IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received June 19, 2020, accepted June 30, 2020, date of publication July 13, 2020, date of current version July 21, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3008747

Optimal Generator Dispatching With Uncertain Conditions for Islanded Microgrid

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This work was supported by the Vietnam National University Ho Chi Minh City (VNU-HCM) under Grant number B2019-20-07.

ABSTRACT This paper proposes the models to solve the optimal generator dispatching problem in an islanded Micro grid with different uncertainties in the constraint and in the objective coefficient. The optimal problem with interval in the power balance constraint is considered as a linear parametric optimization problem, focusing on optimal solutions based on the lower and upper ends of this interval. When the coefficients of cost per power unit caused by load shedding are imprecise and expressed as intervals, the proposed model will be based on the two ends of interval and the problem is converted to a two-objective problem. With uncertainties in both constraint and objective coefficient, the problem will be treated as a four-objective one, considering the lower and upper ends of all intervals. All models are expressed in the linear forms and the linearization is carried out by Max-Affine method. To solve this multi-objective problem, the Bellman-Zadeh approach and Particle Swarm Optimization (PSO) algorithm are applied. The rationality of the proposed models is confirmed in the case study with one low voltage Micro Grid.

INDEX TERMS Linearization, linear parametric optimization, Bellman- Zadeh approach, PSO, load shedding, microgrid.

I. INTRODUCTION

The penetration of renewable sources is increased in Micro Grid (MG). The distributed generators based on wind and solar are considered to be non-dispatchable because they depend on natural conditions. The optimal dispatching problem of distributed generators (DG) is based on coordinating the output power of dispatchable sources [1].

The forecasting of electricity price [2], of load [3], [4] and weather [5] are influenced factors in solving the MG optimal dispatching. The optimality of dispatch and the accuracy of forecasting are concomitant in MG. The uncertainty in optimal problem shown through forecasted values of load is mentioned in [3], [6].

The sources based on the weather condition such as solar and wind play significant role. Meanwhile, determining their output power makes some troubles. The error of wind power, PV power prediction is about (15-20%) and the accuracy is much lower than the accuracy of load forecasting. The accurate forecasting of the wind power is a major challenge. One approach is to forecast wind power in the form of intervals [7], [8] or probability. Many MGs do not have their own forecast data for wind speed and solar radiation. They rely on data from meteorological forecasting centers, which often give the interval values, for example, the wind speed is 8-9 m/s. It makes the forecasted output powers of wind or solar generation be in the form of interval values $[P_{renew\_1}, P_{renew\_2}]$.

With the significant role of electric vehicles in smart grid, the load forecasting faces big challenges. Time and amount of charged and discharged electricity are unpredictable. It makes higher error for forecasted load. Plus, with the problem of the output power forecasting of wind and solar sources, the final forecasted load (after excluding wind and solar power) of MG may have high error and it falls into the large interval values.

The optimal dispatching problem in MG became then the optimization with uncertainties in the power balance constraint. There are several main methods presented in the literature to handle uncertainties: additional reserve requirement, multi-scenario stochastic, fuzzy, robust and interval optimization.

The additional reserve is used to compensate the differences between fluctuating load and its expected forecasted value. Many works used the optimal dispatching

The associate editor coordinating the review of this manuscript and approving it for publication was Salvatore Favuzza.

model based on the expected value, and the reserve is expressed in constraint [9], [10]. But when the interval is large, the required additional reserve may not be sufficient or caused unnecessary elevated resource costs. In [11], [12], the reserve cost was added in the objective function. The [11] used the probability density functions for load, wind and PV power to calculate the expected values, and then used the probabilistics sequence of equivalent load for calculating the reserve constraints. It is rather a hard work because it is not easy to deal with probability functions.

The multi-scenario stochastic models are based on the relevant probability density function. For instance, Weibull and Beta density functions are usually adopted to describe uncertainties of wind speed and solar irradiance, respectively [13]. In [14]–[16], a large number of scenarios needs to be generated, and in [17] Monte Carlo method is carried out, using the probabilistic information, which is usually expensive.

In the fuzzy optimization method, the uncertain renewable power is represented as a fuzzy variable, and fuzzy memberships are set for establishing the fuzzy dispatch model. Typically, in [18] the fuzzy and Particle Swarm Optimization (PSO) are used to tackle the uncertainty of wind power. However, specifying values of such memberships is subjectively determined by power system dispatchers. In this way, the obtained optimal solution may be confronted with strong subjectiveness [19]–[21].

The robust optimization finds the solution with the worst-case scenario, which is robust against most possible realizations within the uncertainty set [22]–[24]. The robust optimizations are with multi layers or stages such as in [25], [26]–[28]. In [29], [30] the stochastic and robust optimization model are combined. To overcome the shortcomings of falling in the scenario that is almost impossible in reality, [31] proposed the interval partioned uncertainty (IPU) sets. However, by analyzing the worst-case scenario, a solution is evaluated using the realization of uncertainties that is most unfavorable, so it is rather over conservative [25].

Another method, which is interval optimization that minimizes the interval of dispatching objective rather than the worst case scenario in robust optimization, is mentioned in [32]–[37]. Using the virtual power plants, [36] presents an economic dispatch model based on interval optimization. Like [33], [37] used the middle point value of the objective function. For each combination of generator's output power, calculate the lower and upper value of the objective function, then the middle point is determined. The optimal combination is the one with the smallest middle point value. And [37] developed this model for multi objective problem such as voltage deviation minimization, using Group Search Optimizer with multiple producers. However, when the interval is large enough and the generation cost function of the slack generator has the high slope, the difference between the lower and upper value of the objective function is large. Therefore, the smallest middle point value may not reflect the optimality of objective function.

This paper proposes another approach, based on the ends of interval to improve the problem solution. The optimal solution is the one that simultaneously moves towards to the best and worst optimal solution. This makes the operating cost close to the optimal operating cost curve for all intervals.

The power management in isolated MG related to load shedding. The amount of shed load is depended on the satisfaction factor. It is expressed in the objective function through the coefficient of cost per one shed power unit. This coefficient may change over time during the day. For many reasons, it is hard to determine this coefficient in the MG where the database of the customer's satisfaction is not sufficient. These coefficients are imprecise and expressed as intervals. However, all works on interval optimization are usually used to deal with the interval in constraint, not in objective function. Therefore, it is worth further investigating the combination of the uncertainty in both constraint and objective function.

This paper focused on the uncertainty of optimal dispatching problem. Because the models, based on two ends of intervals, are in the linear form, the conversion of the original non-linear problem to linear problem is necessary and is presented in Section II. The uncertainty of the constraints will be examined first in section III, then uncertainty of coefficient relating to the load shedding is mentioned in Section IV. In Section V, both the uncertainty in constraint and objective function will be presented. The application for one MG is carried out in Section VI.

II. CONVERTING NONLINEAR PROGRAMMING PROBLEM TO LINEAR PROGRAMMING PROBLEM

The operating cost of MG for one hour includes the cost for generation and load shedding:

$$TT = \sum_{i=1}^{n} (\alpha_i + \beta_i P_i + \gamma_i P_i^2) + \eta P_{shed} \quad (1)$$

where:

- n: the number of dispatchable generators;
- TT: operating cost of n generators (in $ or currency unit) and cost related to load shedding (in $);
- η: cost per power unit caused by load shedding, ($/kWh or $/MWh);
- P_{shed}: shed load (kW or MW);

Function (1) needs to be brought to the linear form, using a linearization algorithm. The paper uses a piecewise linearization technique based on the Max-Affine function [38]. For each F_i, the next algorithm will be carried out:

Given partition $P_1^{(0)}, P_2^{(0)}, \ldots, P_K^{(0)}$ with K segments of {1,2,... m} data points, the number of iterations l_{max}

For $l = 0,\ldots, l_{max}$:

-At j segment: form the straight line $a_j x + b_j$. Determine coefficients a_j, b_j by Least square method.

-Form the new partition $P_1^{(l+1)}, P_2^{(l+1)}, \ldots, P_k^{(l+1)}$ based on these lines.

-Quit if $P_j^{(l)} = P_j^{(l+1)}$ for j=1, 2,..., k or if maximum number of iterations is reached

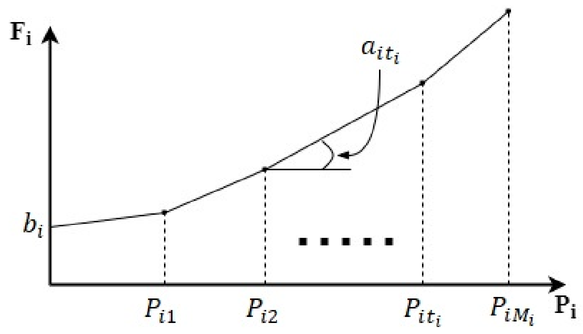

FIGURE 1. Linearization of F_i.

After linearizing F_i, the set of M_i segments are obtained with the segmental values $\{P_{i,1}, P_{i,2},\ldots, P_{i,Mi}\}$ (see Fig. 1). Adding a new variable:

$$x_{it_i} = \begin{cases} P_{i,ti} - P_{i,t_i-1}, & \text{if } P_i > P_{i,ti} \\ P_i - P_{i,t_i-1}, & \text{if } P_{i,t_i-1} \le P_i \le P_{i,ti} \\ 0 & \text{if } P_i < P_{i,t_i-1} \end{cases}$$

$$\sum_{t_i=1}^{M_i} x_{i,ti} = P_i \tag{2}$$

Each F_i can be written as follows:

$$F_i = b_i + \sum_{t_i=1}^{M_i} a_{it_i} x_{it_i}$$

And (1) has the form:

$$TT = C^T X + D \tag{3}$$

$with\ X = [x_{it_i}, P_{shed}]^T,\ t_i = 1, .., M_i;\ \ i = 1, \ldots, n$

The optimal dispatching problem is minimizing operating cost and now can be written as the following:

$$TT \to \min \Leftrightarrow T(X) = C^T X \to \min \tag{4}$$

With the constraints:

The power balance in MG:

$$\sum_{i=1}^{n} P_i + P_{shed} = P_L - P_{renew} = P'_L \tag{5}$$

Output power constraint for i generator:

$$P_{i\_min} \le P_i \le P_{i\_max} \tag{6}$$

Load shedding limit:

$$P_{shed} \le P_{shed\_max} \tag{7}$$

where:

- P_{renew}: total power generation of wind and solar sources (kW or MW);
- P_L: Required load (forecasted load), including power loss (kW or MW);
- P_{i_min}, P_{i_max}: minimum and maximum output power of the i generator (kW or MW);
- $P_{shed\ max}$: maximum load shedding (kW or MW). It depends on the base load P_{base} (base load is the load that is not to be cut). $P_{shed\ max}$ =P_L- P_{base}.
- P'_L-the final load of MG.

The charged (discharged) power of storage devices for each hour is known as the result of day- ahead energy management. Therefore, it is included in P_L.

The intermittent renewable generation depends on the weather and may be given in the form of interval $[P_{renew1}, P_{renew2}]$. Therefore, the power balance equation (5) will be as the follow:

$$\sum_{i=1}^{n} P_i + P_{shed} = P'_L = P_L - [P_{renew1}, P_{renew2}]$$
$$= [P'_{LL}, P'_{LR}] \tag{8}$$

If η is uncertain and expressed in form of interval $[e, f]$, the problem becomes a problem with the objective function coefficient in an uncertain form.

The emission-related objective may be added into (4), but the whole idea of the proposed method is not changed.

III. OPTIMAL DISPATCHING PROBLEM WITH INTERVAL RIGHT HAND SIDE EQUALITY CONSTRAINT

A. PARAMETRIC RIGHT-HAND SIDE LINEAR PROGRAMMING PROBLEM

(5) can be rewritten as:

$$AX = P'_L$$

with $P'_L \in [P'_{LL},\ P'_{LR}]$ or

$$AX = P'_{LL} + \mu(P'_{LR} - P'_{LL})\ \ with\ \ \mu \in [0, 1] \tag{9}$$

where

$$X = [x_{it_i}, P_{shed}]^T, \quad t_i = 1, .., M_i;\ \ i = 1, \ldots, n$$

C: coefficients of generation cost function (after linearization) and η;

A: is the unit matrix.

This is a parametric right-hand side linear programming problem (parametric RHS LP) [39]. For every μ, (4) has a certain optimal value. When μ varies from 0 to 1, these optimal values form a continuous curve T^*(see Figure 2).

Consider the properties of this curve. Denote the optimal value T^* in case of $\mu = 0$ as T_{best} and in case of $\mu = 1$ as T_{worst}. At a certain μ, the optimal T^*_μ has X^*_μ, corresponding to the set of optimal power generation and amount of load shed

$$\{P^*_{1\mu}, P^*_{2\mu}, \ldots, P^*_{n-1\mu}, P^*_{shed\,\mu}, P^*_{n\mu}\}$$

Keep $\{P^*_{1\mu}, P^*_{2\mu}, \ldots, P_{n-1\mu}, P^*_{shed\,\mu}\}$ unchanged, reduce the output power of the last generator when μ decreases to *0.*

Since the cost function of generator increases with increasing P, the value of function T at $\mu = 0$ is smaller than T^*_μ and so smaller than T_{best}. This is unreasonable because T_{best} is the smallest one at $\mu = 0$.

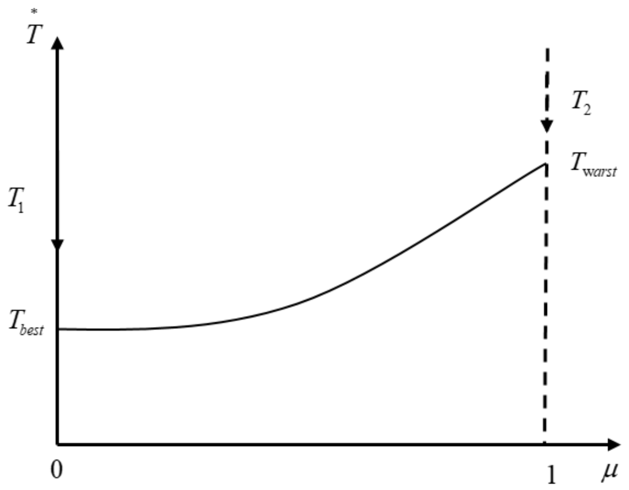

FIGURE 2. Optimal cost T by μ.

Therefore, when μ changes from 0 to 1, the optimal value set will create a continuously increasing curve. When P'_L changes in the interval [P'_{LL}, P'_{LR}], the optimal value of T will always belong to the interval [T_{best}, T_{worst}].

To find the T_{best} (with $\mu = 0$) and T_{worst} (with $\mu = 1$), this paper used the PSO algorithm.

B. METHOD BASED ON TWO ENDS OF FINAL LOAD INTERVAL

Use n^{th} generator as a swing (slack bus) to ensure the power balance condition. Initialize the generation power value of the (n-1) first generators and the value of power load shedding {P_1, P_2,…,P_{n-1}, P_{shed}}, using (9) to determine the outputs of the last generator (denoted as swing generator) $\{P^L_{sw}, P^R_{sw}\}$ that ensure the power balance at P'_{LL} and P'_{LR}. Based on (2) then calculate:

$$T_1 = C^T X_L$$
$$T_2 = C^T X_R \tag{10}$$

where X_L, X_R are corresponded to $\{P_1, P_2, \ldots, P_{n-1}, P_{shed}, P^L_{sw}\}$ and $\{P_1, P_2, \ldots, P_{n-1}, P_{shed}, P^R_{sw}\}$).

Find the solution of the generation and load shedding values so that the T_1 and T_2 are as close as possible to T_{best}, and T_{worst}.

The problem becomes a two-objective problem: T_1 moves closer to the best optimal solution (when $\mu = 0$) and T_2 -closer to the worst optimal solution (when $\mu = 1$) (see Figure 2). In other words, the proposed method is based on two ends of load interval.

One approach to solve the multi objective problem is based on fuzzy set theory, using membership function and Bellman-Zadeh's principle [40]. The following problem is proposed:

$$Max\{\min\{\lambda_1, \lambda_2\}\} \tag{11}$$
$$\lambda_1 = \frac{T_{worst} - T_1}{T_{worst} - T_{best}}, \lambda_1 \geq 0 \quad \lambda_2 = \frac{T_{worst} - T_{best}}{T_2 - T_{best}} \tag{12}$$

λ_i expressed the level of achieving the i-goal. With any solution {P_1, P_2,…,P_{n-1}, P_{shed}}, selecting the smallest {λ_1, λ_2} means focusing on the worst solution. When min {λ_1, λ_2} becomes maximum, both goals are achieved.

This problem uses PSO algorithm with fitness function (11) and constraints (6), (7). With the optimal solution, at P'_{LL}, the value of T will be T^*_1 and at P'_{LR}, will beT^*_2. Due to the increasing property of T^* and T by μ, the curve from T^*_1 to T^*_2 (when μ changes) will be as close as possible to the curve T^*.

From the solution of (11), calculate the optimal value of TT by using (3). (9) is always satisfied because the output power of swing generators shall be in form of interval.

The role of swing generation is to ensure the power balance in the above interval value. In principle, its power can receive any value in that interval. When P'_L receives any value in the interval, the frequency may deviate from the rated value; this swing generator will change its power to ensure power balance. However, its outputs are always in the above interval and the cost function TT always belongs to left-right ends [T^*_1+D, T^*_2+D]. These two left and right ends are as close as possible to (T_{best}+D) and (T_{worst}+D).

IV. OPTIMAL DISPATCHING PROBLEM WITH UNCERTAINTY IN OBJECTIVE FUNCTION

Examine the case where η is expressed in the form of interval $[e, f]$ and the output power of intermittent sources is a determined value.

Now the coefficient matrix C in (3) is a column matrix but in the form of interval:

$$C \in [C_{Low}, C_{Up}]$$

where C_{Low}, C_{Up} –the lower and upper end of the interval

The constraint (5) is in the matrix form:

$$AX = B = P'_L \tag{13}$$

Pay attention on that column C_{Low} and column C_{Up} have the same elements except the last one (last row).

C_{Up} have the same elements except the last one (last row). For C_{Low}, the last element is e and for C_{Up}, is f

To solve this problem, divide the problem into two small problems [41]:

$$T_1 = C^T_{Low} X \rightarrow \min \tag{14}$$
$$T_3 = C^T_{Up} X \rightarrow \min \tag{15}$$

Resolve independently (14) and then (15), the optimal solutions is X^*_{Low}, T_{1min} and X^*_{Up}, T_{3min}.

Calculate the following values:

$$T_{1\max} = C^T_{Low} X^*_{Up}$$
$$T_{3\max} = C^T_{Up} X^*_{low} \tag{16}$$

Reasonably supposed that the decision maker desires to get a solution with the following properties:

$$T_{1\max} \geq T_1; T_{3\max} \geq T_3 \tag{17}$$

Applying fuzzy theory, the following membership functions are proposed:

$$\lambda_1 = \frac{T_{1\max} - T_1(X)}{T_{1\max} - T_{1\min}}$$
$$\lambda_3 = \frac{T_{3\max} - T_3(X)}{T_{3\max} - T_{3\min}} \quad (18)$$

Consider the problem as the two-objective problem:

$$\lambda_1 \to \max$$
$$\lambda_3 \to \max \quad (19)$$

Indeed, when X makes $T_3 \to T_{3min}$ then $\lambda_3 \to 1$ and vice versa when $T_1 \to T_{1min}$ then $\lambda_1 \to 1$. In other words, the proposed method is based on the two ends of coefficient interval.

This two objective problem is solved, using the Bellman-Zadeh's principle:

$$\lambda = \min\{\lambda_1, \lambda_3\} \to \max \quad (20)$$

The problem (20) with the constraints (13), (17), (6), (7) will be solved with PSO algorithm

V. OPTIMAL DISPATCHING PROBLEM WITH UNCERTAINTY IN OBJECTIVE FUNCTION AND IN EQUALITY CONSTRAINT

Now with the uncertainty in the both objective function and in the equality constraint, the problem will be equivalent to:

$$TT \to \min \Leftrightarrow T = C^T X \to \min$$
$$with\ \ C = [C_{Low}, C_{Up}]$$
$$AX = P'_{LL} + \mu(P'_{LR} - P'_{LL}), \quad \mu \in [0, 1] \quad (21)$$

For each combination $\{P_1, P_2, \ldots, P_{n-1}, P_{shed}\}$, due to the condition $AX = P'_{LL} + \mu(P'_{LR} - P'_{LL}) with\ \mu \in [0, 1]$ there are two values of X: X_L corresponds to $\{P_1, \ldots, P_{n-1}, P_{shed}, P^L_{sw}\}$; X_R corresponds to $\{P_1, \ldots, P_{n-1}, P_{shed}, P^R_{sw}\}$.

There will be 4 problems:

$$T_1 = C^T_{Low} X_L \to \min \quad (22)$$
$$T_2 = C^T_{Low} X_R \to \min \quad (23)$$
$$T_3 = C^T_{Up} X_L \to \min \quad (24)$$
$$T_4 = C^T_{Up} X_R \to \min \quad (25)$$

Solve (22), (24) independently: the solution of (22) is X^*_{LLow} and T_{1min}, of (24) is X^*_{LUp} and T_{3min}.

Simillarly, the solution of (23) is X^*_{RLow} and T_{2min}, of (25) is X^*_{RUpp} and T_{4min}.

Then assign:

$$T_{1\max} = C^T_{Low} X^*_{LUp}$$
$$T_{2\max} = C^T_{Low} X^*_{RUp}$$
$$T_{3\max} = C^T_{Up} X^*_{LLow}$$
$$T_{4\max} = C^T_{Up} X^*_{RLow} \quad (26)$$

Supposed that the decision maker desires to get a solution with the following properties:

$$T_{1\max} \geq T_1$$
$$T_{2\max} \geq T_2$$
$$T_{3\max} \geq T_3$$
$$T_{4\max} \geq T_4 \quad (27)$$

The problem becomes a four-objective problem:

With C_{Low}, there are two objectives T_1, T_2: Similarly to (10), find the solution of the generation and load shedding values so that T is as close as possible to its optimal solutions: best optimal solution (T_{1min} when $\mu = 0$) and to the worst optimal solutions (T_{2min} when $\mu = 1$).

With C_{Up}, there are two objectives: Find the solution so that the left and right ends of the function T are as close as possible to the best (T_{3min} when $\mu = 0$) and the worst optimal solution (T_{4min} when $\mu = 0$).

In other words, the proposed method is based on two ends of final load interval and of coefficient interval.

The membership functions will be:

$$\lambda_i = \frac{T_{i\max} - T_i(X)}{T_{i\max} - T_{i\min}} \qquad i = \overline{1, 4} \quad (28)$$

(22)- (25) will be equivalent with:

$$\lambda_1 \to \max$$
$$\lambda_2 \to \max$$
$$\lambda_3 \to \max$$
$$\lambda_4 \to \max \quad (29)$$

Solve (29) with the constraints (27), (7), (6), using the Bellman- Zadeh principle and PSO algorithm:

$$Fitness = max\ \{min\ \{\lambda_1, \lambda_2, \lambda_3, \lambda_4\}\} \quad (30)$$

VI. APPLICATION

The 380V low voltage micro grid based on [42] is studied. There are 3 dispatchable generators: two Micro turbines and one Fuel cell; one wind generator; one solar PV and three loads.

Gen 3 will be treated as the swing (slack) bus.

The base load is 70% of total consumption load. For all PSO application in this paper, the following parameters are used: $c_1 = c_2 = \sqrt{2}$, the number of populations is 50, the number of iterations is 50.

A. WITH THE INTERVAL CONSTRAINT

1) METHOD BASED ON TWO ENDS OF FINAL LOAD INTERVAL

With $P'_L = [560, 610]$ kW, three cases of η are investigated: η(€/kWh) = 0.04; η (€/kWh) = 0.05 and η (€/kWh) = 0.06. The results are given in Table 2 and Table 3.

In the cases 1, 2 and 3, for the same amount of required load, as η increases, the amount of load shedding gradually decreases. Generators 1, 2 reach their maximal power. Comparing the cost for shedding, Generator 3 did not produce its maximal output power.

TABLE 1. Parameters of dispatchable generators.

Generator	Cost function (€/h)	Output Power limit (kW)
1	$10.10^{-55}.P^2+20.10^{-55}.P+20.10^{-55}$	[0, 260]
2	$20.10^{-55}.P^2+50.10^{-55}.P+100.10^{-55}$	[0,160]
3	$100.10^{-55}.P^2+40.10^{-55}.P+140.10^{-55}$	[0,240]

TABLE 2. Optimal power of generator with P'_L = [560, 610] kW.

η	Optimal output power (kW)				λ
	Gen 1	*Gen 2*	*Load shedding*	*Gen 3*	
0.04	260	160	102	[38,88]	0.91
0.05	260	160	86	[54,104]	0.95
0.06	260	160	70	[70,120]	0.93

TABLE 3. Value of TT (€) with P'_L = [560, 610] kW.

Case	T_{best}+D	T_1^*+D	T_{worst}+D	T_2^*+D
1	8.13	8.34	10.13	10.34
2	8.83	9.03	11.33	11.53
3	9.36	9.56	12.36	12.57

TABLE 4. The results with middle value of [560, 610] kW.

Case	T_1^*+D ((€)	T_2^*+D (€)	Power(kW)			
			Gen 1	Gen 2	Shed Load	Gen 3
1	8.29	10.4	260	160	98	[42, 92]
2	9.06	11.5	260	160	88	[52,102]
3	9.53	12.60	260	160	68	[72,122]

2) COMPARE WITH OTHER METHODS USING THE MIDDLE POINT OF LOAD INTERVAL

With a heay load when P'_L = [560, 610] kW and the middle value is 585 (as expected value), determine the optimal solution. Calculate the power of swing generator (as required reserve) that ensure the power balance at P'_{LL} and P'_{LR}. The results are mentioned in the Table 4.

For further investigation, suppose P_{SW} slsides from P_{sw}^L to P_{sw}^R, take the integral:

$$S = \int_0^1 \{(100.10^{-5.5}P_{SW}^2 + 40.10^{-5.5}P_{SW} + 140.10^{-5.5}) + \eta P_{shed}\}d\mu$$
$$\text{with } P_{SW} = P_{SW}^L + \mu(P_{SW}^R - P_{SW}^L) \quad (31)$$

The integral S corresponds to the possible area scanned by P_{SW} and P_{shed} when P'_L fall into [560, 610] kW. It corresponds to the total cost caused by Gen 3 and load shed when P'_L slides in the above interval (Gen1 and Gen 2 are ignored because their output powers are not changed).

TABLE 5. Optimal result with middle point value of TT method.

Case	1	2	3
Shed load(kW)	98	85	67
Gen 3(kW)	[42, 92]	[55, 105]	[73,123]
T_1 +D (€)	8.28	9.02	9.51
T_2 +D (€)	10.41	11.54	12.62

Denote the possible area S for Table 2 as S_1 and for Table 4 as S_2. The differences (S_1-S_2) are negative with three cases of η. That means the expected value of cost caused by Gen 3 and load shed when P'_L takes a random value in [560, 610] in Table 2 is smaller than in Table 4. The results based on the two ends of P'_L interval are better than the way based on the middle point of [560, 610] kW.

Now, with a light load, the case with P'_L = [390, 440] kW will be examined. The method based on the two ends of load interval gives the optimal solution: Gen 1:260 kW; Gen 2: 127 kW and Gen 3: [3], [53] kW.

Taking the middle point of this load interval, with P'_L = 415 kW, solve the problem (1) - (4), the optimal output of generators is: Gen 1:260 kW; Gen 2: 136 kW and Gen 3:19 kW. The interval value of the swing generator will be [19]–[25], [19] + [25]. Therefore, there is no solution with this approach. This emphasizes that it can not resolve the problem based on the middle point of load interval.

Using the middle point of interval of objective function

Examine the cases with P'_L = [560, 610] KW using the middle point of objective function method, proposed in [37]. Find $\{P_1, P_2, \ldots, P_{n-1}, P_{shed}\}$ that minimize the half of sum of TT ($P_1, \ldots, P_{n-1}, P_{shed}, P_{sw}^L$) and TT($P_1, \ldots, P_{n-1}, P_{shed}, P_{sw}^R$). The results are mentioned in Table 5. Here T_1+D is the value of TT ($P_1, \ldots, P_{n-1}, P_{shed}, P_{sw}^L$) and T_2+D is the value of TT($P_1, \ldots, P_{n-1}, P_{shed}, P_{sw}^R$) at the optimal solution. The output of Gen1is 260 kW and of Gen 2 is 160 kW.

Denote the possible area scanned by Gen 3 and shed load of Table 5 as S_3. The values of $\Delta S = S_1 - S_3$ for three cases of η are negative: −0.005; −0.0003; −0.004. That means the results based on two ends of P'_L interval are better than the way based on the middle point in [37].

B. WITH UNCERTAINTY OF η

1) METHOD BASED ON TWO ENDS OF COEFFICIENT INTERVAL

η will be given in the following intervals: [0.04, 0.05]; [0.05, 0.06]; [0.06, 0.07]. P'_L = 610 kW. The output power of Gen 1 and 2 are the same as presented in the above section. The power of Gen 3 and shed load are mentioned in Table 6.

2) COMPARISON WITH OTHER METHODS

If taking the middle value of the above mentioned interval of η, the optimal solution is shown in Table 7. The output power of Gen 1 and 2 are the same as presented in the above section.

The optimal values T^*+D are always in the intervals of [T_1^*+D, T_3^*+D]. And it gives the same picture with any value in the interval of η.

TABLE 6. Power of Gen 3 and shed load with interval of η.

Case	1	2	3
Shed load(kW)	119	87	86
Gen 3(kW)	71	103	104
T_1^*+D	10.16	11.35	12.39
T_3^*+D	11.35	12.38	13.25
λ	0.55	0.8	0.74

TABLE 7. Power of Gen 3 and shed load with the middle value of interval of η.

Case	1	2	3
Shed load(kW)	123	99	91
Gen 3(kW)	67	91	99
T^*+D	10.75	11.87	12.82

TABLE 8. Optimal results with uncertainty in objective function and constraint.

Case	1	2	3
Shed load(kW)	95	79	63
Gen 3(kW)	[45, 95]	[61, 111]	[77,127]
T_1^*+D (€)	8.24	8.93	9.46
T_2^*+D (€)	9.2	9.72	10.09
T_3^*+D (€)	10.47	11.67	12.7
T_4^*+D (€)	11.42	12.45	13.33
λ	0.85	0.88	0.9

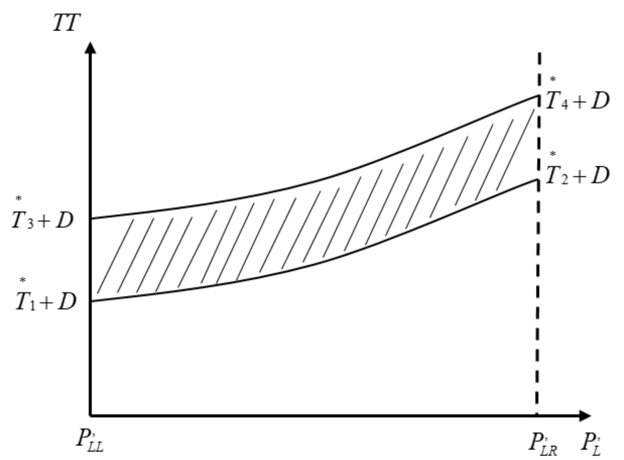

FIGURE 3. Received TT with uncertainties in constraint and in objective coeffient when when P'_L changes.

C. WITH UNCERTAINTY IN THE OBJECTIVE FUNCTION AND CONSTRAINT

The results with $P'_L = [560, 610]$ kW and with $\eta = [0.04, 0.05]; [0.05, 0.06]; [0.06, 0.07]$ are shown in the Table 8.

Here the output powers of Gen. 1 and 2 are 260 and 160 kW.

Figure 3 presents the curves drawn by received TT when P'_L changes. For any specified P'_L and η in their intervals, the corresponding optimal TT will always belonge to the area marked with parallel lines.

VII. CONCLUSION

For islanded MG, the cost of power generation and load shedding must be considered in optimization. This problem may be faced with the inaccuracy of the power output forecasting problem of the intermittent source, with the imprecise of the satisfactory coefficients. The developed model could explicitly address the complexities of various system uncertainties, where parameters were represented as interval numbers.

To solve the problem with the interval in the equality constraint and in the coefficient of objective function, the linearization to get linear optimization is necessary. The Max-Affine algorithm here proves effective.

For the interval in the equality constraint, the proposed method is based on the two ends of the final load interval. The solution must simultaneously move towards to the best and the worst optimal solutions.

To tackle with the uncertainty in the objective function and constraint, the four-objective problem was proposed, based on the ends of the final load interval and of the objective coefficient interval.

The Bellman- Zadeh's principle is applied to find solutions for multi-objective problems.

The present method can lead to useful extensions in incorporating other components into the objective function such as the emission cost to get more perfect picture of optimization in MG.

ACKNOWLEDGMENT

The authors thank the support of time and facilities from the Ho Chi Minh City University of Technology and VNU-HCMC for this study.

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