Contents list available at IJRED website

International Journal of Renewable Energy Development

Journal homepage: https://ijred.undip.ac.id

Research Article

Demand response based microgrid's economic dispatch

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Abstract. The development of energy management tools for next-generation Distributed Energy Resources (DER) based power plants, such as photovoltaic, energy storage units, and wind, helps power systems be more flexible. Microgrids are entities that coordinate DERs in a persistently more decentralized fashion, hence decreasing the operational burden on the main grid and permitting them to give their full benefits. A new power framework has emerged due to the integration of DERs-based microgrids into the conventional power system. With the rapid advancement of microgrid technology, more emphasis has been placed on maintaining the microgrids' long-term economic feasibility while ensuring security and stability. The objective of this research is to provide a multi-objective economic operation technique for microgrids containing air-conditioning clusters (ACC) taking demand response into account. A dynamic price mechanism is proposed, accurately reflecting the system's actual operational status. For economic dispatch, flexible loads and air conditioners are considered demand response resources. Then, a consumer-profit model and an AC operating cost model are developed, with a set of pragmatic constraints of consumer comfort. The generation model is then designed to reduce the generation cost. Finally, a microgrid simulation platform is developed in MATLAB/Simulink, and a case is designed to evaluate the proposed method's performance. The findings show that consumer profit increases by 69.2% while ACC operational costs decrease by 18.2%. Moreover, generation costs are reduced without sacrificing customer satisfaction.

Keywords: Air-Conditioning Cluster (ACC), Demand Response (DR), Distributed Generation (DG), Economic Operation, Micro- gas turbine (MGT), Microgrid (MG)

Received: 24th Sept 2022; Revised: 16th April 2023; Accepted: 20th June 2023; Available online: 30th June 2023

1. Introduction

Microgrids are an integral part of today's smart grid. Microgrids serve as an effective interface for distributed generators (DG), loads, energy storage systems (ESS), and control units while sustaining DG's cost-effectiveness, environmental protection, and flexibility. They supply high-quality power to ensure that consumers' power usage is safe and reliable. The microgrid operation mode, on the other hand, is extremely adaptable (Saeed *et al.,* 2021a). For operation, MGs can be incorporated into a large power grid. They can also operate independently of the electric grid in autonomous/islanded mode. The remote islanded MGs operate in the event of a power grid breakdown to ensure the power supply of important loads (Mhankale & Thorat, 2018; Liu *et al.,* 2021; Dashtdar *et al.* 2022; Saeed *et al,* 2022). Economy, reliability, and energy-saving are three characteristics that must be considered in the operation of islanded-operated microgrid systems (Saeed *et al.,* 2021b; Recalde *et al.,* 2020; Xu et al., 2020; Pothireddy *et al.,* 2022). With the continuous development of microgrid control technologies, MGs have achieved safe and stable operation, and their reliability has been greatly guaranteed (Saeed *et al.,* 2022; Salkuti 2022). Therefore, researchers are paying more attention to the economics of MG operation (Battula *et al.* 2021; Wang et al. 2010).

The two types of economic power system dispatch are static dispatch and dynamic dispatch (Ross *et al.,* 1980; Han, 2001; Attaviriyanupap, 2002; Basu, 2008). Based on the system's operational conditions during each independent period, static economic dispatch determines the equipment's priority and mode of operation. The dynamic economic dispatch takes into account the scheduling cycle's lowest cost and coordinates across the various distribution generations (DGs) throughout several periods , so it is better adapted to the needs of a system in actual operation. Researching the dynamic economic dispatch is therefore crucial. It is challenging to resolve the dynamic economic dispatch problem with renewable energy sources because they are prone to randomness and disruptions (Calderaro *et al.,* 2014).

Hsiao *et al.* (2021) developed an MG energy optimization approach that combined reliability and economy to realize the dynamic economic operation. Salkuti *et al.* (2015), and Salkuti (2017) presented a novel multi-objective day-ahead market clearing (DAMC) process that incorporates demand response offers while taking into account an extensive voltage-dependent load model. Salkuti *et al.* (2016) also suggested a dynamic reserve activation strategy that is most effective in case of a line outage, a load rise, or both. He considered the spinning reserves provided by traditional thermal generators, hydropower units,

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https://doi.org/10.14710/ijred.2023.49165
ISSN: 2252-4940/© 2023.The Author(s). Published by CBIORE

and load demands. Salkuti (2018) developed an optimum emergency strategy utilizing the coordinated activity of slow and rapid reserves for the safe functioning of the power system at the least expensive and proved that the dynamic emergency reserve activation strategy has an advantage over the sequential reserve activation approach.

Murty & Kumar (2020) developed a mathematical model for the economics of an MG consisting of a combined heat and power (CHP) system that took environmental conditions into account. The simulation results show that scheduling batteries optimally can lower the system's overall running cost. However, it does not consider the reliability of the islanded operation of the system.

As multi-objective optimization targets, Ma *et al.* (2015) examines three indicators of active power loss, pollutant gas emissions, and system voltage stability. Through modeling and analysis, it provides ideas for the monitoring and operation of smart grids. As a relatively cheap economic dispatch resource, demand response not only expands the MG's economic dispatch capabilities but also benefits the demand response users (Vardakas *et al.,* 2015), (Rajkumar *et al.,* 2011), (Chen *et al.,* 2011), (Wang *et al.,* 2020), and (Pourbabak *et al.,* 2018). Jindal *et al.* (2018) proposed a novel analysis and management scheme that considers equipment adjustment variables, electrical priority indicators, and electrical product priority, as well as several algorithms for DR decision-making. Ali *et al.* (2022) established price-based demand response models, including wind power, diesel engines, and energy storage systems to solve the optimal operating strategy through multi-objective wind driven optimization (MOWDO), and verified the method's effectiveness through real-time simulations. To maximize the Microgrid's total profit, Nguyen *et al.* (2018) proposed a novel smart grid pricing plan based on a demand response model including time-varying loads and finally used the alternating direction method of multipliers to solve the optimization problem analytically. Hao *et al.* (2021) proposed a new chaotic binary gravitational search algorithm (IBGSA) for an islanded microgrid. The results show that implementing the demand response strategy in the optimal allocation process can effectively alleviate the systems' investment cost, maintain the power supply's reliability, and aggravate the renewable energy consumption. John et al. (2008) designed a framework for incorporating wind energy systems in the economic dispatch problem considering the overestimation and underestimation of the available power and numerically solved the optimization problem using the stochastic wind speed characterization based on the Weibull probability density function.

Wu *et al.* (2014) built a CHP microgrid system with various distributed energy resources and used the maximum comprehensive benefits as the objective function for dynamic economic dispatch. The objective function is solved using an improved particle swarm optimization (PSO) technique paired with Monte Carlo simulation. Zachar & Daoutidis (2016) employed economic model predictive control to keep costs down while still achieving the constraints. The suggested dispatch approach can successfully reject forecasting errors and satisfy the defined energy exchange and storage level goals. Imtiaz *et al.* (2021) implemented an incentive-based demand response model in a grid-connected microgrid and solved the economic dispatch problem with the dragonfly algorithm (DA). The objective of the proposed method is to achieve the lowest fuel cost, the lowest transferable power cost, and the highest demand response benefit for the microgrid operator. The findings of DA are compared to those of other modern algorithms such as the crow-search algorithm, the ant-lion Optimizer, particle swarm optimization, and the genetic algorithm.

In practice, a microgrid contains a variety of DG types. The DGs will exhibit various aspects in the dynamic economic dispatch when operating in various modes and according to various scheduling schemes. Unpredictability and discontinuities will make the economic dispatch more challenging (Kumar *et al.,* 2019).

This research suggests a dynamic electricity price mechanism based on the real-time electricity price mechanism that can more accurately reflect the operating status of the system for MGs with significant renewable energy penetration.

2. Dynamic electricity price mechanism

Supply and demand must always be matched in power systems (Ulbig et al., 2014). Dynamic electricity tariffs are commonly mentioned as instruments for demand-side management to ensure this grid stability (Dutta and Mitra, 2017). The adoption of real-time pricing tariffs is attributed to a rise in overall economic efficiency because dynamic prices per unit of electricity reflect their short-run societal marginal costs of provision better than constant prices per unit of electricity do (Borenstein, 2005).

Usually, the time-sharing tariff strategy is exploited to adjust the consumer's electricity consumption behavior according to the pre-set price. However, this strategy does not reflect the changes in the system's operating environment for real-time operation, particularly in the autonomous MGs having a high penetration rate of renewable energy resources. The presence of a large number of DERs makes the operating environment of the autonomous MG greatly affected by the ambient and complex. The island's changing environment also reduces the accuracy of the time-sharing power price mechanism period. Therefore, a dynamic electricity price mechanism which reflects the real-time operational status of the system can address the user's electricity consumption behavior more effectively.

The real-time update of dynamic electricity price affects the access volume of user-side adjustable load, and the plausible dynamic tariff mechanism can promote demand-side response and maximize user-side revenue. Electricity price is determined by the average marginal cost of system operation, while renewable energy resources and micro-gas turbines mainly provide the power in a microgrid. So, the dynamic electricity price mechanism consists of base electricity price, renewable energy power price adjustment, and micro gas-turbine power price adjustment. The base price is fixed and is the basis for forming the dynamic electricity price. The electricity price adjustment of renewable energy generation units is related to the actual power production by RERs. The adjustment of the electricity price of the micro-gas turbine is related to the power produced by the micro-gas turbine. When the amount of renewable energy generation increases, the dynamic electricity price should be reduced, and the user side should be guided to increase the access volume of adjustable load to promote electricity consumption. Therefore, dynamic electricity prices are negatively correlated with renewable energy power. The cost of generation of the micro-gas turbine increases with the increase of its generated power, which eventually increases the average operating cost of the microgrid. At this stage, to alleviate the burden on the generation-side of the microgrid, dynamic electricity prices should be increased to guide users to reduce the access volume of adjustable load. Therefore, dynamic electricity price is positively correlated with micro-gas turbine force. To sum up, defining dynamic tariffs is as follows:

$$c_d(t) = c_b - c_{reg}(t) + c_{mt}(t) \quad (1)$$

Where, $c_d(t)$ represents the dynamic electricity price for the t-period, c_b represents the base price of electricity, $c_{reg}(t)$ represents the amount of electricity price adjustment for renewable energy generation in the t-period, $c_{mt}(t)$ represents the amount of electricity price adjustment for micro-gas turbine power generation during the t-period.
$c_{reg}(t)$ is determined by the total amount of renewable energy power generation collected by the system during t−1 period, and the total amount of power generation by the microgrid is given by the following formula:

$$c_{reg}(t) = k_{reg}.\frac{\sum p_i^{reg}(t-1)}{\sum p_i^{reg}(t-1)+p_i^{mt}(t-1)} \quad (2)$$

Here, k_{reg} represents the electricity price adjustment factor for renewable energy generation, $p_i^{reg}(t-1)$ represents the power output of the i[th] RER in the time t−1. $p_i^{mt}(t-1)$ denotes the power output of the i[th] micro gas turbine during period t−1. It can be seen from equations (1) and (2) that when the MGT's output remains unchanged with an increase of renewable energy generation, the amount of electricity price adjustment for renewable energy generation increases. And the dynamic price reduction encourages users to connect more adjustable loads to promote electric energy consumption.

From equation (12), it can be obtained that the cost of generation of the MGT becomes a convex quadratic function of its output. The increase in the cost of generation from MGTs will increase dynamic electricity prices. So, the exact definition of the electricity price adjustment coefficient of the MGT power generation as the second convex function of its output is shown in the following formula:

$$c_{mt}(t) = a.(\sum \mathrm{p}_\mathrm{i}^{mt}(t-1))^2 + b.(\sum \mathrm{p}_\mathrm{mt}^{i}(t-1)) \quad (3)$$

Where a and b represent the electricity price adjustment coefficient of the MGT respectively. When the renewable energy power generation remains unchanged with the increase in output of the MGT, the electricity price adjustment amount of the MGT's generated power increases and can be calculated by equation (2).

The amount of electricity price adjustment for renewable energy power generation will reduce, so the dynamic electricity price will rise, limiting adjustable load access.

Based on the renewable energy generation and micro-gas turbine power generation in the previous period, the system determines the dynamic tariff to be executed in the next period and updates the dynamic electricity price before the following time period.

3. The multi-objective demand response model

The conventional microgrid economic optimization model focuses on the microgrid power generation side or demand side and neglects the user's comfort. In the future, microgrid development needs to optimize the power generation side and demand side as a whole to improve the economy and reliability of microgrid operation. Therefore, based on the proposed dynamic electricity price mechanism, this section establishes a multi-objective economic operation model that integrates the generation- side and demand-side of the MG.

For optimal demand side scheduling, the communities for adjustable loads and air conditioning are used as demand response resources. To maximize user benefits and reduce ACC operating costs while maintaining user comfort, the air-conditioning cluster's (ACC) operating cost and adjustable user benefit model were developed. To ensure that the cost of power generation is kept to a minimum while the microgrid is in operation, a cost model for power generation has been devised.

3.1. User-side revenue model

The revenue function on the user side consists of a utility function and a cost function. The utility function represents the relationship between the size of the power consumption of the load and the benefits generated. The parameters σ_i and ω_i are introduced to describe the utility of different adjustable loads. The electricity utility of load i can be expressed as follows:

$$U_i(t) = \begin{cases} \sigma_i l_i^{fl}(t) + \frac{\omega_i}{2}\left(l_i^{fl}(t)\right)^2 & , \ 0 < l_i^{fl}(t) < -\frac{\sigma_i}{\omega_i} \\ \frac{\sigma_i^2}{2\omega_i} & , \ l_i^{fl}(t) \geq -\frac{\sigma_i}{\omega_i} \end{cases} \quad (4)$$

Thereinto σ_i, ω_i represent the parameters of adjustable load i, satisfying $\omega_i > 0$, $\sigma_i > 0$, determined by the type of load. l_i^{fl} represents the adjustable load i during the time-period t, $U_i(t)$ represents the electrical utility of adjustable load k, at $l_i < \sigma_i < \omega_i$ time. $U_i(t)$ is directly proportional to the access amount l_i^{fl} of the adjustable load i. When $l_i^{fl} \geq \sigma_i\omega_i$, even if the adjustable load connection amount l_i^{fl} continues to increase, the electricity utility $U_i(t)$ of the adjustable load remains unchanged. The cost function represents the user's electricity bill, following the user's specific usage trends. The cost of electricity for adjustable loads can be expressed as follows:

$$F_i(t) = c_d(t) - l_i^{fl}(t) \quad (5)$$

Here, $F_i(t)$ represents the cost of electricity for adjustable load i.
The combined utility function and the cost function can be represented by the user-side revenue function as follows:

$$P = \sum \mathrm{U_i}(t) - \sum \mathrm{F_i}(t) \quad (6)$$

When the dynamic tariff increases, the utility of adjustable load will remain unchanged, and the cost of electricity will increase. This results in lower revenue on the user side, so the adjustable load will be reduced to ensure maximum benefit on the user side. When the dynamic tariff is reduced, access to adjustable load will increase due to the reduction of electricity charges to obtain more significant revenue on the user side.

3.2. Air conditioning operating cost model

Air- conditioning has periodic operating characteristics. The indoor temperature fluctuates up and down between user-set temperature ranges. When the air conditioning in cooling mode is on and running, the lower-temperature limit T_{down} is reached in the room. When the air conditioner stops working, the room temperature continues to rise. The air conditioner starts running again with the room temperature reaching the upper-temperature limit T_{up}. The thermal power process of the air conditioner can be simulated by the equivalent thermal parameter model (ETP), and the expression for the room temperature is as follows:

$$\begin{cases} T_i^{t+1} = T_0^t - (T_0^t - T_i^t)e^{-\frac{\Delta t}{RC}}, S = 0 \\ T_i^{t+1} = T_0^t - \eta pR - (T_0^t - \eta pR - T_i^t)e^{-\frac{\Delta t}{RC}}, S = 1 \end{cases} \quad (7)$$

In the above expression, T_i^{t+1} and T_i^t represent t+1 and t-moment room temperature, respectively. T_0^t represents the ambient temperature at the t-moment. p indicates the cooling/ thermal power (kW) when the air conditioner is operating, η represents the energy efficiency ratio of the air conditioner, C is the equivalent thermal capacity (J/C), R is the equivalent thermal resistance (C/W), Δt Represents the interval (s). S indicates the operating status of the air conditioner, S =0 indicates that the air conditioner is out of service, $S = 1$ indicates that the air conditioner is in operation.

The operating cost function of air conditioning consists of its electricity cost function and maintenance cost function. The electricity cost function is used to describe the power cost consumed when air conditioning is in operation, which can be expressed as follows:

$$N_i(t) = c_d(t).p_i^{AC}(t) \quad (8)$$

thereinto $p_i^{AC}(t)$ indicates the cooling/ thermal power of the i[th] air conditioner, $N_i(t)$ represents its corresponding cost of electricity.

The maintenance cost function of the air conditioner is used to describe the depreciation and maintenance costs generated by the operation of the air conditioner. Considering the differences between different air conditioners, the maintenance cost can be defined as the quadratic convex function of the power of the air conditioner. It is expressed as follows:

$$M_i(t) = m.\left(p_i^{AC}(t)\right)^2 + n.p_i^{AC}(t) + l \quad (9)$$

In above equation, m, n, and l are the maintenance cost factors for air conditioning, respectively. $M_i(t)$ represents the maintenance cost of the air conditioner. The function of electricity cost and maintenance cost of integrated air conditioning can be obtained as follows:

$$W(t) = \sum N_i(t) + \sum M_i(t) \quad (10)$$

At the same time, influencing factors of electricity price are introduced into the comfort constraints of users so that the air conditioners' set temperature is affected by the two factors of electricity price and user comfort. The set temperature can be formulated as:

$$T_{set}^{t+1} = T_{set}^t + C_1.\frac{c_d - c_d^{min}}{c_d^{max} - c_d^{min}} + C_2.\frac{T_{set}^t - T_{set}^{ori}}{T_{up} - T_{down}} \quad (11)$$

In the above expression, T_{set}^{t+1} and T_{set}^t represent the air conditioning set temperature at t+1 and t-moment, respectively. C_1 and C_2 are the influence coefficients of electricity price and user comfort on the set temperature of air-conditioning. c_d^{max} and c_d^{min} are the maximum and minimum value of the electricity price, and T_{up} and T_{down} are the upper and lower limits of the user's set temperature, T_{set}^{ori} represents the initial set temperature of the air conditioner. The dynamic electricity price increases is directly proportional to the operating cost of air conditioning. At this time, the air conditioning temperature increases and reduces the operating time of air conditioning to save electricity costs. When the set temperature of air conditioning increases to a particular value, by the user's comfort limit, the setting temperature of air conditioning is reduced to ensure the user's comfort.

3.3. *Generation side cost model*

In the microgrids operating in an isolated mode, the cost of electricity generation from renewable sources is generally ignored, and only the generation cost from micro-gas turbines is considered. The generation cost is usually defined as the quadratic convex function of power output for conventional micro-gas turbines as (Boyd *et al.,* 2012):

$$C_i = \alpha_i (p_i^{mt})^2 + \beta_i p_i^{mt} + \gamma_i \quad (12)$$

Thereinto $\alpha_i, \beta_i, \gamma_i$ are i[th] MGT's cost parameters, and meet $\alpha_i > 0,\ \beta_i > 0,\ \gamma_i > 0$. p_i^{mt} represents the active output of the micro-gas turbine i, C_i represents the cost of generation for i[th] MGT.

The objective function of the microgrid generation side can be expressed as follows:

$$\min C = \sum_{i=1}^{n} C_i(p_i^{mt}) \quad (13)$$

The incremental cost λ_i of micro-gas turbines is defined as the 1[st] derivative of its generating cost electricity C_i w.r.t. active output pi, represented as follows (Wood *et al.,* 2013):

$$\lambda_i = \frac{\partial C_i(p_i^{mt})}{\partial p_i^{mt}} = 2\alpha_i p_i^{mt} + \beta_i \quad (14)$$

According to the criterion of equal small increase rate, when the incremental cost of all MGTs is the same, the optimal output of each MGT is obtained. At this time, the cost of generation of the MG is the smallest.

4. Constraints

Equality and inequality constraints are introduced to ensure the reliable operation of the MG. Equality constraints ensure the power balance between the generation side and the consumption side of the microgrid during operation, which is a prerequisite for the stable operation of the MG. Inequality constraints consider the output limit of micro-gas turbines in microgrids and the access limit of adjustable load.

4.1. *Power balance constraint*

For an MG, the total output of power generation from RERs, ESD, and MGTs should be balanced with the total load on the user side, which can be expressed as follows:

$$\sum p_i^{mt}(t) + \sum p_i^{reg}(t) + p^{ess}(t) = \sum l_i^{fl}(t) + \sum l_i^{cl}(t) + \sum p_i^{AC}(t) \quad (15)$$

Here, $p_i^{reg}(t)$ represents the output power of the i[th] RER unit at the t-moment, $p^{ess}(t)$ represents the output of the ESD at t-moment.

4.2. *MGT's output constraint*

The output of the MGT is limited by its rated capacity and other physical conditions. To ensure an adequate output of the MGT during the optimization process, the constraints are set as follows:

$$\min(p_i^{mt}) \le p_i^{mt}(t) \le \max(p_i^{mt}) \quad (16)$$

Here, $\min(p_i^{mt})$ and $\max(p_i^{mt})$ represent the minimum and maximum output of the i[th] MGT.

4.3. Adjustable load Constraint

The access volume of the adjustable load is adjusted with the change of the dynamic tariff to maximize the user-side revenue. Due to the limitation of the physical conditions of the adjustable load, the access volume is restricted as follows:

$$\min(l_i^{fl}) \le l_i^{fl}(t) \le \max(l_i^{fl}) \qquad (17)$$

hereinto $min(l_i^{fl})$ and $max(l_i^{fl})$ represent the minimum and maximum access volumes of the **i^th** adjustable load.

4.4. User comfort constraints

The indoor temperature should be maintained within the user's comfort level. When the indoor temperature exceeds the upper-temperature limit, the air conditioner starts working to reduce the room temperature. When the indoor temperature is less than the lower temperature limit, the air conditioner stops working. When the indoor temperature is within the comfort zone, the air conditioner stops working or keeps working according to the control command. At the same time, influencing factors of electricity price are introduced into the comfort constraints of users so that the set temperature of the air conditioner is affected by the two factors of electricity price and user comfort. The set temperature of the air conditioner can be expressed as follows:

$$T_{down} < T_i(t) < T_{up} \qquad (18)$$

In the formula, T_{up} and T_{down} represent the upper and lower temperature limit set by the user. The upper limit is 2 degrees higher than the user set temperature, and the corresponding lower limit is 2 degrees lower than the user set temperature.

5. Simulation model

A radial MG operating in islanded mode is established in MATLAB/Simulink to verify the effectiveness of the proposed multi-objective economic dispatch method. The microgrid simulation model consists of 12 distributed power generation units and 12 loads, and its topology is shown in Figure 1.

The distributed power generation units include micro gas turbines {DGi| i=1,3,5,7,11}, renewable energy generation units {DGi| i=2,6,8,9,10,12} and energy storage systems DG4. There are three types, namely fixed loads {Loadi| i=4,8,10,12} adjustable load {Loadi| i=1,3,5,11} and ACC load {ACi| i=2,5,6,9}. Renewable energy power generation units, including photovoltaics and wind turbines, are considered to work in Maximum Power Point Tracking (MPPT) mode. Considering

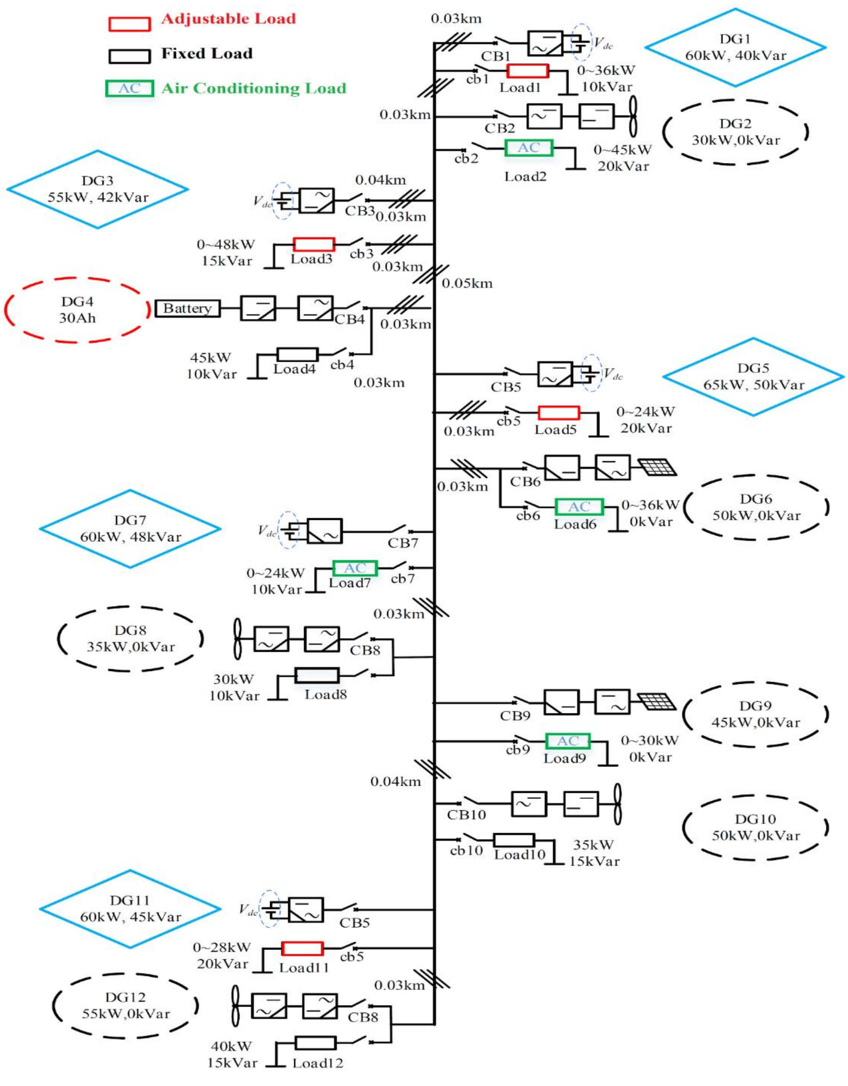

Fig 1. The topology of microgrid simulation platform

ISSN: 2252-4940/©2023. The Author(s). Published by CBIORE

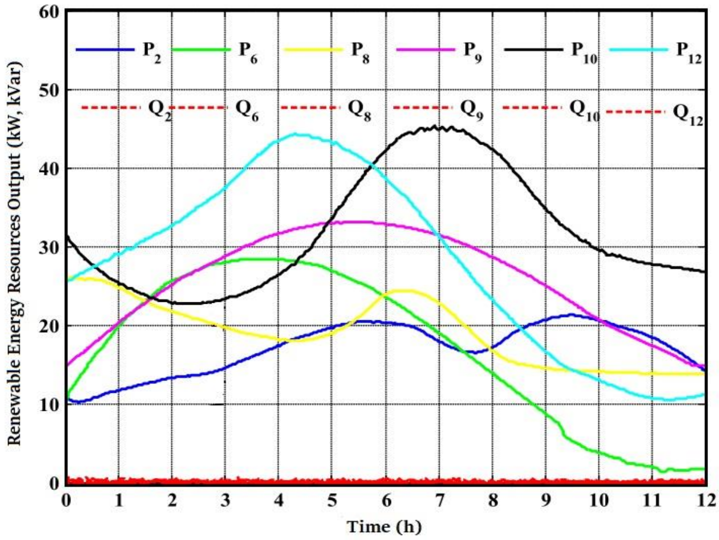

Fig 2. Outputs of renewable energy generation units

that this paper studies the dynamic economic dispatch of microgrids, the renewable energy power generation units are set not to generate reactive power. In the simulation process, the output curve of the renewable energy power generation unit is shown in Fig. 2. The micro gas turbine works in the PQ control mode to compensate for the power gap between renewable energy generation units and the load. Since the islanded microgrid lacks the support of the main grid, the energy storage system works in the V/F mode as the voltage and frequency support of the microgrid. Taking into account the energy storage system's capacity and output power limitations, a micro gas turbine is set to share the energy storage output. So, the energy storage system only supplies power when the load changes suddenly, and then its output power is shared by the micro gas turbine. Resultantly, the overcharge and discharge of the energy storage system are avoided, and the safe and stable operation of the microgrid is ensured.

The air-conditioning load in the microgrid is assumed to be inverter air-conditioning with a maximum rating of 3 kW. In addition, the air conditioners in each area are centrally controlled by the corresponding central controller, and the indoor temperature in the same area remains the same. The specific parameters of air conditioning load are shown in Table 1. The related parameters of distributed generation units (DG) and loads in the microgrid are listed in Table 2 and Table 3, respectively. The line losses are introduced in the system to make a real-time simulation model for the microgrid. The line impedance is set to 0.641 + j0.101 Ω/km, and the system voltage and frequency are set to 380 V and 50 Hz, respectively.

Table 1
Setups and Parameters of AC

Serial #	No. of AC Units	Initial Temperature (°C)	m	n	l
2	15	24	-0.328	3.42	0.80
6	12	24.5	-0.174	2.86	0.83
7	8	23	-0.360	2.32	1.00
9	10	25	-0.198	2.99	1.50

Table 2
DG Parameters

Serial #	Active/ Reactive Ratings (kW, kVar)	Mode	α	β	γ
1	60, 40	PQ	0.059	6.71	80
2	30, 0	MPPT	-	-	-
3	55, 42	PQ	0.066	6.29	43
4	30 Ah	V/F	-	-	-
5	65, 50	PQ	0.046	7.53	35
6	50, 0	MPPT	-	-	-
7	60, 48	PQ	0.069	4.57	48
8	35, 0	MPPT	-	-	-
9	45, 0	MPPT	-	-	-
10	50, 0	MPPT	-	-	-
11	60, 45	PQ	0.058	0.058	54
12	55, 0	MPPT	-	-	-

Table 3
Load Parameters

Serial #	Load Type	Load Range (kW)	ω	σ
1	Adjustable	0- 36	-0.123	9.625
2	ACC	0- 45	-	-
3	Adjustable	0- 48	-0.163	13.02
4	Fixed	30	-	-
5	Adjustable	0- 24	-	-
6	ACC	0- 36	-0.198	13.12
7	ACC	0-24	-	-
8	Fixed	30	-	-
9	ACC	0-30	-0.207	10.99
10	Fixed	35	-	-
11	Adjustable	0-28	-	-
12	Fixed	40	-	-

6. Model's Solution

Based on the specifications of the microgrid simulation model, the MATLAB Function module in the User-defined functions library is added to Simulink. Then user benefit model, air-conditioning operating cost model, and power generation cost model are established in the module. The centralized interior-point optimization function 'fmincon' is called to solve the model; a function minimizer with linear and nonlinear constraints. The specific steps are as follows:

a) Read the current operational time of each micro gas turbine, energy storage system output, adjustable load, ACC power, indoor temperature, ambient temperature, and dynamic electricity price.
b) Based on the current dynamic electricity price, the centralized optimization function 'fmincon' solves the user side revenue model and the air-conditioning operating cost model. And the optimal connection plan of the adjustable load and the optimal operating power of the ACC is obtained.
c) The output of the V/F controlled- energy storage system is allocated to the micro gas turbine to avoid overcharge and discharge of the energy storage system to ensure the microgrid's stable operation.
d) The total output of micro gas turbines is updated. The centralized optimization function 'fmincon' is called to solve the power generation cost model to ensure that all micro gas turbines have incremental costs and minimize power generation costs.
e) The adjustable loads, the operating power of the ACC, and the output power of the micro gas turbine are updated and the arrival of the following optimization period is entertained in the same way.

7. Results & discussion

A simulation study is designed for the microgrid simulation model to verify the validity of the proposed multi-objective economic scheduling model. The simulation duration is 6 hours. The operation and economic benefits of the microgrid under normal conditions and multi-time economic dispatch strategy are compared and analyzed, and the simulation results under different strategies are shown in the following figures.

Comparing the dynamic electricity price and the change of adjustable load in Fig. 3 (a) and (b), it can be seen that when the dynamic price increases, the amount of variable load access decreases and the cost of electricity for adjustable load decreases. While the cost of the adjustable load has decreased, fewer devices modify their consumption in response to price

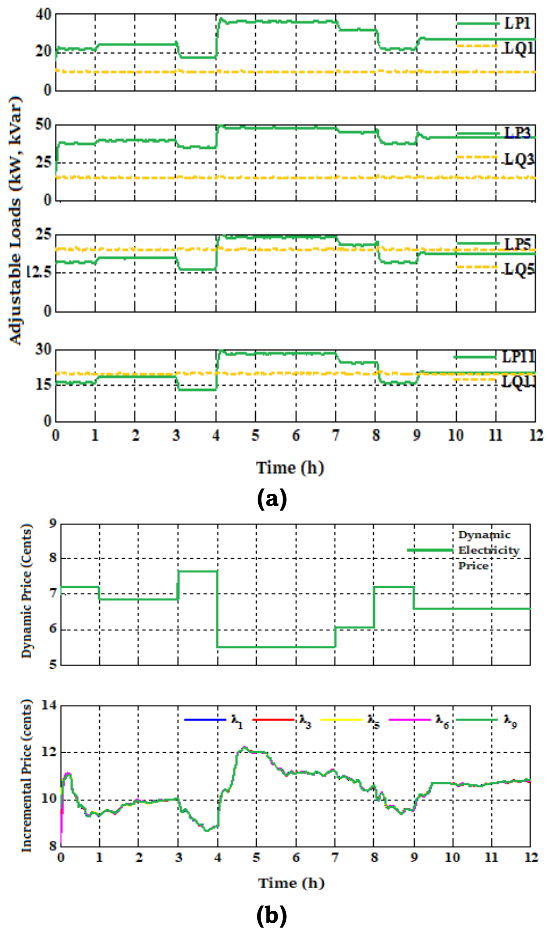

Fig. 3 (a) Connected amount of flexible loads **(b)** the incremental cost of MTs and the dynamic price signals. This is due to the ability of users to move their electricity usage to cheaper times of the day. When demand is strong or the supply is constrained, both impacts result in a more balanced and effective use of electricity. When the dynamic electricity price decreases, the amount of adjustable load access increases. Although the adjustable load electricity cost increases, the utility of the adjustable power load increases more than the cost of electricity, so the total income of the users increases. The expansion of adjustable load access enables consumers to switch their consumption to cheaper times of the day (Julia & Victor 2022, Maximilian 2022). . The increased utility gained by using power during cheaper times leads to an overall rise in total income or benefit for users, notwithstanding the possibility of an increase in the cost of electricity for adjustable loads. Fig. 3(b) shows the incremental cost curve of micro-gas turbines, which shows that the incremental costs of micro-gas turbines are consistent throughout the simulation period for all the values of **λ**, thus minimizing the total cost of power generation on the power generation side of the microgrid. The reason is that they may modify their power output while a demand response program is active based on the grid's requirements and pricing cues. The turbines can continue to operate steadily and efficiently during the simulation time because these modifications often take place within a narrow range. In Fig. 3(b), the dynamic cost decreases drastically after 4 hr due to rise in incremental cost of micro-turbine, and then increases gradually after 7 hrs with the decline in the incremental cost of micro-turbine.

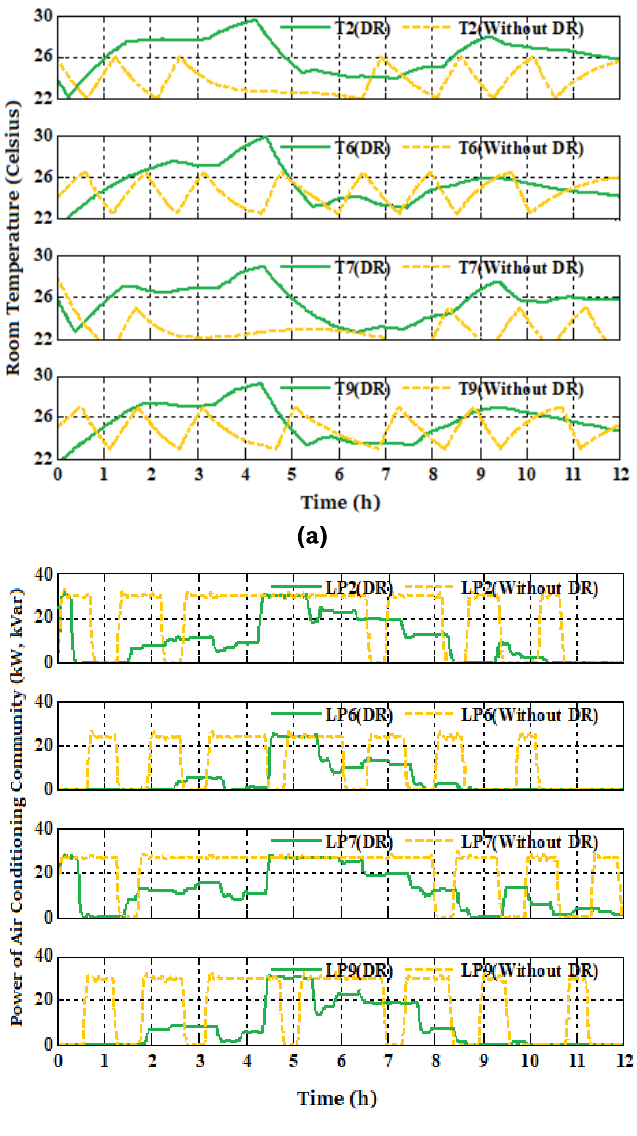

Fig. 4 (a) the room temperature **(b)** the power of AC

Fig. 4 (a) and (b) show the user room temperature variation and ACC power variation with and without introducing the proposed method. It is clear that under the proposed method, the power consumption of the ACC is lower than that without the introduction of the proposed method with the constraints of user comfort. The increased temperature variation is caused by equipment- cycling, in which the cooling or heating system frequently switches from on to off operation. During times of peak demand, this cycle can be employed to reduce overall electricity use. As the system alternates between times of active cooling or heating and periods of inactivity, it can also result in temperature changes within the space. There are two reasons behind the decreased ACC power variation:

- *Setpoint adjustments:*

In order to balance the grid's demand for electricity, the DR program requires consumers to change the setpoints on their thermostats or permit a wider range of temperatures. Users may need to tolerate slightly higher room temperatures than their preferred comfort levels. The units may cycle on and off more frequently to maintain the greater temperature range as a result of these setpoint alterations, which might lead to increased power variances within the air conditioning cluster (David *et al.* 2015)..

- *Consumer response heterogeneity:*

Users' reactions to DR signals can differ, resulting in various power fluctuation patterns within the ACC. While some users may have more variable usage patterns, others may be more receptive to price signals or demands for demand reduction, leading to higher power variations. This fluctuation in user responses may be a factor in the cluster's higher power variability(Waseem *et al.* 2021)..

Figure 5 shows the voltage and frequency of the microgrid system and the output of the energy storage system. It is clear from the figure that under the proposed economic dispatch strategy, the voltage and frequency of the system remain stable. For a microgrid's safe and reliable operation, certain voltage limitations must be maintained. The proposed economic dispatch method takes these restrictions into account and allocates generation resources to keep voltage levels within reasonable bounds. The economic dispatch approach contributes to system stability by sticking to these voltage constraints and avoiding voltage instability or voltage collapse. Only when the load changes suddenly, there will be small fluctuations, but it will return to normal soon.

The economic dispatch strategy aims to balance the generation and load within the power system. By optimizing the allocation of generation resources, it ensures that the total power supplied matches the total power demanded in real-time. This balance helps maintain a stable frequency as the generation and load fluctuations are minimized. Dynamic response capabilities allow energy storage systems to respond quickly to changes in load or generation, helping to regulate frequency and voltage within the microgrid. The energy storage system only outputs or absorbs power to maintain the power balance of the microgrid system when the load changes suddenly. But the output is quickly shared by the micro gas turbine and returns to zero, thus avoiding the overcharge and discharge of the energy

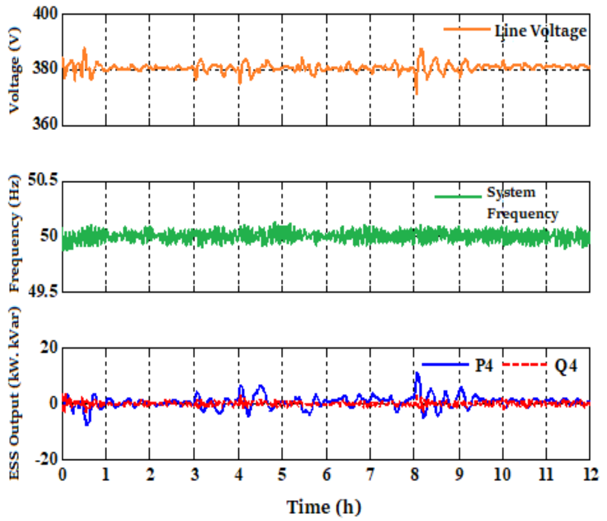

Fig. 5 The frequency and voltage of the microgrid and the outputs of ESS

storage system to ensure the safety and stability of the microgrid operation

Fig. 6 compares the benefits of adjustable load users and the operating costs of air-conditioning communities. It can be seen from the figure that the introduction of the demand response economic dispatch method reduces the operating cost of ACC. It can be seen from Table 4 that the adjustable user benefit of introducing the demand response economic dispatch method is 69.2% higher than the benefit of the user when it is not introduced, and the operating cost of the ACC is reduced by 18.2%. The reason is that the proposed method enables load shifting, where the air conditioning cluster can adjust its cooling operation to shift the peak demand to lower-demand periods. By reducing or limiting cooling during peak hours, when electricity prices are typically higher, the cluster can avoid costly peak demand charges and achieve cost savings.

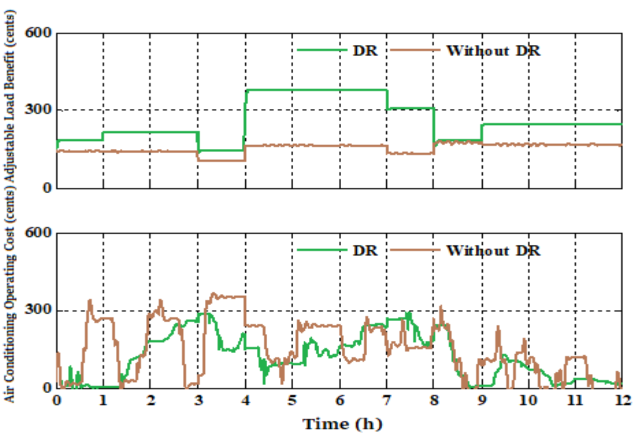

Fig. 6 The profit of consumers and operation cost of AC

Table 4
User benefits and air conditioning operating costs

Scheduling Method	User Benefit (cents)	AC- Operating Cost (cents)
DR	3,126	1,459
Without DR	1,848	1,785

8. Conclusion

The problem is the current time-of-use electricity price mechanism cannot reflect the real-time status of the microgrid system. So, this paper proposes a dynamic electricity price mechanism that can better reflect the operating status of the microgrid under a high rate of renewable energy penetration. Then, air conditioners and adjustable loads are considered as demand response resources to participate in the economic dispatch of the microgrid. The income function of the adjustable load user and the operating cost function of the air conditioner are established, and a series of constraints such as user comfort is considered. According to the criterion of equal small increase rate, the output distribution model of the micro gas turbine is established to minimize the cost of the power generation side of the microgrid. Finally, a microgrid simulation model is built in MATLAB/Simulink to verify the proposed multi-objective demand response economic dispatch method. From the simulation results, it can be concluded that under the multi-objective economic dispatch method, the benefit of adjustable users has increased by 69.2%, and the operating cost of the air-conditioning cluster has been reduced by 18.2% ensuring user comfort. At the same time, the output of the micro gas turbine is distributed through the equal micro-increase rate criterion to minimize the power generation cost of the microgrid, thereby realizing the optimal economic operation of the micro-grid.

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