Multi-objective Demand Responding Micro Grid Dispatch Optimization based on Energy Storage Operation with Uncertain RES Power

Sicheng Hou, Tomohiro Murata

Abstract—**To response the challenge of modern micro grid MG (system) efficiently, which requires suppling sufficient power to user with higher reliability, less cost and emission. This paper proposes a comprehensive multi-objective MG dispatch optimization model by introducing the operations of demand response (DR) based on peak clipping technology and incentive price mechanism, as well as energy storage (ES) for storing the produced renewable energy resource (RES) power efficiently. To verify the effectiveness of proposed model, under uncertain RES power generation, simulated experiments are concluded by implementing multi-objective particle swarm optimization (MOPSO), where the results show that the introduced DR and ES operation are beneficial for obtaining the power supply solution with less cost and emission, as well as better reliability simultaneously.**

Index Terms—**multi-objective MG dispatch optimization, demand responding, energy storage, multi-objective particle swarm optimization**

I. INTRODUCTION

THE Micro Grid (MG) is defined as a small-scale power supply network which always provides power for residential community, and small industry factory, etc. [1]. In MG system, a group of distributed power resources are constructed for supplying sufficient power to user, including a set of generators using fossil fuel, battery device and the access to utility power grid. To deal with the energy risk efficiently, power generated from renewable energy source (RES), such as solar, wind, geothermal and biomass, has been widely integrated into MG system for recent years. The conventional MG dispatch optimization concentrated on single-objective economic target, which aims to satisfy load demand with less operation cost. In literature [2]–[4], practical MG economic dispatch optimization models were constructed by considering distributed energy storage operation, real-time pricing tool and agent-based community, respectively. Nowadays, since the continuously increasing concerns resulting from serious global pollution emission issue, environmental MG dispatch optimization problem, where the target is trying to minimize the pollution emission produced during power supply process, has become another important topic of MG system dispatch optimization.

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Sicheng Hou is currently pursuing the Ph.D. degree at the Graduate School of Information, Production and Systems, Waseda University, Japan. (sicheng_hou@fuji.waseda.jp).

Tomohiro Murata is a Professor of the Graduate School of Information, Production and Systems, Waseda University, Japan. (t-mura@waseda.jp)

Thus, the multi-objective micro grid dispatch optimization, of which the objective is to reduce cost and emission simultaneously, was proposed accordingly [5]–[7].

To reduce operation cost and pollution emission as well as improve reliability of power supply process furthermore, on the one hand, demand response (DR), also could be termed as demand side management (DSM), which refers to a cooperated agreement between MG and user for changing load consumption pattern by incentive price, load control and pricing tool [8]–[9], was widely introduced into MG system. Specifically, during some peak hours of higher load demand, instead of producing more power to ensure the power supply balance, some unimportant load consumption, like electric hot water heaters, coffee makers, and dryers, etc., could be reduced or delayed for few hours, so that peak demand, operation cost and pollution emission produced during peak hours, could be reduced efficiently. On the other hand, from viewpoint of power supply side, uncertain RES power generation results to fluctuation during power supply process. To compensate fluctuations efficiently, energy storage (ES) operation could be utilized for improving the stability and flexibility of power supply process [9]–[10] which means, some generated RES power could be stored into battery device of MG during off-peak hours when load demand is at a lower-level degree, and this process could be termed as charging status of battery device. Accordingly, during peak hours of higher load demand degree, the stored energy could discharge from battery device to MG for satisfying higher load demand of user. Through efficient charging and discharging process of battery device, the usage efficiency of RES power could be improved well with less produced cost and emission.

Based on above motivation, this paper proposes a comprehensive multi-objective MG dispatch optimization model for minimizing cost and emission, as well as improving reliability of power supply solution simultaneously. Two efficient operations: DR and ES are introduced into MG system. Specifically, the contribution of this paper could be concluded as follows:

1. A comprehensive multi-objective MG dispatch optimization model is constructed by introducing ES operation, as well as DR operation based on peak clipping technology and incentive price mechanism.
2. Multi-objective particle swarm optimization (MOPSO) is implemented for searching feasible and optimal power supply solution with less cost and emission simultaneously.
3. A MG system is simulated under uncertain RES power generation for verifying merits of the proposed model.

4. Experiment results demonstrates effectiveness of the introduced DR and ES operations in terms of cost and emission reduction, as well as reliability improvement.

The remaining paper is organized as follows: section II explains formulation of proposed multi-objective optimization problem, including DR operation model based on peak clipping technology and incentive price mechanism, ES operation model, and multi-objective MG dispatch optimization model, respectively. Section III illustrates the implemented methodology of MOPSO. A MG system under uncertain RES power generation is simulated in section IV. Section V shows the experimental results. Conclusion and future work are presented is section VI.

II. PROBLEM FORMULATION

A. Demand Response Operation Model based on Peak Clipping Technology and Incentive Price Mechanism

As mentioned before, DR operation is a cooperative agreement between MG system and user for changing load consumption pattern by incentive price, and load control, etc. This paper builds a DR model driven by incentive price for clipping peak demand of MG system. The procedure of proposed DR operation is given in Figure 1. Firstly, according to power supply condition, MG sends DR proposal to user for requesting to reduce some unimportant load demand. Then, according to DR incentive price paid by MG system, user decides whether to response the load reduction proposal and how much load demand is reduced. Finally, according to the actual load demand reduction amount responded by user, MG system pays incentive cost to user.

This paper introduces DR operation established by peak clipping technology, which is a simple way and easy to implement among all possible DSM tools. The actual load reduction amount responded by user is represented by equation (1):

$$DR(t) = DR_{proposal}(t) \times Acceptance_k, \forall t \in T \quad (1)$$

where $DR(t)$ and $DR_{proposal}(t)$ is actual load reduction amount responded by user, and suggested load reduction amount sent by MG system, respectively. T is total hour for one day, and $Acceptance_k$ is user acceptance degree to DR proposal of the k^{th} type. Note that the DR proposal amount sent by MG system could not exceed the maximum DR proposal amount $DR_{max}(t)$, which is pre-determined by the

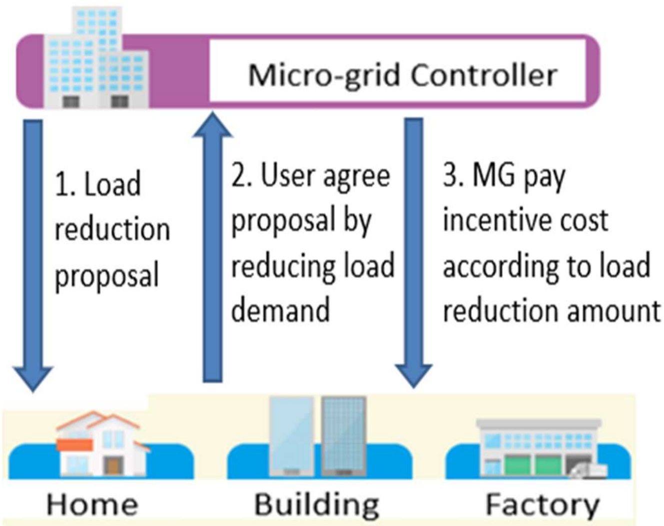

Fig. 1. Procedure of DR operation

cooperative policy between MG and user and shown in equation (2):

$$0 \le DR_{proposal}(t) \le DR_{max}(t), \forall t \in T \quad (2)$$

In this paper, user acceptance degree is assumed to be driven by DR incentive price and satisfies normal distribution as shown in equation (3):

$$Acceptance_k \sim N(\mu_k, \sigma_k^2), k = 1,2,3 \quad (3)$$

where k is type of DR proposal, which is determined by the ratio of DR proposal amount to the maximum DR proposal amount as shown in equation (4):

$$k = \begin{cases} 1,, \; 0 \le DR_{proposal}(t) \le 33\% \times DR(t)_{max} \\ 2, 33\% < DR_{proposal}(t) \le 66\% \times DR(t)_{max} \\ 3, 66\% < DR_{proposal}(t) \le 100\% \times DR(t)_{max} \end{cases} \quad (4)$$

Accordingly, based on different type of DR proposal, the incentive price is calculated by equations (5) – (6):

$$C_{DR}(\mathrm{t}) = \pi_k \times DR(t), \forall t \in T \quad (5)$$

$$\pi_k = \begin{cases} \pi_1, \; 0 \le DR_{proposal}(t) \le 33\% \times DR(t)_{max} \\ \pi_2, \; 33\% < DR_{proposal}(t) \le 66\% \times DR(t)_{max} \\ \pi_3, \; 66\% < DR_{proposal}(t) \le 100\% \times DR(t)_{max} \end{cases} \quad (6)$$

where C_{DR} is DR incentive price paid by MG according to the actual load reduction amount of user, π_k is DR incentive price based on the DR proposal ratio k. Apparently, with increment of DR proposal sent from MG system, DR incentive price also rises, results to the higher user acceptance degree to DR proposal. To sum up, the relationship between DR proposal amount, user acceptance degree and incentive price are shown in Figure 2 – 3, respectively.

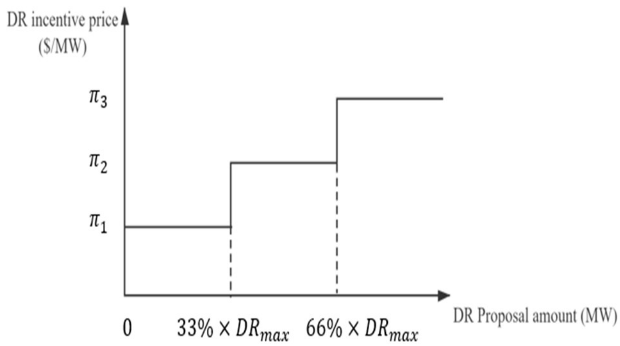

Fig. 2. DR incentive price determined by DR proposal amount

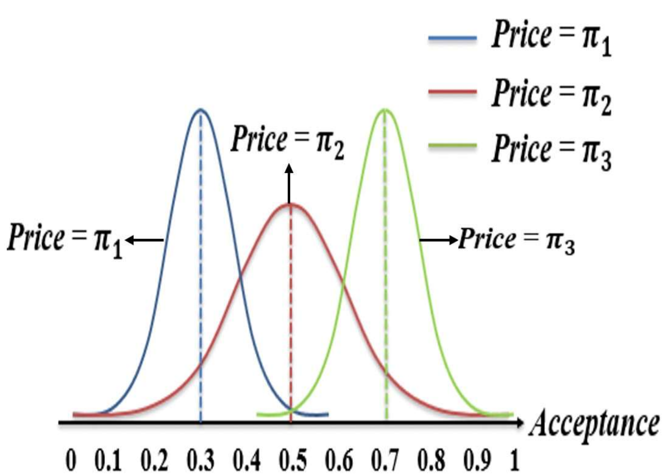

Fig. 3. User acceptance degree driven by incentive price mechanism

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B. Energy Storage Operation Model

In MG system, ES operation is finished by battery device, through efficient charging and discharging process, RES power produced during off-peak hours could charge to battery device and discharge for satisfying the load demand during peak hours. Specifically, the status of power stored in battery device could be calculated by equations (7) – (9):

$$SOC(t) = SOC(t-1) + \delta_{t-1} \times R(t-1), \forall t \in T \quad (7)$$

$$0 \le SOC(t) \le SOC_{max}, \forall t \in T \quad (8)$$

$$R_{min} \le R(t) \le R_{max}, \forall t \in T \quad (9)$$

where $SOC(t)$, $R(t)$ are remaining power amount stored in battery device, and charging/discharging power amount during the t^{th} hour, respectively. SOC_{max} is the maximum storage capacity of battery device. δ_t is a discrete variable, indicating battery device status during the t^{th} hour, where $\delta_t = 0$ when no charging/discharging power amount, $\delta_t =$ -1 when battery device is charging from RES power during off-peak hours, and $\delta_t = 1$ when battery device is discharging to MG system during peak hours. R_{min} and R_{max} are the minimum and maximum power charging/discharging rate of battery device, respectively. Besides, the ES operation cost $C_{ES}(t)$ is calculated by equation (10):

$$C_{ES}(t) = \xi \times |\delta_t \times R(t)|, \forall t \in T \quad (10)$$

where ξ is storage price of battery device.

C. Multi-objective MG Dispatch Optimization Model

In the proposed model of multi-objective MG dispatch optimization, two objectives: economic cost and environmental emission, need to be minimized simultaneously, based on above constructed DR and ES operation model, the first objective function of minimizing operation cost is calculated by equations (11) – (13):

$$Min\ F_1 = \sum_{t=1}^{T}[C_{Fu}(t) + C_{Ut}(t) + C_{DR}(t) + C_{ES}(t)] \quad (11)$$

$$C_{Fu} = \sum_{i=1}^{N}[a_i \times {P_i}^2(t) + b_i \times P_i + c_i] \quad (12)$$

$$C_{Ut} = \psi(t) \times O(t) \quad (13)$$

where $C_{Fu}(t)$ and $C_{Ut}(t)$ are fuel cost of fuel generators installed in MG system, and purchasing cost from utility power grid during the t^{th} hour, respectively. a_i, b_i and c_i are cost coefficient of the i^{th} fuel generator, $P_i(t)$ is the power output by the i^{th} fuel generator during the t^{th} hour. N is total number of fuel generator in MG system. $\psi(t)$, $O(t)$ are electricity market price, and the purchasing power amount from utility power grid during the t^{th} hour respectively.

The second objective function, which aims for minimizing the produced pollution emission for one day, is calculated by equations (14) – (16):

$$Min\ F_2 = \sum_{t=1}^{T}[E_{Fu}(t) + E_{Ut}(t)] \quad (14)$$

$$E_{Fu}(t) = \sum_{i=1}^{N}[x_i P_i^2(t) + y_i P_i(t) + z_i] \quad (15)$$

$$E_{Ut}(t) = \sum_{t=1}^{T}[\zeta \times O(t)] \quad (16)$$

where $E_{Fu}(t)$, $E_{Ut}(t)$ are emission amount produced by fuel generator and utility power grid, respectively. x_i, y_i and z_i are emission coefficient of the i^{th} fuel generator, ζ is emission coefficient of utility power grid.

In this model, the decision variable is power supply solution during each specific hour for one day, which could be presented as follows:

$$\left[P_1(t), \ldots P_i(t), O(t), DR_{proposal}(t)\right], \forall t \in T, \forall i \in N$$

where $P_i(t)$, $O(t)$, and $DR_{proposal}(t)$ indicate the power output from the i^{th} fuel generator, purchasing power amount from utility grid, and DR proposal amount sent by MG system during the t^{th} hour, respectively.

As for constraints involved in the proposed model, following conditions must be satisfied:

1. Power balance constraint: To ensure the required load demand of user during each specific hour is satisfied by the provided power supply solution, power balance constraint is shown as follows:

$$d(t) \le \sum_{i=1}^{N}[P_i(t)] + O(t) + P_{RES}(t) + R(t) \times \delta_t + DR(t), \forall t \in T \quad (17)$$

$$P_{RES}(t) = P_{Wind}(t) + P_{PV}(t) \quad (18)$$

where $d(t)$, $P_{RES}(t)$ are load demand of user, and RES power produced during the t^{th} hour, respectively. $P_{RES}(t)$ is sum of power generated from wind turbine $P_{Wind}(t)$ and solar photovoltaic $P_{PV}(t)$.

2. Ramp rate constraint of fuel generator: To ensure safety of fuel generator, the upper and down ramp rate, which limits increasing/decreasing power amount of fuel generator during two continous hours, is defined in equations (19) – (20):

$$P_i(t) - P_i(t-1) \le U_{Ri}, \forall t \in T, \forall i \in N \quad (19)$$

$$P_i(t) - P_i(t-1) \le D_{Ri}, \forall t \in T, \forall i \in N \quad (20)$$

where U_{Ri}, D_{Ri} are upper and down ramp rate of the i^{th} fuel generator, respectively.

3. Power generation capacity constraint: The power output from fuel generator and RES generator could not excess their generation capacity:

$$P_i^{Min} \le P_i(t) \le P_i^{Max}, \forall t \in T, \forall i \in N \quad (21)$$

$$O(t) \le P_{Ut}^{Max}, \forall t \in T \quad (22)$$

$$0 \le P_{Wind}(t) \le P_{Wind}^{Max}, \forall t \in T \quad (23)$$

$$0 \le P_{PV}(t) \le P_{PV}^{Max}, \forall t \in T \quad (24)$$

where P_i^{Min}, P_i^{Max} are the minimum and maximum power generation capacity of the i^{th} fuel generator, respectively. P_{Ut}^{Max} is the maximum power transferring capacity of utility power grid. P_{Wind}^{Max} and P_{PV}^{Max} are the maximum power generation capacity of wind turbine and solar photovoltaic, respectively.

III. SOLVING METHODOLOGY

In this paper, multi-objective particle swarm optimization (MOPSO) is implemented for searching the feasible and optimal power supply solution. The original particle swarm optimization (PSO), which was inspired by flocking birds and proposed in [11], is designed for solving single-objective optimization problem. To extend PSO for solving multi-objective optimization problem efficiently, it is necessary to modify it by the concept of Pareto non-dominated concept and MOPSO was proposed in [12] accordingly. Specifically, in MOPSO, the position and velocity of each particle are defined as follows:

$$x_{index}^{ite}(t) = \left[P_1(t), \ldots P_i(t), O(t), DR_{proposal}(t)\right] \quad (25)$$

$$v_{index}^{ite}(t) = \left[v_{P1}(t), \ldots v_{Pi}(t), v_O(t), v_{DRproposal}(t)\right] \quad (26)$$

$\forall t \in T, \forall i \in N, \forall ite \in [1, MaxIte], \forall index \in [1, PopSize]$

where $x_{index}^{ite}(t)$, $v_{index}^{ite}(t)$ are position and velocity of the $index^{th}$ particle during the ite^{th} itereation of the t^{th} hour, respectively. $MaxIte$ and $PopSize$ are the maximum iteration number and particle population size, respectively.

The updating equation of particle velocity and position are shown in equations (27) – (28):

$$v_{index}^{ite+1}(t) = \omega v_{index}^{ite}(t) + c_1 r_1 \left(pbest_{index}^{ite}(t) - x_{ind}^{ite}\ \ (t)\right)$$

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$$+c_2 r_2 \left(gbest^{ite}(t) - x_{index}^{ite}(t)\right) \quad (27)$$

$$x_{index}^{ite+1}(t) = x_{index}^{ite}(t) + v_{index}^{ite+1}(t) \quad (28)$$

where $pbest_{index}^{ite}(t)$,$gbest^{ite}(t)$ are personal best position searched by the $index^{th}$ particle, and global best position searched by whole population during the ite^{th} itereation for the t^{th} hour, respectively. c_1,c_2 are acceleration factors of personal best and global best position, respectively. r_1, r_2 are random value within the range of [0,1]. ω is weight factor of particle itself during the current iteration, to balance exploitation and exploration ability of whole population well, it is updated by equation (29) over iterations:

$$\omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{MaxIteration} \times ite \quad (29)$$

Based on above encoding scheme, the procedure of implementing MOPSO to search feasible and optimal MG power supply solution for one day is shown in Figure 4.

IV. EXPERIMENTAL PREPARATION

A. Uncertain Solar Photovoltaic Power Simulation

The power output from solar photovoltaic could be simulated by following equations [13]:

$$P_{PV}(t) = P_{PV}^{Max} \times \frac{I_S(t)}{1000}\left(1 + \gamma(T_c(t) - 25)\right), \forall t \in T \quad (30)$$

$$T_c(t) = T_\gamma(t) + \frac{I_S(t)}{800} \times (T_N(t) - 20), \forall t \in T \quad (31)$$

where $I_S(t)$, $T_c(t)$ are solar irradiance, and photovoltaic cell temperature during the t^{th} hour, respectively. γ is temperature coefficient of solar photovoltaic cell, $T_\gamma(t)$ and $T_N(t)$ are ambient temperature, and ambient temperature based on the photovoltaic cell's nominal operating cell temperature, respectively. To simulate uncertain soalr irradiance during one day efficiently, normal distribution is utilized, where the probability density function (PDF) is shown in equation (32):

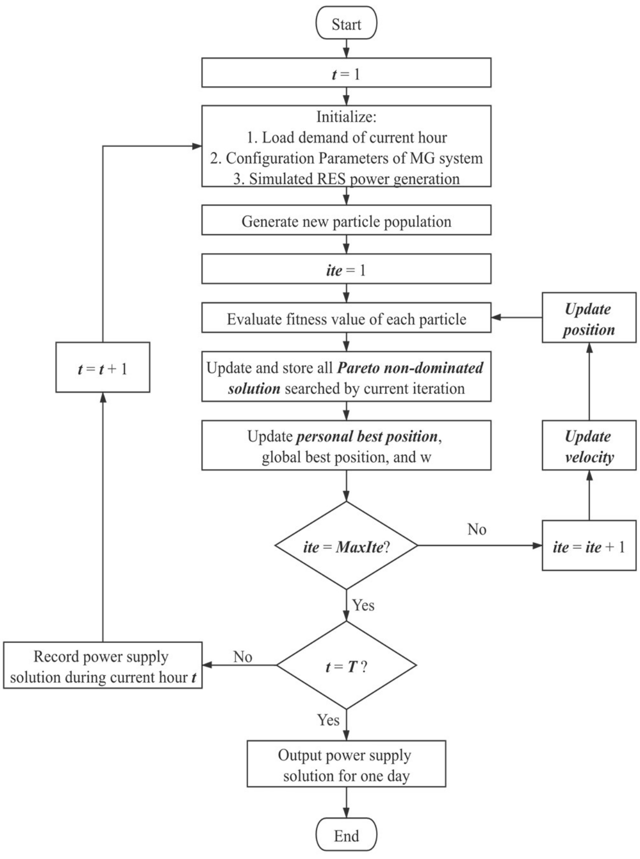

Fig. 4. Procedure of implemented MOPSO

$$f(I_s(t)) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\left(-(I_S(t)-\mu)\right)^2/2\sigma^2}, \forall t \in T \quad (32)$$

where μ , σ are mean and variance of solar irradiance, respectively.

B. Uncertain Wind Power Simulation

The uncertain wind power output from wind turbine could be simulated by following equations [14]:

$$P_W(t) = \begin{cases} 0, & if\ v(t) < v_{in}\ or\ v(t) > v_{out} \\ \frac{v(t) - v_{in}}{v_r - v_{in}} \times P_{Wind}^{Max}, & if\ v_{in} \le v(t) < v_r \\ P_{Wr} & if\ v_r \le v(t) \le v_{out} \end{cases}, \forall t \in T$$

……………………………………………………………(33)

where v_r, v_{in} and v_{out} are rated speed, lower and upper feasible wind speed, respectively. The Weibull distribution function is utilized for simulating the uncertain wind speed $v(t)$, where the PDF is shwon as equation (34):

$$f(v(t)) = \frac{k}{c}\left(\frac{v(t)}{c}\right)^{k-1} e^{\left[-\left(\frac{v(t)}{c}\right)^k\right]}, \forall t \in T \quad (34)$$

where k, c are shape factor and scale factor, respectively.

C. MG System Configuration

In this paper, a potential applied scenario of MG system is simulated for verifying the effectiveness of proposed model. The load demand of user for one day is plotted in Figure 5. The configuration parameters of fuel generator and RES generator are listed in Table I–III, respectively. The parameters of DR operation policy, utilized battery device, and utility power grid are listed in Table IV–VI, respectively.

TABLE I
COEFFICIENT OF FUEL GENERATOR

Type	Cost Coefficient	Emission Coefficient
T1	0.0096, 5, 100	0.012, 8, 120
T2	0.01, 8, 105	0.006, 6, 100

TABLE II
POWER GENERATION CAPACITY OF FUEL GENERATOR

Type	Ramp Rate (MW)	Maximum Capacity (MW)	Minimum Capacity (MW)
T1	[60, 60]	400	150
T2	[50,50]	300	150

TABLE III
POWER GENERATION CAPACITY OF RES GENERATOR

Type	Maximum Capacity (MW)	Minimum Capacity (MW)
Wind Turbine	50	0
Solar Photovoltaic	70	0

TABLE IV
PARAMETERS OF DR OPERATION POLICY

Maximum DR Proposal (MW)	DR Proposal Range (MW)	Incentive Price ($/MW)	User Acceptance (Normal Distribution)
300	[0,99]	4	$N(0.35,\ 0.116^2)$
	(99,198]	7	$N(0.5,\ 0.167^2)$
	(198,300]	10	$N(0.65,\ 0.116^2)$

TABLE V
PARAMETERS OF BATTERY DEVICE

Capacity (MW)	Charging Rate (MW)	Discharging Rate (MW)	Storage Price ($/MW)
300	50	50	5

TABLE VI
CONFIGURATION PARAMETERS OF UTILITY POWER GRID

Capacity (MW)	Electricity Market price($/MW)		Emission Coefficient (kg/MW)
	Peak Hours	Off-peak Hours	
500	25	18	120

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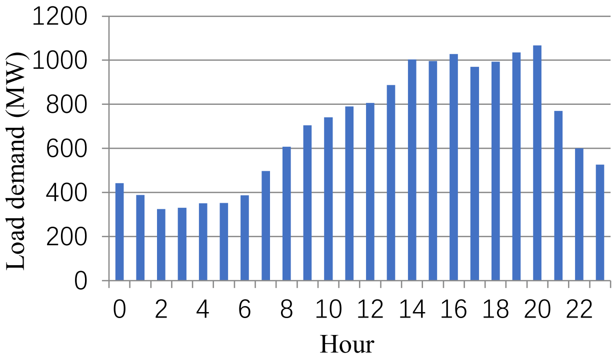

Fig. 5. Load demand of user for one day

V. EXPERIMENT RESULTS

In the experiments designed by this paper, the built multi-objective MG dispatch optimization is performed 30 times for obtaining the performance after introducing DR and ES operations. Table VII gives average performance comparison obtained by power supply solutions of without and with DR/ES's operations, in terms of load demand, operation cost and pollution emission, respectively. It could be found that after introducing DR and ES operations into MG system, the load demand needed to be satisfied decreases from 16593 MW to 14564 MW efficiently with 12.2% reduction, which means those two operations are beneficial for improving reliability of power supply process. Moreover, both of operation cost and pollution emission reduce apparently, where operation cost decreases from 174831 \$ to 166579 \$ with 4.7% reduction, and pollution emission decreases from 391011 kg to 372964 kg with 4.6% reduction.

Figure 6 plots the load demand and power supply solution for one specific day, while the detailed power output composition comparison from different sources during night hours and day hours are given in Table VII – VIII, respectively. From above results, it could be found that during night hours with less load demand than day hours, the power output from fuel generator T2 (38%) is higher than the power output from T1 generator (35%), however, during day hours with more load demand, the power output from T1 generator (32%) is higher than it from T2 generator (30%). As for reason analysis, on the one hand, since the load demand of user and electricity market price of utility power grid during some night hours are at a low level, for reducing pollution emission efficiently, power output from T2 generator with less emission coefficient is much than it from T1 generator. On the other hand, when load demand increases obviously during day hours, T1 generator with larger generation capacity needs to produce more power for ensuring the power balance constraint is satisfied. Besides, it could be found that with the increasement of load demand, the load demand reduction amount caused by DR operation, and the purchasing power from utility power grid also arise accordingly. Furthermore, the generated RES power is at

TABLE VII
AVERAGE COST AND EMISSION COMPARISON

Operation	Load Demand (MW)	Operation Cost (\$)	Pollution Emission (kg)
Without DR and ES	16593	174831	391011
With DR and ES	14564 **(-12.2%)**	166579 **(-4.7%)**	372964 **(-4.6%)**

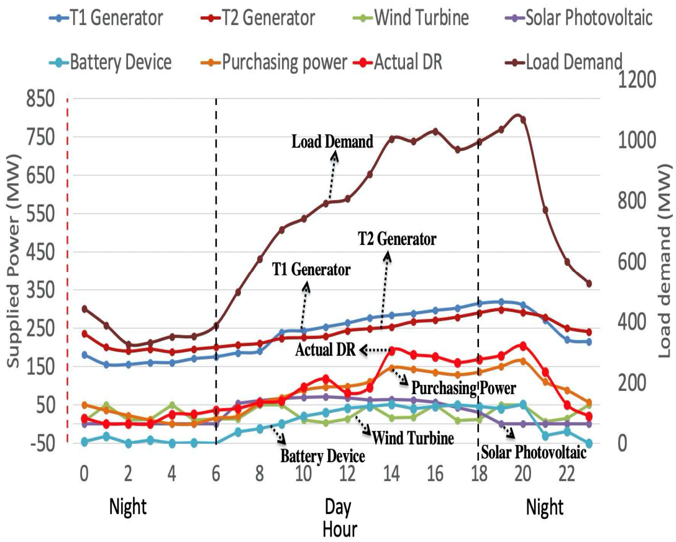

Fig. 6. Load demand and power supply solution for one specific day

TABLE VII
DETAILED POWER COMPOSITION DURING NIGHT HOURS

Source	Output Composition
T1 Generator	35%
T2 Generator	38%
Wind Turbine	4%
Solar Photovoltaic	1%
Battery Device	0%
Utility Power Grid	11%
Demand Response	11%

TABLE VIII
DETAILED POWER COMPOSITION DURING DAY HOURS

Source	Output Composition
T1 Generator	32%
T2 Generator	30%
Wind Turbine	3%
Solar Photovoltaic	7%
Battery Device	2%
Utility Power Grid	12%
Demand Response	14%

charging status to battery device during off-peak hours, while during peak hours, power stored in battery device could discharge to MG system for compensating the required demand, so that both of operation cost and pollution emission reduce efficiently.

VI. CONCLUSION AND FUTURE WORK

To response the challenges of modern MG system efficiently, this paper constructs a comprehensive model of multi-objective MG dispatch optimization by introducing DR operation based on peak clipping technology and incentive price mechanism, as well as ES operation. Besides, MOPSO is implemented for searching feasible and optimal power supply solution with the minimum cost and emission simultaneously. Under uncertain RES power generation, experiment results have demonstrated the effectiveness of proposed DR and ES operation in terms of better reliability, less operation cost and pollution emission.

In future, more practical technologies of DR operation, such as load shifting, valley filling and strategic growth, etc., could be introduced into MG system, and vairous kinds of battery devices also could be combined to exploit the benefits of ES operation furthermore.

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Sicheng Hou He received the B.E. Degree from ShaanXi Normal University, China, in 2018, and the M.E. Degree from Waseda University, Japan, in 2020. He is currently pursuing the Ph.D. degree at the Graduate School of Information, Production and Systems, Waseda University. His research interests include swarm intelligence algorithm, multi-objective and multi-model optimization application.

Tomohiro Murata He is a professor at the Graduate School of Information, Production and Systems, Waseda University, Japan. He received the PhD degree in System engineering from Tokyo Institute of Technology, Japan, in 1989. He had been worked for Systems Development Laboratory, Hitachi, Ltd as a senior researcher. His research interests include modeling and development of decision support systems, methodologies of multi-objective programming, and product information management.