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Reliable and Environmental Economic Dispatch in a Microgrid with Renewable Energy Sources

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***Abstract*—This paper contrasts the Genetic Algorithm (GA) strategies to solve the problem of Economic Dispatch (ED) in a Microgrid (MG). An environmental ED strategy for MG is proposed through maintaining the system reliability requirements at acceptable level. Two additional cost terms such as the CO_2 emission penalties and load curtailment charges are added to the traditional objective function of the ED problem. Also, cost and reserve supply of the network are considered. Since the load curtailment cost is highly dependent to the network reliability indices, specifically those determining network inability to supply demand, the Expected Energy Not Served (EENS) reliability index is used to calculate the curtailment costs. By illustrating the advantages of Inherit Based Genetic Algorithm (IBGA) over the other two strategies, namely Simple Genetic Algorithm (SGA) and 3-matrices Genetic Algorithm (3MGA), IBGA is used to solve the proposed Reliable, Environmental Economic Dispatch (REED) problem in a MG.**

***Index Terms*--Environmental/economic dispatch, Micro grid, Reliability, Renewable energy sources (RESs), Genetic algorithm.**

I. INTRODUCTION

Combining various energy sources in an efficient way, MGs supply local loads, operable in on and off-grid systems. These controllable, renewable subsystems generate power from the Distributed Energy Resources (DERs) [1]. The MGs were first developed by the Consortium for Electric Reliability Technology Solutions (CERTS) [2]. The conventional ED finds out the generation output power [3, 4] in such a way that the total cost of generation is minimized and the system constraints are not violated. However, it is worth noting that the conventional ED does not satisfy the entire requirements of today's environmental protection policies and is not appropriate for MGs with RESs owing to the fact that only the fuel cost is minimized. As a consequence, there is a need for a dispatch which takes the minimization of both economic and emission impacts into account (i.e. economic/emission dispatch) [5-8].

As gas emission has unsuitable effects on the environment [9], this term is also considered to be minimized in objective function [10-14]. Moreover, Ref. [15] minimizes the global warming potential of different emissions. Aydin et al. solved the combined economic and NOx emission dispatch problem by minimizing the objective function (OF) combined with the weighted sum method (WSM) considering the system constraints [16].

In this paper, power scheduling of DERs in MGs with RESs is implemented with the aim of minimizing the total cost of generation and reducing the amount of emissions and maintaining the system loss of load probability as low as possible. Unlike other schemes in this field, the proposed method accommodates the emission and reliability terms as the objective function to be minimized, instead of constraints to be satisfied. Moreover, price penalty factor approach is used to compute the emission costs. To acquire the loss of load probability, EENS [17-21] as an efficient reliability index is applied knowing the Capacity Outage Probability Tables (COPTs) of the generating units. The proposed COPT of the wind unit is obtained from the multi-state discrete model of the wind output power elicited from its corresponding Weibull distribution. The valve-point effect [22, 23] is also considered in the cost function of generators. The proposed REED is executed by the IBGA proved to be the most efficient among the three GAs evaluated namely SGA, 3MGA and IBGA.

II. MATHEMATICAL FORMATION OF THE PROPOSED REED

In this section, the proposed objective function for the reliable and environmental economic dispatch of a MG DERs is presented. The optimization problem is formulated as follows:

$$Min\ f_T \tag{1}$$

$$s.t:$$

< power balance constraint>

< generators' capacity and reserve limit constraint>

Proposed Objective function terms

The objective function consists of different cost terms containing generation cost, CO2 emission penalty cost, and loss of load cost:

$$f_T = w_1.f_{Gen} + w_2.f_{Em} + w_3.f_R \tag{2}$$

where:

wi: Weighting coefficients,

f_{Gen}: Total cost of generation for demand and reserve supply,

f_{EM}: Total costs imposed to generating units as penalties for their amount of CO2 emission, and

f_R: Total expected cost due to the amount of energy not served.

A.1. Generation cost

The power generation cost of units corresponding to their output power scheduled for supplying main demand and reserve for an operating point of the system are added, respectively.

$$\begin{aligned} f_{Gen} &= f_{Gen}^{d} + f_{Gen}^{res} \\ &= \sum_{i=1}^{n_{Gen}} \left\{ \begin{aligned} &\left(a_i + b_i.PG_i + c_i.PG_i^{\,2}\right) + \\ &\left| e_i.\sin\left(f_i.\left[PG_i^{\min} - PG_i\right]\right)\right| \end{aligned} \right\} \\ &+ \sum_{j\in\psi_{\mathrm{Res}}} \left\{ r1_j + r2_j\, PG_i^{\mathrm{Res}} \right\} \end{aligned} \tag{3}$$

where f_{Gen}^{d} and f_{Gen}^{res} are quadratic and linear functions corresponding to the cost of generating units for supplying main load and reserve, respectively and a_i, b_i, c_i, e_i, f_i, $r1$, and $r2$ are their corresponding coefficients.

A.2. CO2 emission penalty costs

The cost of CO2 emission imposed to the generating units is calculated using the price penalty factor approach proposed in [13]. According to the approach, the cost function of emission for utilities is calculated as follows:

$$f_{Em} = pf_n \cdot \left\{ \sum_{i=1}^{n_{Gen}} \left(\alpha_i + \beta_i.PG_i + \gamma_i.PG_i^2 \right) \right\} \tag{4}$$

Where f_{Em} is the total emission cost of utilities, α, β, γ are coefficients of the quadratic relationship between the output power and the amount of Co2 emission by utilities, and pfn is the common penalty factor obtained according to the bellow procedure:

- $pf_n[i]$ of the ith DER is calculated as:

$$Pfn[i] = \frac{\sum_{i=1}^{n_{Gen}} \left(a_i + b_i \times PG_{i\max} + c_i \times PG_{i\max}^2 \right)}{\sum_{i=1}^{n_{Gen}} \left(\alpha_i + \beta_i \times PG_{i\max} + \gamma_i \times PG_{i\max}^2 \right)} \tag{5}$$

- The values of pfn_i are arranged in ascending order. Then, the demand supply process is started from the generator with the smallest pfn_i. The pfn_i of the last generator which satisfies the equation (6) is considered as the pf_n.

$$\sum PG_{i\max} \geq PD \tag{6}$$

A.3. Expected energy not served cost

The EENS of a set of generators with known Capacity Outage Probability Tables (COPTs) scheduled to supply the demand for a given operating point is calculated by first constructing the collective COPT of the appointed generating units and then adding up the weighted amount of the energy not served corresponding to the COPT states with a possible loss of load.

$$\begin{aligned} EENS_{PD} &= \sum_{o\in\Omega_{PD}} \left(P_D - P_o^{avail} \right).\mathrm{Pr}_o \\ f_R &= EENS_{PD} \times c_{lol} \end{aligned} \tag{7}$$

where Ω_{PD} is the set of COPT states O with their available capacities (P_o^{avail}) below the demand power (P_D) and consequently leading to a possible loss of load, Pr_o is the probability of the state O and c_{lol} is the per-unit loss of load cost.

Constraints

B.1. Power balance constraints

$$\sum_{i=1}^{n_{Gen}} PG_i - P_D - P_{loss} = 0 \tag{8}$$

where P_D and P_{loss} are the demand and loss of the MG for a given operating point, respectively. The virtual generator 1 which is modeled as the main network power transfer with the MG, is considered as the slack bus, and consequently its output power is equal to the amount of power required to balance the generation, demand, and loss of the MG. It is common practice to express the network loss as a quadratic function of the generator power outputs through B-coefficients namely Kron's loss formula.

$$p_{loss} = \sum_{i=1}^{n_{Gen}} \sum_{j=1}^{n_{Gen}} PG_i B_{ij} PG_j + \sum_{i=1}^{n} B_{0j} PG_i + B_{00} \tag{9}$$

where B_{ij} are loss coefficients with units MW^{-1}. They can be regrouped to form a symmetrical square matrix of dimension $N \times N$. Unit of B_{oo} matches that of P_L and it contains a single element while units of B_{oi} are dimensionless and elements of B_{oi} form $1 \times N$ matrix. Substituting (9) in (8) and rearranging the equation (8) on the PG_1, the following equation will be obtained:

$$\begin{aligned} &B_{11} PG_1^2 + \left(2\sum_{i=2}^{n} B_{1i} PG_i + B_{0i} - 1 \right) PG_1 \\ &+ \left(P_D + \sum_{i=2}^{n} \sum_{j=2}^{n} PG_i B_{ij} PG_j + \sum_{i=2}^{n} B_{0i} PG_i - \sum_{i=2}^{n} PG_i + B_{00} \right) = 0 \end{aligned} \tag{10}$$

Solving the quadratic equation (10) for PG_1, positive roots of the equation are considered as the feasible amount of output power for generator 1:

$$PG_1 = \frac{-Y \pm \sqrt{Y^2 - 4XZ}}{2X} \tag{11}$$

where:

$$\begin{cases} X = B_{11} \\ Y = \left(2\sum_{i=2}^{n} B_{1i} PG_i + B_{0i} - 1 \right) \\ Z = \left(P_D + \sum_{i=2}^{n} \sum_{j=2}^{n} PG_i B_{ij} PG_j + \sum_{i=2}^{n} B_{0i} PG_i - \sum_{i=2}^{n} PG_i + B_{00} \right) \end{cases} \tag{12}$$

B.2. DERs capacity and reserve limit constraints

The scheduled output power corresponding to the DERs for demand and reserve supply must be within their limits, respectively.

$$PG_{i,\min} \leq PG_i \leq PG_{i,\max} \tag{13}$$

$$PG_{i,\min}^{\mathrm{Res}} \leq PG_i^{\mathrm{Res}} \leq PG_{i,\max}^{\mathrm{Res}} \tag{14}$$

III. GA APPLICATION TO ED PROBLEMS

A. Review of simple GA

So far, GA looks for the best solution among some possible solutions represented by one point in the search space. GA attacks to population of possible solutions. GA raises a couple of important features. First, it is a stochastic algorithm; randomness plays an essential role in GAs which both selection and reproduction need random procedures. Second, GA always deals with a population of solutions. Doing so, keeping in memory more than a single solution at each iteration offers many advantages.

Theoretically and empirically speaking, GA has been proven to provide robust search in complex spaces. Numerous literature substantiate the validity of the technique in optimization and control applications. Most of the GA works are based on the Goldberg's SGA framework. Typically, SGA consists of the steps named Creation of initial Population, Evaluation, Selection, Crossover, Mutation, and Replacement.

B. GA in ED problems

In this paper, three GA methods have been used for ED propose. The used methods are SGA, IBGA, and 3MGA which are distinguished by cross over and mutation steps. As a first step to apply GA for the ED problem of a MG, it is necessary to build up the chromosomes in a sensible manner.

Hence, each chromosome contains two parts: the first part corresponds with the DERs' scheduled powers and the second part correlates about the reserve powers supplied by responsible units. Each chromosome's gen index depends on the number of DER units and the number of units which are responsible for reserve generation.

The algorithm is ceased when the convergence of population satisfied toward the optimal solution or environmental criteria such as time or iteration number.

Creating initial population: To generate the initial population, a population which has ten times expander size in compare of initial population is created randomly. In all the chromosomes, first gen and the last gen represent the transferred power between MG and main network and the output power of a unit responsible for reserve generation balance, respectively. Consequently, their values are calculated based on the power and the reserve balance equalities, respectively. By building up the chromosomes, ones with their first and last genes within limits are accepted chromosomes from which the first population is formed.

Evaluation: The fitness value of all chromosomes is calculated, and chromosomes are sorted.

Selection: N_{keep} best chromosomes are selected for cross over.

Cross over: The IGA is used to combine different values from two parents into new values in the descendent. Two selected parents are called as dad and mother parent. So, two pointers are produced randomly whose point out to the exact place of variables which should be changed. In the first offspring, variables before the first pointer are exactly propagated from father parent.

Likewise, the variables after the second pointer are propagated from mother parent (Similarly, in second offspring variables before the first pointer are exactly propagated from mother parent, and the variables after the second pointer are propagated from father parent.). In both offsprings, the variables between two pointers are produced in a way that, offspring could inherit properties of both mother and father. To do so, the variables between two pointers are produced according to equation (15) and (16).

$$P_{new\,1} = P_{mn} - \beta\left(P_{mn} - P_{dn}\right) \tag{15}$$

$$P_{new\,2} = P_{dn} + \beta\left(P_{mn} - P_{dn}\right) \tag{16}$$

Where β is a random number within the interval [0, 1], P_{mn}, and P_{dn} are the nth variable in the mother and father chromosome, respectively. Also, $P_{new\,1}$ and $P_{new\,2}$ represent the nth value of the first and second offspring, respectively.

Mutation: A gen of each offspring is changed randomly while maintaining the power and reserve balance constraints.

Replacement: After generating new offspring, the fitness of offsprings is calculated, and selected offspring are replaced by chromosomes with low fitness in population matrix.

IV. EVALUATION OF THE DIFFERENT GA STRATEGIES APPLIED TO A SIMPLE ED

In this section, three different strategies for cross over and mutation of GA are used and evaluated by applying them to the MG power scheduling problem. The strategies are SGA, IBGA and 3MGA. The performance of the methods is evaluated based on different factors, namely the calculation run-time, objective function value, and consistency of the power scheduling results. Table I shows the simulation data used for the different GAs.

The simulation has been implied on a simple MG with five DERs, four diesel generators, and micro turbines connected to the buses 2-5 and a wind unit connected to the bus 6. The main network is modeled with a generator connected to the bus 1 which is considered as the slack bus of the micro grid. Cost coefficients and capacity limits of DERs are illustrated in Table II. The loss of load charge (c_{lol}) is supposed to be 1000 \$/MW. B-coefficients matrix which are necessary for power balance constraint, are as below.

$$B = \begin{bmatrix} 0.4355 & -0.1694 & 0.1482 & -0.2684 & -0.0925 \\ -0.1694 & 0.2366 & -0.0247 & -0.0061 & -0.0689 \\ 0.1482 & -0.0247 & 0.1636 & -0.2391 & -0.1046 \\ -0.2684 & -0.0061 & -.02391 & 0.6517 & 0.1987 \\ -0.0925 & -0.0689 & -0.1046 & 0.1987 & 0.1864 \end{bmatrix} \tag{17}$$

$$B_{0i} = \begin{bmatrix} -0.0326 & -0.0314 & 0.0057 & -0.0018 & 0.0005 \end{bmatrix} \tag{18}$$

$$B_{00} = \begin{bmatrix} 0.0014 \end{bmatrix} \tag{19}$$

TABLE I. SIMULATION DATA FOR DIFFERENT GA METHODS

Pop size	**Iteration**	N_{keep}
60	200	0.4

TABLE II. DERS DATA

parameters	Unit types and connected bus numbers					
	Main net.	DG1	DG2	DG3	DG4	wind
	1	2	3	4	5	6
a_i	10.193	2.035	0.5768	1.1825	0.338	-
b_i	105.18	60.28	57.783	65.34	89.1476	60
c_i	62.56	44	-133.0915	44	-547.619	-
e_i	50	50	40	20	-	-
f_i	12	6.3	9.8	4	-	-
$r1_i$	3	3.5	2.5	2.5	-	-
$r2_i$	100	190	320	320	-	-
α_i	0.0126	0.00693	0.01375	0.00765	0.00693	-
β_i	-1.355	-1.302	-1.249	-0.805	-0.902	-
γ_i	22.983	65.51	137.37	330.70	365.51	-
$PG_{i,max}$	500	200	80	100	30	133.5
$PG_{i,min}$	0	40	16	20	6	0
FOR_i	0.05	0.01	0.15	0.1	0.02	multi-state model

To simplify the comparison process, only the generation cost term is considered in the objective function of the power scheduling problem and also wind unit is disconnected from the micro grid. The results of three different methods of GA are shown in tables III-V. According to the tables, IBGA algorithm has three main advantages over the other two methods. First, the cost of IBGA for each run is the lowest. Second, the allocated power of DERs in each run does not change so much. Third, the run time of IBGA is less than 3MGA. However, the run time of SGA is slightly less than IBGA which may be ignored because the ED does not require real-time calculation.

V. NUMERICAL EVALUATION OF THE PROPOSED REED METHOD

In this section as described above, the effects of the different factors on power scheduling results of the MGs with RESs and their consequent costs are studied by changing the weighting coefficients of the generation, emission, and reliability cost terms in the proposed objective function.

According to Table VI, by increasing the influence of generation cost, a series of events happen: a reduction in the production of DG units, an increase in production of wind unit, a reduction in cost of generation, and an increase in the cost of reliability.

The up and downs in results confirms that the wind unit is not a reliable unit and has no emission. Therefore, by augmenting the influence of generation cost, the total cost is increased extensively due to high production of wind unit and the increment of load loss. In Table VII, by enhancing the influence of penalty cost of emission, DG units -especially units with high emission- decrease their production and subsequently, wind unit boosts its production for supplying main demand and reserve. Also, the cost of reliability term is raised since the wind unit is not a reliable one and afterwards, the total cost goes up because of low reliability of wind unit. In Table VIII, similar to the previous table, the increase in the influence of reliability term reduces the production and the cost of reliability term. DG units enhance their production for supplying main demand and reserve so the cost of generation is increased.

Due to high uncertainty production of RES, which results in high load loss and subsequently the inflected cost of load loss, the term of reliability should be considered for ED in MGs because the total paid cost rises if the reliability term is not considered.

TABLE III. ED WITH IBGA

Run number	Main net.	DG1	DG2	DG3	DG4	Res.3	Res.4	Res.5	Cost($)	Time
1	0	121.8	78.9	41.3	6.1	0.98	0.12	23.69	31.31	40.2
2	0	117.26	79.95	44.73	6.1	0.02	1.13	23.64	31.37	39.88
3	0	109.76	78.8	53.2	6.3	0.7	0.8	23.3	31.39	48.5
4	0	100.19	79.59	62.3	6.2	0.2	0.8	23.75	31.37	43.3
5	0	108.17	79.19	54.7	6.1	0.45	0.5	23.84	31.33	45.45

TABLE IV. ED WITH SGA

Run number	Main net.	DG1	DG2	DG3	DG4	Res.3	Res.4	Res.5	Cost($)	Time
1	0	91.5	74.1	74.4	8.9	3.7	0	21.1	31.63	38
2	0	76.96	71.9	91.75	9.6	4.4	0	20.36	31.88	41.37
3	0	84.5	74.4	82	8.6	3.4	0	21.4	31.68	39.46
4	0	71.2	71.5	99.5	8.8	3.5	0	21.2	31.98	43.3
5	0	88.3	63.1	89.4	9.5	4.3	0	20.46	32.12	42.9

TABLE V. ED WITH 3MATRIXES GENETIC ALGORITHM

Run number	Main net.	DG1	DG2	DG3	DG4	Res.3	Res.4	Res.5	Cost($)	Time
1	0	77.9	78.8	86.8	6	0.35	0.5	23.9	31.55	48.48
2	0	88.9	76.5	75.9	7.5	1.35	0.98	22.45	31.69	48.5
3	0	76.4	79.1	87.3	6.8	0.7	0.9	23.2	31.65	49
4	0	102.8	77.4	60.8	7.2	1.6	0.7	22.5	31.56	49
5	0	90.7	78.8	72.8	6.4	0.7	0.5	23.6	31.48	49

TABLE VI. THE INCREASE IN THE INFLUENCE OF THE GENERATOR AND RESERVE COSTS

W_1 (W_2=W_3=1)	f_{Gen}^{d}	f_{Gen}^{res}	f_{Em}	f_R	**FT**
1	30.1705	13.5724	3.5461	7.3003	54.5893
5	28.7315	13.3687	3.2602	9.3399	54.7003
7	30.0681	13.9637	2.2226	11.5972	57.8516
10	26.7698	14.1993	1.5371	20.0296	62.5358
15	25.5295	14.6756	1.1911	28.0598	69.456

TABLE VII. THE INCREASE IN THE INFLUENCE OF THE EMISSION COST

W_2 (W_1=W_3=1)	f_{Gen}^{d}	f_{Gen}^{res}	f_{Em}	f_R	**FT**
0	30.7456	13.5481	3.5890	7.9743	55.857
1	30.1705	13.5724	3.5461	7.3003	54.5893
5	32.0230	14.4862	2.0020	14.4862	62.9974
7	33.1129	13.8371	1.7100	11.2222	59.8822
10	32.3153	14.6588	1.5690	12.1483	60.6914

TABLE VIII. THE INCREASE IN THE INFLUENCE OF THE EENS COST

W_3 (W_1=W_2=1)	f_{Gen}^{d}	f_{Gen}^{res}	f_{Em}	f_R	**FT**
0	27.4041	14.1175	1.0904	26.9250	69.537
1	30.1705	13.5724	3.5461	7.3003	54.5893
5	41.1128	13.3861	2.1277	2.9809	59.6075
7	42.7397	14.3487	2.3200	2.6850	62.0934
10	44.5455	13.4183	2.4297	1.9710	62.3645

Subsequently, the output powers of each unit with respect to their related cost influences are shown for five cases (Fig. 1-3).

In Fig. 1, by extending the influence of generation cost, the production of units 2 and 3 is restricted to their minimum generation capacity based on high generation costs of mentioned units.

In contrast to unit 4, unit 5 does not slow down its production because this unit has the minimum generation cost and it produces its maximum generation capacity. It is obvious that the wind unit should enhance its production capacity for supplying main demand and reserve.

In Fig. 2, by penetrating the high influence of emission penalty cost, the wind without emission enhances its production. Adversely, units 3 and 4 lessen their production to minimum generation capacity because of their high emission. Unit 5 does not significantly reduce its production because the cost of generation for aforementioned unit is lower than others and its maximum capacity is modest so it does not have high emission. At last, the production of unit 2 falls for supplying main demand and reserve due to its slighter emission production.

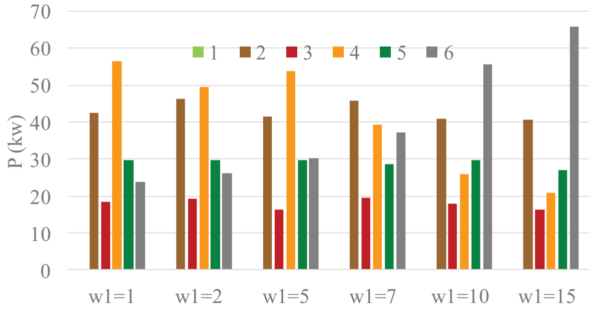

Figure 1. The output power of each unit with respect to the influence of generator and reserve cost for five cases.

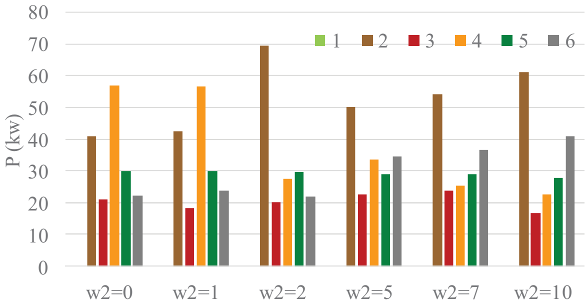

Figure 2. The output power of each unit with respect to the influence of emission cost for five cases.

In Fig. 3, by enhancing the influence of reliability term, the production of wind unit decreased intensively because of its trivial reliability. Unlike wind unit, the production of unit 2 rises for supplying main demand and reserve regarding this unit has better reliability than other units. Also, unit 5 approximately operates at its maximum generation capacity considering this unit has the acceptable reliability and in return, units 4 and 3 produce their minimum generation capacity due to their low reliability.

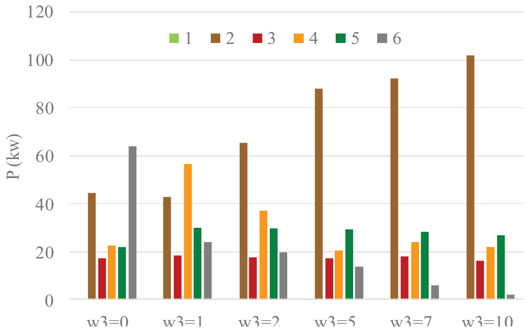

Figure 3. The output power of each unit with respect to the influence of EENS cost for five cases.

VI. CONCLUSION

In this paper, first the main features of different GA strategies are evaluated and compared by applying them to a simple traditional ED problem. The variation in allocated power of each DER unit with reserve cost variation proves the efficiency of IBGA. Then different cost terms containing generation cost, CO_2 emission penalty cost, and cost of load loss are added to the objective function and different cases are discussed. The comparisons among three algorithms of SGA, IBGA, and three matrices GA revealed that IBGA has three consequential advantages over other two methods; first, the cost of IBGA for each run is the least. Second, the allocated power of DERs in each run does not deviate eminently. Third, the run time of IBGA is minor than 3MGA. However, the run time of SGA is slightly less than IBGA, which may be ignored based on the offline calculation of ED. Then, the proposed REED method is applied to dispatch the DERs of a simple MG efficiently in response to its demand with four traditional diesel generators or micro turbines and a wind unit. The results illustrate that due to the high uncertainty production of RES (which results in high load loss and subsequently the inflected cost of load loss), the term of reliability should be considered for ED in MGs because the total paid cost rises if the reliability term is not considered.

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