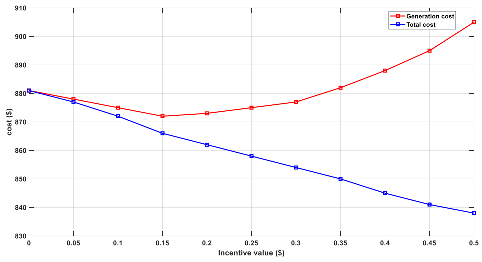

Figure 6: Change in generation cost and total cost for the MG system for different incentive values

With an incentive value of $0.15, the system's load demand with and without the demand response (DR) program is shown in Figure 7. The participation in the DR program led to an

8.3% reduction in peak demand, lowering it from 180 kW to 165 kW.

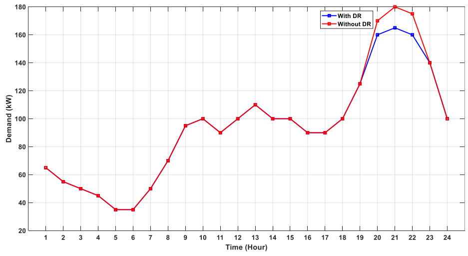

Figure 7: Load Demand with and without DR Program

Figures 8, and 9 illustrate the hourly outputs of Distributed Energy Resources (DERs) for scenarios 1, and 3, respectively, corresponding to the associated costs. In Figures 8 and 9, the utility grid is shown purchasing electricity from the active microgrid, indicated by the grid's negative hourly production. This contributes to a bigger reduction in the system's generating cost, as already demonstrated in Table 2.

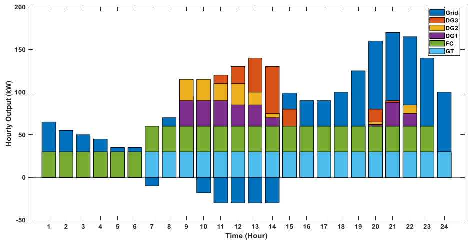

Figure 8: Hourly output of DERs for Scenario 1 (Without RES) with DR using MFOJAYA algorithm

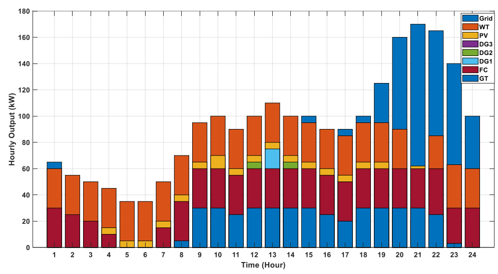

Figure 9: Hourly output of DERs for Scenario 3 (Passive/TOU) with DR using the MFOJAYA algorithm

When comparing the cost component breakdown between Scenario 1 and Scenario 2, Figures 10 and 11 clearly show that the price reduction in Scenario 2 is primarily due to the decrease in penalized emission costs, resulting from the use of Renewable Energy Sources (RES).

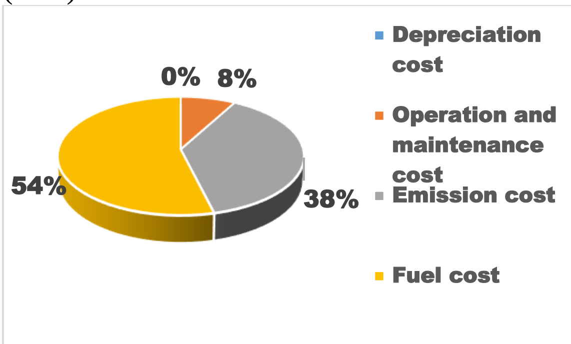

Figure 10: Cost components break up for Scenario 2

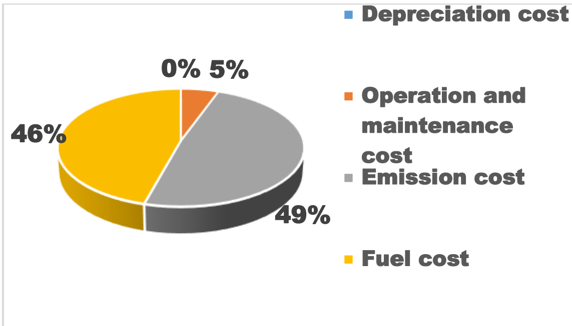

Figure 11: Cost components break up Without RES for Scenario 1

6.0 Conclusion

This work presents a comprehensive optimal scheduling of Distributed Energy Resource (DER) outputs across five different scenarios to reduce the total generation cost of a low voltage (LV) microgrid system. Due to its effective integration with the power market price based on the Time-of-Use (TOU) methodology, the grid-connected operation of microgrids resulted in the lowest possible production cost. Incorporating Renewable Energy Sources (RES) directly reduces the system's penalized emission expenses. When exploring microgrid energy management, using demand response (DR) program-based techniques with varying levels of flexible load participation in both is essential and practical, as they substantially lower the system's generation costs. The MFOJAYA algorithm demonstrated both speed and robustness, delivering superior results more quickly than many other algorithms. Its effectiveness is further highlighted by its low standard deviation and its ability to complete the majority of iterations in a shorter time, showcasing the algorithm's overall efficiency.

[3]. Weibull distribution for determination of wind analysis and energy production

Table 2: Generation cost in different scenario

S/N	Analysis	Scenario	CSAJAYA	MFOJAYA
1	Compulsive Analysis	Without RES	1699.2	1675.35
2	Compulsive Analysis	Grid-Tie (Active grid/ Time of Usage)	880.95	868.43
3	Extensive Analysis	Grid Tie (Passive grid/ Time of Usage)	989.77	980.82
4	Extensive Analysis	Grid Tie (Active grid/ Fixed price)	939.17	925.55

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