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Optimal Generation Schedule in Micro-Grids Considering the Possible Damage by Uncertainties of Forecasts

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Abstract: The optimal generation schedule of controllable generators is necessary considering both the supply-demand balancing and the economy of generation. The conventional methods minimize the operation cost with a constraint to guarantee that the operating generators can readily change their outputs to meet the demand variation. Installation of nature-affected generations such as wind turbines and photovoltaic generation makes it harder for operating generators to compensate the variation, because their forecasts contain significant errors. In this research, the damage caused by possible supply-demand imbalance arising from the large uncertainties of forecasts is evaluated by penalty which represents the necessary additional cost to fix the imbalance. Due to the random nature of the forecast errors, the penalty is evaluated as an expectation. The optimal generation schedule is obtained by minimizing the summation of expectation of penalty and the operation cost. The simulation results indicate that the proposed method can achieve the generation schedule with less total cost than the conventional methods.

Keywords: Micro-grid, Penalty, Adaptability, Uncertainty of forecast

1. Introduction

The installation of renewable energy devices is increasing in recent years. However, the fluctuation and uncertainty of distributed renewable energy generations' outputs increase the difficulty to ensure the power supply-demand balance when they are connected to the power grids. One solution is to take a hierarchical approach and to view some generation equipment and associated loads as a subsystem or a micro-grid[1]. Generally, the micro-grid could consist of distributed renewable energy generations such as the photovoltaic (PV) generations and wind turbines, the controllable generators such as diesel engine generators and fuel cell, the loads, and the energy storages. The micro-grid tries to keep its own power supply-demand balance, which reduces the effect of uncertainty of distributed renewable energy generations' outputs to the main grid. Therefore, the economical generation scheduling of controllable generators in the micro-grid becomes an essential problem. Several methods have been put forward to achieve the optimal generation schedule of controllable generators in the micro-grid, which are reviewed in [2)-5)].

In this paper, we take the micro-grid power system which consists of the PV generations, the controllable generators, and the loads as an example. The net power demand, which is to be generated by the controllable generators, is the difference between load demand and PV outputs. The demand forecasts and PV output forecasts are with errors or uncertainties, which may cause the imbalance of power system. In order to avoid the damage caused by the possible imbalance of power, some researchers plan the generation schedule with the spinning reserve for the possible shortage of power supply so that an extra generating capacity is available by increasing the power outputs of controllable generators that have already been started up[6]. Due to the existence of PV devices, there are also situations where the actual net demand becomes significantly smaller than the forecasted net demand. Therefore some researchers also introduce the spinning reserve for the possible excess of power supply so that certain generation can be reduced by decreasing the outputs of controllable generators that have already been started up[7]. The spinning reserves for the possible shortage and excess of power are used to prevent the micro-grid from the damage by possible imbalance in micro-grid. In conventional methods, if the ranges of possible output of a certain generation schedule are smaller than the spinning reserves, the imbalance is unacceptable and therefore the damage caused by the possible imbalance is considered as infinite. Otherwise this generation

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schedule is acceptable and the damage caused by the possible imbalance is considered as zero. In fact, the imbalance of power in the micro-grid can be compensated by sending excess power to the main grid or buying shortage power from the main gird. An extra expense (penalty) is required when the power exchange happens. Furthermore, with the increasing penetration of PV generations, the tail events have been occurring more frequently[8]. The power exchange with utility grid becomes more important and necessary, and the penalty apparently exists. Therefore, we introduce the expectation of penalty (defined in Section 2) to evaluate the possible damage caused by the imbalance, and combine the expectation of penalty with the conventional operation cost as the objective function. Also, considering the strict request on the reliability of power system, the operators may prefer a more adaptable generation schedule to an economical schedule. Therefore, we also propose the optional constraints to control the possible imbalance within a maximum probability that the operators can accept.

In Section 2, the problem is formulated and the main differences between the proposed method and conventional method are declared. The techniques for generation schedule problems are explained in Section 3. A simulation of generation schedule for micro-grid is presented and a comparison with the conventional method is made in Section 4. The conclusion is drawn in Section 5.

2. Formulation

The scheduling problem is essentially the unit commitment (UC) and economic dispatching control (EDC) problem. One certain generation schedule has its own adaptability to cope with the uncertainties of forecasts. However, the adaptability cannot cope with the uncertainties all the time. Considering the uncertainties of forecasts, the damage for the imbalance of power supply and demand exists when the scheduled controllable generators cannot adapt to the actual net demand. We represent the damage by the sum of penalty which represents the necessary cost to fix the imbalance. Due to the random nature of the forecasts errors, the penalty is evaluated as an expectation. Therefore, considering the uncertainties of forecasts, we combine the expectation of penalty with the conventional operation cost together as the objective function, which is defined as,

$$TC = \sum_{t=1}^{T}\sum_{i=1}^{NG}[ST_{i,t}FC_i\ (P_{i,t}) + ST_{i,t}(1-ST_{i,t-1})SC_i] + \sum_{t=1}^{T} EP_t\left(ST_{i,t}, P_{i,t-1}\right), \tag{1}$$

where T is the total number of time intervals; NG is the total number of controllable generators; $ST_{i,t}$ is the state of controllable generator i in time interval t ($ST_{i,t}$=1,when the generator is operating; otherwise, $ST_{i,t}$=0); $FC_i(P_{i,t})$ is the fuel cost function of generator i, which is the function of $P_{i,t}$; $P_{i,t}$ is the power output of generator i in time interval t; SC_i is the start up cost of generator i; TC is the total cost; EP_t is the expectation of penalty in time interval t and is the function of $ST_{i,t}$ and $P_{i,t-1}$, and the rest of the right hand side of Eq. (1) is the operation cost.

The constraints include the power supply-demand balance constraint, the ramp rate constraint, the minimum on and off time constraint, and the minimum and maximum output constraint. They are shown respectively as follows:

$$\sum_{i=1}^{NG} P_{i,t}ST_{i,t} + p_t = D_t \quad \left(t = 1,\cdots T\right), \tag{2}$$

$$\begin{cases} -\Delta P_i^{down} \le P_{i,t} - P_{i,t-1} \le \Delta P_i^{up} & for \quad ST_{i,t}ST_{i,t-1} = 1 \\ P_i^{\min} \le P_{i,t} \le \Delta P_i^{up} + P_i^{\min} & for \quad ST_{i,t-1} = 0, ST_{i,t} = 1 \\ P_i^{\min} \le P_{i,t-1} \le \Delta P_i^{down} + P_i^{\min} & for \quad ST_{i,t-1} = 1, ST_{i,t} = 0 \end{cases}$$
$$(i = 1,\cdots NG; t = 2,\cdots T), \tag{3}$$

$$\begin{cases} \left(Ton_{i,t} - Ton_i^{\min}\right)\left(ST_{i,t-1} - ST_{i,t}\right) \ge 0 \\ \left(Toff_{i,t} - Toff_i^{\min}\right)\left(ST_{i,t} - ST_{i,t-1}\right) \ge 0 \end{cases}$$
$$\left(i = 1,\cdots NG; t = 1,\cdots,T\right), \tag{4}$$

$$P_i^{\min} ST_{i,t} \le P_{i,t}ST_{i,t} \le P_i^{\max} ST_{i,t}$$
$$\left(i = 1,\cdots NG; t = 1,\cdots,T\right), \tag{5}$$

where p_t is the forecasted power output of PV in time interval t; D_t is the forecasted demand in time t; ΔP_i^{down} is the ramp rate for decreasing output of generator i; ΔP_i^{up} is the ramp rate for increasing output of generator i; Pimin is the minimum output of generator i; P_i^{max} is the maximum output of generator i; $Ton_{i,t}$ and $Toff_{i,t}$ are the consecutive time that generator i has been on and off before time t respectively; Ton_i^{min} and $Toff_i^{min}$ are minimum on and off time of generator i respectively.

Suppose that x denotes the actual net power demand, which is the difference of the actual demand and the actual PV outputs. The actual value x is unknown but assumed to be a random variable with a probability density function $f(x)$. The expectation of penalty contains two parts: the expectation of penalties for power excess and power shortage. The expectation of penalty can be calculated by

$$EP_t = \int_0^{+\infty} u(e_t) g(e_t) e_t d_{e_t} + \int_0^{+\infty} v(E_t) q(E_t) E_t d_{E_t}, \qquad (6)$$

where e_t is the power shortage in time interval t; E_t is the power excess in time interval t; $g(e_t)$ is the probability density function of shortage; $q(E_t)$ is the probability density function of excess; $u(e_t)$ and $v(E_t)$ are the unit price functions of shortage and excess respectively. One possible and simple way to define the unit price functions is as follows,

$$\begin{cases} u(e_t) = \begin{cases} 0 & if \quad e_t \le 0 \\ a & if \quad e_t > 0 \end{cases} \\ v(E_t) = \begin{cases} 0 & if \quad E_t \le 0 \\ A & if \quad E_t > 0 \end{cases} \end{cases}, \qquad (7)$$

where a and A are constants. The unit prices stand for the unit penalties to the micro-grid when it cannot keep the demand and supply balance inside itself but needs sending power to the main grid or buying power from the main gird. The relation of variable e_t and variable x_t is shown in Eq. (8), and the relation of variable Et and variable x_t is shown in Eq. (9). Therefore, the probability density functions $g(e_t)$ and $q(E_t)$ are the linear transformation of $f(x_t)$.

$$e_t = x_t - C_t^{\max}, \qquad (8)$$

$$E_t = C_t^{\min} - x_t, \qquad (9)$$

where C_t^{max} and C_t^{min} are maximum and minimum available outputs of controllable generators in time t, and can be calculated by Eq. (10) and Eq. (11). The penalty happens when the actual net demand cannot be covered by the range of available outputs of controllable generators, which is shown in **Fig. 1**.

$$C_t^{\max} = \sum_{i=1}^{NG} ST_{i,t} \min\{P_i^{\max}, P_{i,t-1} + \Delta P_i^{up}\} \qquad (10)$$

$$C_t^{\min} = \sum_{i=1}^{NG} ST_{i,t} \max\{P_i^{\min}, P_{i,t-1} - \Delta P_i^{down}\} \qquad (11)$$

Figure 2(a) and **Fig. 2(b)** show the relation of expectation of penalty and the output range of scheduled generators used in the conventional method and the proposed method respectively. Considering the uncertainties of forecasts, the conventional ways to prevent the micro-grid from damage by possible imbalance is to plan the generation schedule with the spinning reserves for shortage and excess. The expectation of penalty is considered as infinite when output ranges of scheduled generators are smaller than the spinning reserves for shortage and excess, otherwise, the expectation of penalty is zero as shown in **Fig. 2(a)**. However, the practical situation is that the shortage and excess of power can be compensated by the main grid with a certain penalty when the output range of scheduled generators cannot cover the actual net demand. Therefore, the expectation of penalty for the possible imbalance should be calculated by Eq. (6) rather than infinite. Also, even though the output range of

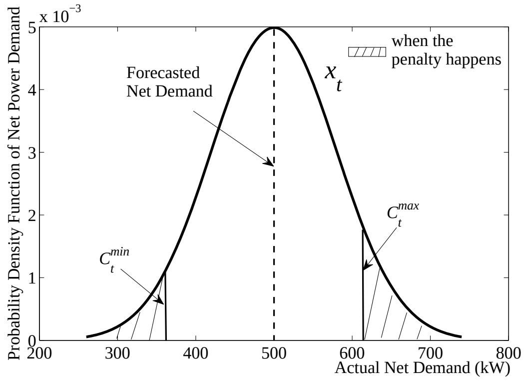
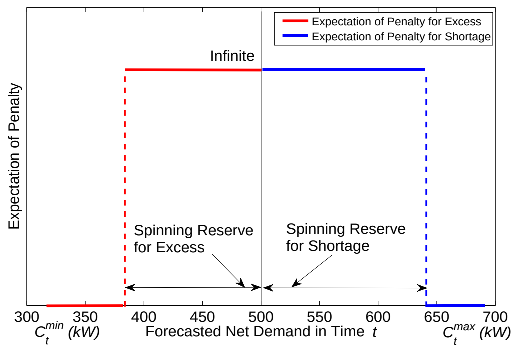
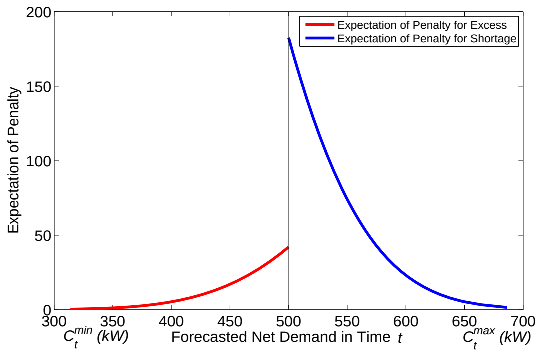


Fig. 1 The conditions when penalty happens.



(a) Conventional method



(b) Proposed method

Fig. 2 Relation of expectation of penalty and the output range of scheduled generators.

scheduled generators can cover a certain range of possible net demand (the spinning reserves for shortage and excess), there is still a possibility that the scheduled generators cannot cover the actual net demand. Then, the expectation of penalty for the possible imbalance should also be calculated by Eq. (6) rather than zero. Therefore, the actual relation of expectation of penalty and the output range of scheduled generators should be the one shown in **Fig. 2 (b)**.

3. Techniques

The UC and EDC problem is a nonlinear mixed-integer optimization problem[9]. The problem can be viewed as a two-level problem, where the upper level is an integer variable optimization problem which determines the states of generators and at the lower level a continuous variable optimization technique is applied to find the minimum operation cost for the given generator states. We employ the tabu search for the upper level problem and a modified equal incremental cost method for the lower level problem.

3.1 Tabu search

Tabu search is an extension of local search, which aims for the global optimization[10), 11)]. In order to avoid being trapped in the local minima, tabu search always moves from one potential solution to the best solution in the neighborhood of the current solution, even thought that solution is not better than the best-so-far solution, until some stopping criterion has been satisfied. Moreover, in order to explore the search area and avoid revisiting, the previously visited solutions within a certain time period, called tabu length, are memorized and forbidden to be visited again. Then, the search path will move to other direction instead of the searched one.

In this paper, tabu search is used to optimize the discrete variables $ST_{i,t}$. The operation schedule of controllable generators' states are expressed by an $NG \times T$ matrix, which can be presented as $[ST_{i,t}]_{NG \times T}$. The definitions of objective function and neighborhood are crucial to the tabu search method.

(1) Definition of objective function: To treat the constrained problem as an unconstrained problem that is suited to tabu search, the objective function of tabu search is defined as Eq. (12),

$$TC + \eta \cdot VIO, \tag{12}$$

where TC is the total cost defined in Eq. (1), η is the penalty coefficient, and VIO is the violation index of the minimum on and off time constraint. η is a big enough positive constant compared with the operation costs. VIO is equal to 0, if there is no violation in the operation schedule $[ST_{i,t}]_{NG \times T}$. Otherwise, VIO is equal to 1.

(2) Definition of neighborhood: The neighborhood of a current solution is a set of the state matrices, whose elements are the same as those of the current solution with one and only one different element.

3.2 Modified equal incremental cost method

Equal incremental cost criterion is used to solve the EDC problem for given generator states. EDC focuses on the outputs of the operating generators. The equal incremental cost criterion comes from the simple EDC problem: the objective function is the summation of the generators' fuel costs; the fuel cost function of each generator is a quadratic function of its output; and the constraint is the power supply-demand balance. The equal incremental cost criterion can be deduced by the Lagrange multiplier method[12)]. The corresponding optimization method for EDC problem is the equal incremental cost method. However, the equal incremental cost method ignores the inequality constraint, namely the minimum and maximum outputs constraint. Therefore, a modified equal incremental cost method is proposed.

When we consider the minimum and maximum outputs constraints, the optimal solution of EDC problem based on the equal incremental cost method may become infeasible. Then, the problem will be how to treat the above situation. Therefore, we put forward the below procedure.

Step 1: Get the incremental costs of all generators, which are under operating, and the minimum and maximum incremental cost for generator i are IC_i^{min} and IC_i^{max}.

Step 2: Calculate the current equal incremental cost (EIC).

Step 3: Find all the generators whose outputs are over their maximum outputs when the optimal solution of EDC by the ordinary equal incremental cost method is applied. Sum all the excess power of these generators (h^{Exc}). Similarly, sum all the shortage power of the generators whose outputs are under their minimum outputs (h^{Sho}).

Step 4: If $h^{Exc} < h^{Sho}$, find the generator with the maximum $IC_i^{min}-EIC$. The output of this chosen generator is forced to be its minimum output. If $h^{Exc} \geq h^{Sho}$, find the generator with the maximum $EIC-IC_i^{max}$. The output of this chosen generator is forced to be its maximum output.

Step 5: The chosen generator from step 4 is excluded from the further consideration, and subtract the minimum or maximum output of the chosen generator from the power demand. Then, recalculate the optimal solution of EDC problem by the ordinary equal incremental cost method.

Step 6: Iterate the step 1 to step 5, until the outputs of all generators are within their corresponding minimum and maximum outputs when the optimal solution is applied.

The above procedure considers the situation that more than one generator's output is over its maximum and also more than one generator's output is below its minimum, when the optimal solution is applied. Both types of the generators mentioned above are defined as the violation generators. We must set the outputs of these violation generators to be their minimum outputs or maximum outputs. It is not wise to set all the violation generators to their minimum or maximum outputs at the same time. The problem is which of the violation generators should be treated. This judgment is done in Step 4 above. We have two steps to determine the order. First, h^{Exc} and h^{Sho} are compared to decide which kind of generators will be considered first. These violation generators, selected in h^{Exc}, are so economic that they are expected to generate more power than their maximum output. On the contrary, those violation generators, selected in h^{Sho}, are so uneconomic that they are expected to generate less power than their minimum outputs. h^{Exc} and h^{Sho} represent the total violation power of the violation generators for the excess power than their maximum outputs and shortage power than their minimum outputs respectively. The bigger one of h^{Exc} and h^{Sho} should be selected, and the corresponding violation generators are taken into prior consideration to reduce more violation power[13]. Second, $IC_i^{min}-EIC$ and $EIC-IC_i^{max}$ are used to evaluate which one of the selected generators should fix its output. For example, when $h^{Exc} \geq h^{Sho}$, all of the violation generators with good characteristic are selected as the options. From these options, the generator with the largest value of $EIC-IC_i^{max}$ is the one whose maximum incremental cost is the least among the options. Therefore, this generator should be selected to fix its output as its minimum or maximum output.

4. Simulation and results

In order to validate our proposal, the simulation is performed. The simulation conditions are shown in details, and then the results and analysis of the results are shown.

4.1 Time elements for generation schedule

The controllable generators in the micro-grid power system are small in size and easy to get ready to generate power. It is possible that the controllable generators can be scheduled in a short time ahead of the implementation based on more accurate information of demand. Therefore, our generation schedule is made few minutes ahead of the implementation. In Japan, the 30-min balancing rule is imposed on power producer and supplier (PPS), which requires the PPS to achieve 30-minute balancing control for stable power supply[14]. Therefore, the generation schedule in this paper is made for every 30 minutes of a day. The generation schedule to be made here consists of planned output of the controllable generators at every two minutes. The total number of time intervals (T) in each 30-minute scheduling horizon is fifteen. **Figure 3** shows the time elements for generation schedule. Actually, smaller scheduling horizons can utilize the more accurate forecasts to achieve a better operation schedule[15]. Here we take the 30-minute horizon as a study case to validate our main proposal, and the simulation results below indicate that the proposed method can also be applied in very short scheduling horizons.

4.2 Simulation conditions

The simulation condition contains the following items: the construction of the micro-grid power system, the demand, the PV output, the parameters of controllable generators, the uncertainties of forecasts, and the unit price for the shortage and excess.

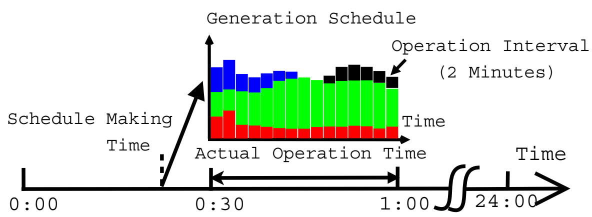


Fig. 3 Time elements for generation schedule.

First, the micro-grid power system consists of the PV generations, ten controllable generators, and the load from the residents. The total capacity of PV generations is 270kW. The total power demand in the peak point is 650kw. The penetration rate of PV generations is about 15%. The capacity of ten controllable generators is 820kW. Second, the hourly actual power demand data is available in[16]. However, the data we need for simulation is the load demand at every two minutes in the 30-minute interval which is forecasted 30 minutes before the interval. Therefore, we make a modification to the actual demand data. Each hourly demand is extended to thirty values of demand in every two minutes in that hour by adding thirty random values respectively. Third, the PV outputs are based on the practical measured value, which is also hourly measured value. The PV outputs data are extended according to the same procedure as the load demand. The demand and PV outputs data are shown in **Fig. 4**. Fourth, the fuel cost coefficients of controllable generators are shown in **Table 1**, and the other parameters of controllable generators are shown in **Table 2**. Those data are based on[17], which are the characteristic of high-power generators. However, in micro-grid power system, the generators are small in size. Thus, we reduce the order of magnitude of the parameters, which are maximum output, the minimum output, the ramp rate for decreasing outputs, and the ramp rate for increasing outputs, from megawatt to kilowatt. Also, we modified the minimum on and off time from hours to several minutes. Fifth, we suppose the probability density function of x_t is the normal distribution. Its mean value is the difference of the forecasted demand and the forecasted PV outputs. The relative error is often used as the indicator of forecasting precision. Therefore, the standard deviation of variable x_t is denoted by the product of the relative error of forecasts and the forecasted net demand. Given the current precision of demand forecasts and PV output forecasts, its standard deviation is set as 16% of its mean value. Lastly, the unit price for shortage and excess are set to be 5.72 and 1.32 respectively.

4.3 Simulation results

According to the above simulation conditions, the generation schedule of the micro-grid power system for a whole day is planned. The total cost of our proposed method is 42263 including 41136 of operation cost and 1127 of expectation of penalty. For each thirty minutes, the execution time for planning the operation schedule is about 146 seconds, which is short enough for generation scheduling. The execution time depends on the size of problem which is related to the number of operation intervals in the scheduling horizons. The

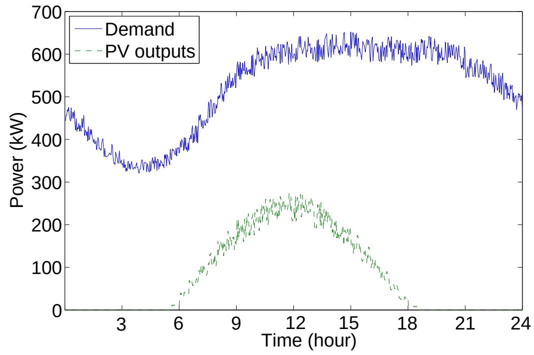


Fig. 4 Data of demand and PV outputs.

Table 1 Fuel cost coefficient of controllable generators.

i	Fuel Cost Coefficient		
	α_i ($/kW^2)	β_i ($/kW)	γ_i
1	0.01	0.5	58
2	0.015	0.8	70
3	0.04	1.4	46
4	0.053	1.6	80
5	0.028	0.95	55
6	0.042	1.2	88
7	0.022	1.4	70
8	0.038	1.5	100
9	0.03	2.2	85
10	0.05	3.1	150

Table 2 Parameters of controllable generators.

i	SC_i	P_i^{min} (kW)	P_i^{max} (kW)	ΔP_i^{down} (kW/min)	ΔP_i^{up} (kW/min)	Ton_i^{min} (min)	$Toff_i^{min}$ (min)
1	36.8	28	90	99	72	8	10
2	68	38	110	121	88	6	8
3	70.8	18	72	79.2	57.6	6	10
4	154	35	100	110	80	8	8
5	51.7	15	70	77	56	8	4
6	90.6	25	80	88	64	8	8
7	60	10	72	79.2	57.6	8	4
8	92.6	20	80	88	64	8	8
9	83.8	20	75	82.5	60	8	8
10	122	10	70	77	56	6	6

acceptable execution time should be no more than its scheduling horizon. In our case study, 146 seconds of execution time is needed for fifteen operation intervals in the 30-minute scheduling horizon. The execution time for planning the generation schedule would be about only 49 seconds if we schedule the generators in an every short time scheduling horizon of five minutes and set the operation interval as one minute. Therefore, in the viewpoint of execution time, our proposed method can be applied in a very short time scheduling horizons.

However, the above results may be not the most desirable operation schedule to the power system operators, even though the generation schedule can achieve the minimum total cost. The operators may take an extra attention on the reliability of power system. The probability of imbalance for power shortage (PIS) and that for power excess (PIE) can be calculated by Eq. (13) and Eq. (14),

$$PIS_t = 1 - F_t(C_t^{\max}), \tag{13}$$

$$PIE_t = F_t(C_t^{\min}), \tag{14}$$

where F_t is the distribution function of variables x_t; PIS_t and PIE_t are the probabilities of imbalance for shortage and excess in operation interval t respectively.

Take the period from 13:30 to 14:00 as an example. **Figure 5** shows the values of PIS in the operation intervals from 13:30 to 14:00. The PIS of the second operation interval is almost twenty which is very high. The high PIS stands for the high risk of imbalance in power systems. It may be not acceptable for the operators considering about the high risk, even though its total cost is desirable. Therefore, we enhance our method by adding the optional constraints, the maximum PIS and PIE constraints, to exclude the situations when the probabilities of imbalance for power shortage and excess are too large to be accepted by operators. The constraint is expressed in Eq. (15),

$$\begin{cases} PIS_t \le PIS_{\max} \\ PIE_t \le PIE_{\max} \end{cases}, \tag{15}$$

where PISmax and PIEmax are the maximum PIS and PIE that the power system operators can accept.

Considering the maximum PIS and PIE constraints, the new simulation is implemented. Here, both PIS_{max} and PIE_{max} are assigned as 10%. Then, the operation schedule is available by solving the UC and EDC problem. Take the same period from 13:30 to 14:00 as the example. **Figure 6** shows the PIS in the intervals of the above time period. The PIS are controlled within its maximum value. In **Table 3**, the operation cost, expectation of penalty, and the total cost in the example time period are listed. Since we add a new constraint, the optimal solution of original proposed method becomes infeasible. The results indicate that the generation schedule with high adaptability to cope with the uncertainty of forecasts is available at the expense of the low economy of generation schedule.

Note that the maximum PIS and PIE constraints are not necessary but an optional constraint which is decided by the system operators according to the control target.

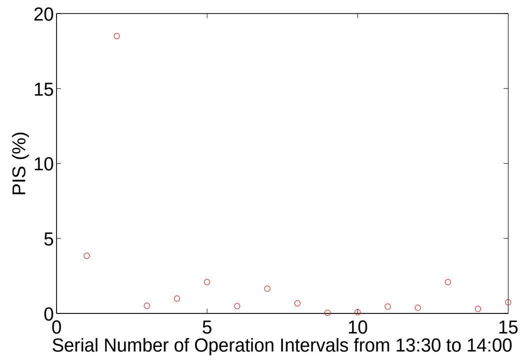


Fig. 5 PIS of operation intervals from 13:30 to 14:00.

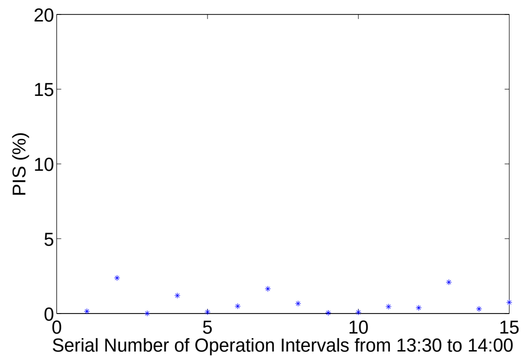


Fig. 6 PIS of operation intervals from 13:30 to 14:00 considering the maximum PIS and PIE constraints.

Table 3 The cost in the period from 13:30 to 14:00.

	Operation Cost	Expectation of Penalty	Total Cost
Original Proposed Method	794	59	853
Proposed Method Adding Maximum PIS and PIE Constraint	885	14	899

In order to validate our proposed method, a comparison is made between the conventional method, the proposed method, and the proposed method considering the maximum PIS and PIE constraints. Basically, the simulation conditions are the same among these three methods. The spinning reserves for power shortage and power excess in the conventional method are assigned as 20.5%, which makes the spinning reserves constraint to be equal to the maximum PIS and PIE constraints when PIS_{max} and PIE_{max} are 10%.

The results of generation schedule for a whole day are shown in **Table 4**. The operation costs of both kinds of our proposed method increase compared with the conventional method. However, our proposed methods have an interesting lower expectation of penalties than the conventional method. Also, the total costs of our proposed methods are lower than that of conventional method. Therefore, our proposed methods can achieve the optimal generation schedule in the viewpoint of minimizing the total cost. As for these two kinds of proposed methods, it is optional to the operators relying on the control target. **Figure 7** shows the PIS of all operation intervals in a whole day of the original proposed method. **Figure 8** shows the PIS of all operation intervals in a whole day of the proposed method considering the maximum PIS and PIE constraints. These two figures can be useful as the references, when the operators make the decisions. Since the PIE in both of these two methods is less than 10%, the figures of PIE are not provided here.

5. Conclusions

This paper focuses on the economically optimal operation schedule of controllable generators in the micro-grid considering the possible damage incurred by failing to cope with the uncertainties of forecasts. The expectation of penalty is introduced to evaluate the possible damage caused by imbalance of power supply and demand. We combine the expectation of penalty with the conventional operation cost together as the objective function of the generation schedule problem. Two main conclusions are drawn. First, our proposed methods can achieve the optimal generation schedule with the less total cost compared with the conventional methods. Second, the optional constraints, the maximum PIS and PIE constraints, are introduced to exclude some extreme situations where PIS or PIE are very large. Generation schedule with high adaptability to cope with the uncertainty of forecasts is available at the expense of the low economy of generation schedule. The proposed constraints are optional and the decision relies on whether the operators desire a more stable system or not.

Table 4 Comparisons.

	Operation Cost	Expectation of Penalty	Total Cost
Conventional Method	40937	3899	44836
Original Proposed Method	41136	1127	42263
Proposed Method Adding Maximum PIS and PIE Constraints	41095	1192	42287

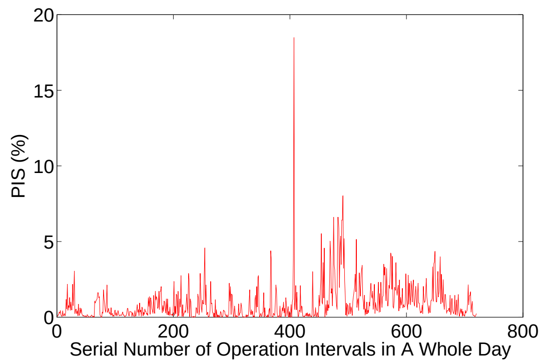


Fig. 7 PIS of operation intervals in a whole day.

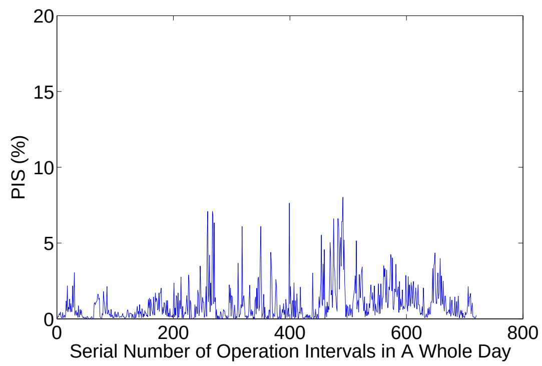


Fig. 8 PIS of operation intervals in a whole day considering the maximum PIS and PIE constraints.

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