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Economic Operation of Low Voltage Smart Micro-grid with Integration of Renewable Energy

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HIGHLIGHTS

- The proposed system model and algorithm can reduce operating costs and meet load requirements.
- The proposed process can be implemented under different loads and takes longer after one day.
- The model can be extended to be applied to the combined heat and power (CHP) microgrids

ARTICLE INFO

ABSTRACT

This paper develops a unit commitment multi-period energy management system to minimize a low voltage microgrid's total operation and emission cost. The optimization problem is formulated in the mixed-integer quadratic program. The environment cost and battery degradation cost are taken into consideration in the proposed optimization approach. The unit commitment strategy is employed to minimize the total cost. A set of constraints are considered in the proposed optimization approach. The proposed energy management system is applied to the low voltage distribution grid, including different distributed generators, such as diesel engines, fuel cells, and microturbines. The microgrid also contains storage batteries, renewable energy resources, wind turbines, and photovoltaic panels. The results reveal that the storage battery charging and discharging operations are controlled to reduce the operation and emission cost even considering the battery degradation cost.

1. Introduction

Recently, renewable resources have become one of the resources used to increase distributed power production according to the international sustainable development policies. Compared with the previous decade, the grids have changed significantly due to storage systems, power components, distributed generation, microgrids, and renewable energy [1]. Improve the system's overall performance, minimize costs, and extend the service life of its components (such as converters, batteries, and fuel) cell). Generally speaking [2]. Renewable energy generation usually covers Wind and solar, while traditional usually consists of micro-turbines (MT), diesel generators, and Fuel cells (FC). One of the most important factors is the MG load. When controlled, it can decrease system interruption. The MG is maintaining a healthy operation for both grid-connected and isolated cases. Moreover, it can provide a large economic profit for the environment at the best operation [3]. RES has deployed as large wholesale electricity and a local distributed power generation facility or private consumption infrastructure. However, usually, the way the association is generated Does not follow the typical demand situation and cannot predict the accuracy is high, and it cannot be dispatched reliably. RES is generally [4]. The electricity market is seen as the cornerstone of liberalization. In the smart grid era, the power system was used locally as "soft management control". they Provide an effective allocation and pricing mechanism for the amount of electricity generated to meet electricity demand [5]. Hybrid microgrids usually contain multiple alternatives Current (AC) power supply and direct current (DC) power supply May be classified as a controllable or uncontrollable source, Meet the power demand together with storage equipment in A localized community [6]. To preserve and protect the environment as a result of pollution resulting from fossil fuel emissions on the one hand and the reduction of traditional fuel sources on the other hand, renewable energies have become one of the most important and promising sources at present in many applications, including those used in micro-grids. The hybrid micro-grids (AC/DC) can be defined as a gateway through which it addresses many of the problems facing the system based on the operational point of view, in addition to improving its operational

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characteristics from the power system [7]. Therefore, renewable energy supports the local energy needs of DC and AC currents, reducing losses resulting from the conversion process between regular currents (alternating-direct-alternating currents). Hybrid micro-grids are characterized by their high reliability, increasing energy consumption standards, and improving system performance by forming an AC/DC hybrid micro-grid, which dominates the AC power system today. Despite this, the use of renewable energy with DC micro-grid is still very limited in some countries due to the development of semiconductors, its access to rural and remote areas, and the increase in the resulting loads. Therefore, using hybrid micro-grids based on renewable energies is unequal in many countries [7]. Another thing to be considered is that the operation must be stable when using a micro-grid due to faults and that it is possible to disconnect and connect to the main network by relying on a switch PPC. On the other hand, it is necessary to adjust the renewable energies to maintain frequency, voltage, system, and local load requirements whenever possible. It is also necessary to point out that the micro-grids work to meet the needs of combined heat and power (CHP) through the use of waste heat, which results in improving and improving the reliability of the system, in addition to reducing transmission losses and distribution according to local requirements [8]. Moreover, the control and operation of micro-grids can be designed for alternating or direct currents, medium or low power requirements, and high or low frequency, and they can be operated in islanded or grid-connected mode based on needs. Finally, micro-grids can be used as a decentralized operation and generate different distributed resources to manage the complexities. Based on the previous benefits, microgrids are promising topics in electric power and developing commercial projects for emerging countries in various applications. This work's main contribution is identifying and logical development of renewable energy sources to control the micro-grid's possible modes of operation by defining the micro-grid's functional elements. Whereas the consumers were the power generators which are the producer of loads, and Prosumers were the battery and main grid [8]. Many researchers proposed algorithms and methods to formulate and solve the optimization problem of microgrids due to enormous benefits not only for the operators but also for the environments. Some of these studies did not consider important cost function components or ignored the emission cost. Other studies override some important constraints. This affects the fidelity of the model and the results. In this paper, the emission cost is incorporated with the optimization problem as a multi-objective optimization. The emission cost is converted into a monetary concept in a single objective function, which can be solved in one step. The battery degradation cost is also considered in the model, with a set of comprehensive constraints in one optimization problem to make the proposed optimization problem close to the real scenario.

2. Mathematical model system

2.1 Distributed Generators Fuel Cost

The fuel cost of the distributed generators (DGs) is a function of real power output, and this cost is calculated by using the following equation [9].

$$C_{DG_i} (P_{DG_i}(t)) = a_i + b_i P_{DG_i} (t) + c_i P^2_{DG_i} (t) \qquad (1)$$

Where a_i (euro/hour), b_i (euro/kWh), and c_i (euro/kWh) are the coefficients of the cost function of the different types of DGs, where these coefficients have different values for each DGs technology. The ith DGs output active power is P_{DGi} (t).

2.2 DGs Maintenance Cost

The maintenance cost of the DGs depends on the real power generation output, and this cost is calculated by employing this equation [10].

$$CM_{DG} = \Sigma^N_{i=1} CM_{DG_i}(P_i) = \Sigma^N_{i=1} KM_{DG_i} P_{DG_i}(t) \qquad (2)$$

KM_{DGi} (euro/kWh) is the maintenance cost coefficient of the different types of DGs.

2.3 Storage Battery Modeling

Within the scope of the MG optimization problem and to model the battery, a linear discrete-time state-space model is used. The state of charge of the storage battery at any time interval equals the previous state of charge, either minus charging power in case of charging or discharging power in case of charging. This equation is as follows:

$$E_b(t) = E_b(t - 1) - \frac{\Delta t P_{bdis}(t)}{\eta_{dis}} + \Delta t P_{bch}(t)\eta_{ch} \qquad (3)$$

$E_b(t)$ and $E_b(t -1)$ represent the current and previous battery state charge, respectively, and it is the sampling time. Discharging and charging powers are $P_{bdis}(t)$ and $P_{bch}(t)$, and the corresponding discharging and charging efficiencies are η_{ch} and $\eta_{dis,}$ respectively. The battery operating cost can be calculated as:

$$C_b(t) = C_{Deg} P_b(t)\Delta t \qquad (4)$$

Where C_{Deg} and $P_b(t)$ are the battery downgrade cost in (Euro/kWh) and absorbed or delivered battery power delivered in (kW), respectively. More details to determine C_{Deg} can be found in [11,12].

2.4 Exchanging Power with the Utility Grid Modeling

The equation below calculates the exchanging power cost with the public grid.

$$C_{gP}(t) = c_{gP}(t)P_g(t) \tag{5}$$

$c_{gP}(t)$ is the price of exchanging power with the public grid, while $P_g(t)$ is the trading power with the utility grid.

2.5 Emissions of Greenhouse Gas Modeling

The emission cost of the greenhouse gases, such as Sulphur dioxides (SO2), emissions of carbon dioxides (CO2) cost, and particulate matter (PM) and nitrogen oxides (NOx) which are considered in this work is calculated by using the following equation.

$$E(t) = \sum_{j=1}^{K} \sum_{i=1}^{N} E_{j,i} C_j P_{DG_i}(t) \tag{6}$$

Where the jth greenhouse gas emission price is C_j (Euro/kg), the jth greenhouse gas emitted by the ith DG of the emission rate is $E_{j,i}$ (kg/kWh), and K are the total number of DG and greenhouse gases, respectively.

2.6 DGs Shutdown and Startup Cost

Equation (8) is used to calculate the ith DG shut down and startup as [13]

$$\begin{cases} SU_{DG_i}(t) = S_{c_i}\left(\delta_{DG_i}(t) - \delta_{DG_i}(t)\delta_{DG_i}(t-1)\right) \\ SD_{DG_i}(t) = S_{d_i}\left(\delta_{DG_i}(t-1) - \delta_{DG_i}(t)\delta_{DG_i}(t-1)\right) \end{cases} \tag{7}$$

Where $\delta_{DGi}(t)$ is the ith DG state.

2.7 Objective Functions

The cost function aims to minimize the total operation and emission cost at each time interval. The cost function includes the functions they demonstrated in the previous sections.

$$\begin{aligned} F = \sum_{t=1}^{T} \Big[&(a_{fc} + b_{fc}.p_{fc}(t) + c_{fc}.p^2{}_{fc}(t)).\delta_{fc}(t) + (a_{MT} + b_{MT}.p_G(t) + c_{MT}.p^2{}_{MT}(t)).\delta_{mt}(t) + \\ &\left(a_{dg} + b_{dg}.p_b(t) + c_{dg}.p^2{}_{dg}(t)\right).\delta_{dg}(t) + km_{fc}.p_{fc}(t).\delta_{fc}(t) + km_{MT}.p_{MT}(t).\delta_{mt}(t) + \\ &km_{dg}.p_{dg}(t).\delta_{dg}(t) + c_b.p_{bdis}(t).\delta_{bdis}(t) + c_b.p_{bch}(t).\delta_{bch}(t) + c_g(t).p_g(t).\delta_{gpur}(t) - \\ &c_g(t).p_{gsell}(t).\delta_{gsell}(t) \Big] \end{aligned} \tag{8}$$

2.8 Constraints

Different constraints are considered in this paper to make the proposed optimization approach close to the real world. These constraints are as follows:

2.8.1 Active power balance

To express the reactive and active, and power balance constraints, the equation below was employed as follows:

$$\begin{cases} \sum_{t=1}^{T} \left\{ \sum_{i=1}^{N} \delta_{DG_i}(t)P_{DG_i}(t) + P_W(t) + P_{PV}(t) \right. \\ \left. + P_{bat}(t) + P_g(t) = P_D(t) \right\} \end{cases} \tag{9}$$

Where PD(t) is the corresponding active load in the MG.

2.8.2 Capacity of Generating

The equation below is used to express the DG in MG in a capacity limit and can be expressed as follows:

$$\begin{cases} \delta_{DG_i}(t)P_{DG_i min} \leq P_{DG_i}(t) \leq \delta_{DG_i}(t)P_{DG_i max} \end{cases} \tag{10}$$

Where, $\boldsymbol{P_{DG_i}}$min and $\boldsymbol{P_{DG_i}}$max represent the DG minimum and maximum output active power, respectively.

2.8.3 Exchanging Power with the Utility Grid Limits

The exchange capacity of MG with the public grid in each period is usually the purchasing or selling power. There is no possibility of exchanging power between MG and public utilities for a certain period. Therefore, the two binary variables are:

$$\delta gb(t) \in [0, 1] \text{ and } \delta gs\ (t) \in [0, 1] \tag{11}$$

To simulate the sale and purchase of power supplies, the equation $\delta_{gb}(t) + \delta_{gs}(t) \leq 1$ has been adjusted to be unequal to 1. Therefore, it is done by determining the minimum and maximum selling for reactive and active powers to the utility grid, P_{gsmax}, and P_{gsmin}.

2.8.4 Storage Battery Limits

Generally, the operating restrictions of battery devices can be divided into the following two main categories.

2.8.5 Charge of Battery state

The battery state charge constraint can be expressed as

$$E_{bmin} \leq E_b(t) \leq E_{bmax} \tag{12}$$

Where, E_{bmax} represents the respective maximum battery state charge, while E_{bmin} represents the minimum battery state charge.

2.8.6 Power of discharging and Charging

Each sampling time, three cases have been chosen as a possible stat for the battery: no alternating current, discharging, and charging. Therefore, there are two variables of binary have appeared.

$\delta_{bch}(t) \in [0, 1]$ and $\delta_{bdis}(t) \in [0, 1]$ Indicates the battery operating status, and set $\delta_{bch}(t) + \delta_{bdis}(t) \leq 1$ to prevent the battery from being charged and discharged at the same time during the optimization process. It can formulate the operational constraints of discharging and charging the battery as

$$\begin{cases} \delta_{bch}(t)P_{bchmin} \leq P_{bch}(t) \leq \delta_{bch}(t)P_{bchmax} \\ \delta_{bdis}(t)P_{bdismin} \leq P_{bdis}(t) \leq \delta_{bdis}(t)P_{bdismax} \end{cases} \tag{13}$$

P_{bchmin} refers to the minimum power of battery discharging, and P_{bchmax} refers to the maximum battery charging power. At the same time, $P_{bdismin}$ represents the respective minimum discharging power, and $P_{bdismax}$ represents the maximum power of discharging the battery.

2.9 Particle Swarm Optimization (PSO)

PSO algorithm was employed in this work because it efficiently solves the nonlinear objective functions. The PSO is one of the stochastic optimizations based on a population algorithm, which is considered an intelligent optimization method that mimics animal behavior like schools, birds, flocks, and fish. The first appearance of this algorithm was in 1995, and many enhancements have occurred to it. It has undergone many enhancements. After learning about this technology, researchers released a new version responding to different needs. New applications have been developed, and many published theoretical research on impact in many fields to optimize many parameters. In this work, the PSO algorithm has been proposed to implement the theoretical analysis.

Moreover, the status of PSO has been analyzed by specifying the selected parameters, parallel PSO algorithm, discrete PSO algorithm, topological structure, multi-objective Optimize PSO, and PSO engineering applications [14]. The proposed process can work offline to obtain the best controller gain with the certificate theorem. The simulation results show that under various operating conditions, there is excellent coordination between system performance and stability. Furthermore, the results show that the high stability associated with parameter changes is associated with excellent speed tracking. A comparative study with the nominal PSO simulation shows that the proposed design has an excellent performance in terms of rising time and overshoot [15]. On the other hand, the PSO plan points out powerful features optimize rules by eliminating invalid particles that also return poor performance. This may undermine stability standards [16]. At last, analyze existing problems and propose future research directions.

3. Case Study

The MG suggested in this article for the case study is shown in Figure 1. The picture can easily get from the MG composed of 18 bus bars and 3 feeders. Among them, residential feeders supply 175 residents, and industrial and commercial feeders supply Respective workshops and commercial loads. The battery capacity is 50 kWh, and the maximum charging capacity emits energy at 22.5 kWh. The power factor assumes that the load is 0.9. Corresponding parameters, the source of distributed generators, come from reference [17,18]. In addition, the typical lumped gated daily load curve, hourly wind power curve, Total solar power generation, and open market electricity consumption per hour Energy prices, Listed in Table 1. Finally, the proposed optimization method is applied simultaneously to MG's grid-connected and isolated modes.
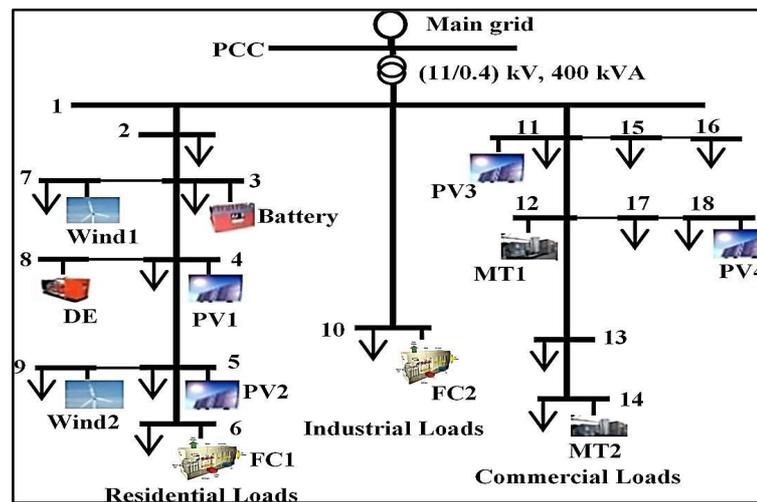
Figure 1: The proposed MG for the case study

Table 1: Hourly overview of wind power and photovoltaic power generation, opening up the market Price and total load

Hours	Wind generation (kW)	PV generation (kW)	Open market price (euros)	Total load (kW)
(1)	(10.67)	(0)	(0.035)	103.35)
(2)	(13.33)	(0)	(0.032)	(94.75)
(3)	(14.44)	(0)	(0.03)	(93.65)
(4)	(16.67)	(0)	(0.03)	(88.5)
(5)	(14.89)	(0)	(0.033)	(95.25)
(6)	(12.44)	(0)	(0.05)	(105.5)
(7)	(8.89)	(0)	(0.047)	(143.5)
(8)	(8.00)	(9.6)	(0.05)	(197.5)
(9)	(8.44)	(26.88)	(0.07)	(235.75)
(10)	(6.67)	(38.4)	(0.08)	(268.75)
(11)	(5.11)	(42.24)	(0.09)	(285)
(12)	(5.56)	(43.2)	(0.12)	(283.75)
(13)	(6.22)	(46.08)	(0.225)	(305.75)
(14)	(7.33)	(48)	(0.1)	(316)
(15)	(10.00)	(43.2)	(0.085)	(300.25)
(16)	(11.11)	(38.4)	(0.15)	(286.75)
(17)	(14.67)	(28.8)	(0.45)	(275)
(18)	(15.56)	(11.52)	(0.15)	(307.85)
(19)	(13.33)	(4.8)	(0.18)	(307.25)
(20)	(12.22)	(0)	(0.16)	(315)
(21)	(10.67)	(0)	(0.31)	(279)
(22)	(8.89)	(0)	(0.05)	(234.25)
(23)	(8.44)	(0)	(0.04)	(184.65)
(24)	(9.11)	(0)	(0.025)	(107)

4. Results and Discussion

Figure 2 shows the optimal hourly output generation of the distributed generators. It can be noticed that the distributed generators are turned off at hours 1 to 10, and the MG supplies its load by purchasing power from the utility grid, battery, and wind generation. This is because the open market price has low values and is lower than the generation of DGs, and the load has low values that can be supplied by utility grid and wind power with battery. At hour 11, the MG turns on the lowest generation cost DG and purchases power from the utility grid to supply its load. It can be seen that the highest generation occurs at hour 17 because the open market price has the highest value. Therefore, the MG sells the highest power to the utility grid to minimize its cost. Figure 3 shows the storage battery's hourly optimal charging and discharging operation. It can be noticed that the battery was charging when the open market price had the lowest value to minimize the operation cost of the MG. Figure 4 shows the hourly scheduling of the exchanging power with the utility grid. This figure shows that the highest-selling power happens at hour 17 when the open market price, where the MG sells the highest power to the utility grid to reduce its cost. The lowest selling power occurs at hour 20 because the load has the highest value, and the solar generation equals zero.

Table 2 lists the optimal hourly scheduling of the output generation of the DGs, charging and discharging of the storage battery, and exchanging power with the utility grid per scheduling day.
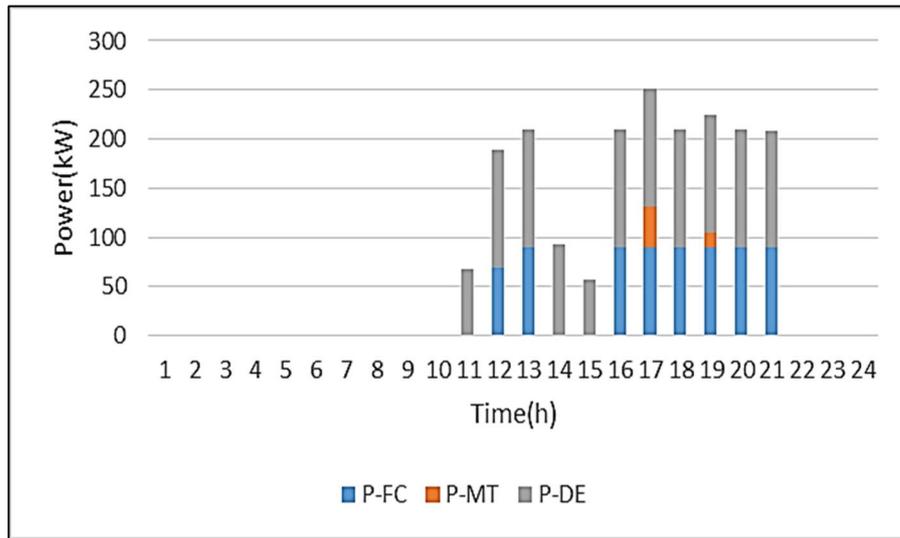
Figure 2: Hourly optimal scheduling of distributed generators
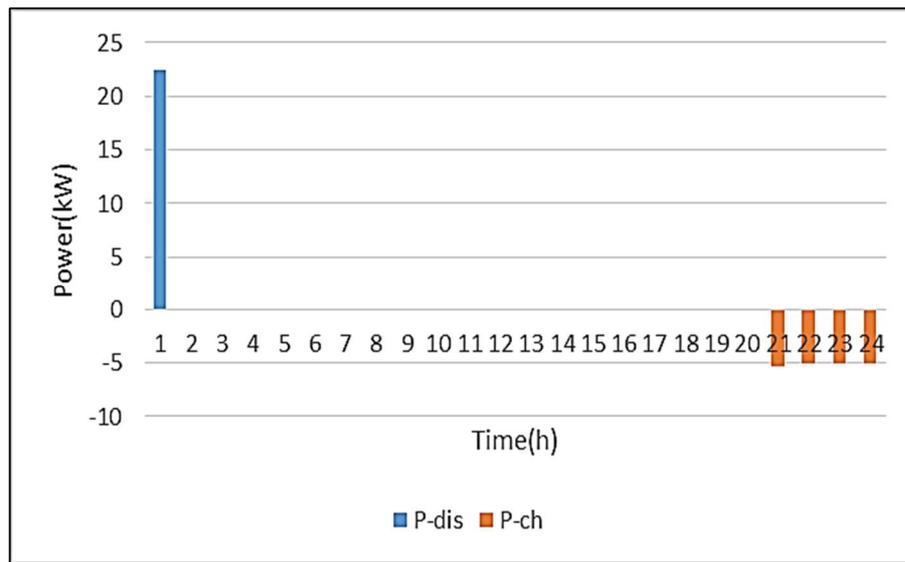
Figure 3: Hourly optimal charging and discharging of the storage battery
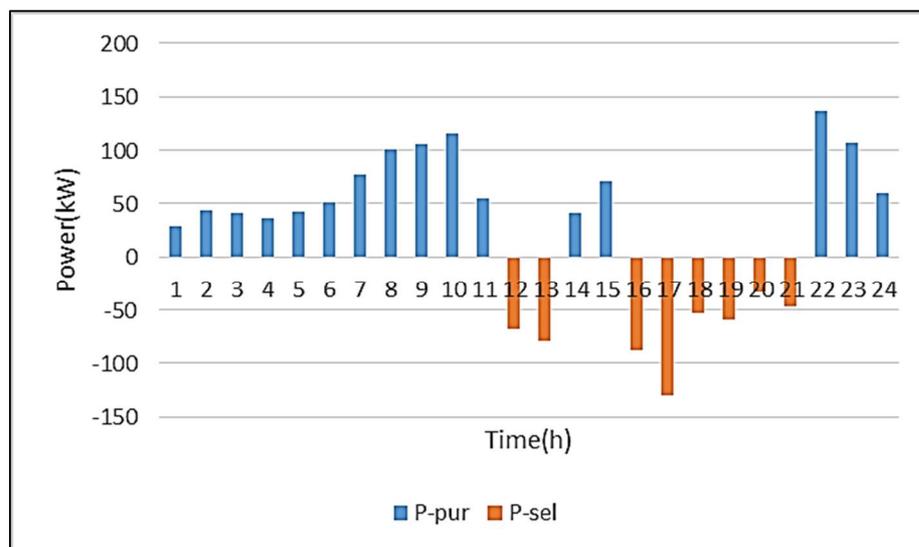
Figure 4: Hourly optimal exchanging power with the utility grid

Table 2: Hourly optimal results of DGs, battery, and exchanging power with utility grid

P_fc	P_mt	P_dg	P_bdis	P_bch	P_gpur	P_gsell	dlt_fc	dlt_mt	dlt_dg	dlt_bdis	dlt_bch	dlt_gpur	dlt_gsell
0	0	0	22.5	0	28.8	0	0	0	0	1	0	1	0
0	0	0	0	0	43.50	0	0	0	0	0	0	1	0
0	0	0	0	0	41.8	0	0	0	0	0	0	1	0
0	0	0	0	0	36.40	0	0	0	0	0	0	1	0
0	0	0	0	0	42.3	0	0	0	0	0	0	1	0
0	0	0	0	0	50.9	0	0	0	0	0	0	1	0
0	0	0	0	0	77.2	0	0	0	0	0	0	1	0
0	0	0	0	0	100.9	0	0	0	0	0	0	1	0
0	0	0	0	0	106.1	0	0	0	0	0	0	1	0
0	0	0	0	0	116.2	0	0	0	0	0	0	1	0
0	0	68.6	0	0	55.1	0	0	0	1	0	0	1	0
69.8	0	120	0	0	0	68.3	1	0	1	0	0	0	1
90	0	120	0	0	0	78.9	1	0	1	0	0	0	1
0	0	93.5	0	0	40.7	0	0	0	1	0	0	1	0
0	0	56.1	0	0	70.9	0	0	0	1	0	0	1	0
90	0	120	0	0	0	87.5	1	0	1	0	0	0	1
90	41.2	120	0	0	0	129.7	1	1	1	0	0	0	1
90	0	120	0	0	0	52.46	1	0	1	0	0	0	1
90	15.3	120	0	0	0	59.1	1	1	1	0	0	0	1
90	0	120	0	0	0	33.2	1	0	1	0	0	0	1
89.8358	0	118.7	0	5.348	0	46.44	1	0	1	0	1	0	1
0	0	0	0	5	136.7	0	0	0	0	0	1	1	0
0	0	0	0	5	107.3	0	0	0	0	0	1	1	0
0	0	0	0	5	60.1	0	0	0	0	0	1	1	0

5. Conclusion

The multi-period unit commitment energy management system minimizes both the low voltage microgrids' operation and emission cost. The multi-objective function is converted to a single function that can be solved in a single step by converting the emission to the monetary concept and considering the emission constraints. The results reveal that the storage battery charging and discharging operation are scheduled to minimize the total operating and emission cost. In addition, the proposed system model and the proposed algorithm can reduce operating costs and meet load requirements. The proposed process can be implemented under different loads and takes longer after one day. The model can be extended to the combined heat and power (CHP) microgrids.

Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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