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Multi-Objective Generation Maintenance Scheduling Using Global Criterion and Lexicographic Methods

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ABSTRACT

Generation maintenance scheduling (GMS) is a power system maintenance model that allows system equipment to provide electricity continuously, while also improving system reliability (SR). However, turning off a distributed generator (DG) for maintenance prevents it from generating power for sale. As a result, revenue that a generation company (GenCo) might potentially receive is decreased. Therefore, reliability and cost outcomes should be considered when planning maintenance. Several studies recommend the GMS model, based on multi-objective problems solved through optimization methods. The global criterion and lexicographic methods, by contrast, are two mathematical approaches individually applied in distinct network topologies, objectives, and constraints. In addition, the coefficient search space, specified as a single constant, is also used in the lexicographic method. This paper uses the GMS model with global criteria and lexicographic methods in the same systems to assess efficiency of multi-objective problem solutions based on cost and system reliability for both methods. Coefficient search space is adjusted for the lexicographic method, depending on the first objective. Based on the IEEE 6 and IEEE 18-bus test networks, a numerical example is investigated. Results indicate that the two methods provide distinct GMS plans for a GenCo to select. If the GMS problem is based on a few objectives, DGs, or loads, the global criterion is preferable to the lexicographic method for mathematical findings. The main objective of coefficient search space settings for the lexicographic method should be adjusted to obtain results close to the main objective.

Keywords: Coefficient search space; Global criteria method; Generation maintenance scheduling; Generation maintenance cost; Lexicographic method; System reliability

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1. Introduction

1.1 Motivation and literature review

Generation maintenance scheduling (GMS) is a model for power system maintenance that allows the distributed generator (DG) to receive maintenance. This can increase the DG's lifetime and reduce the frequency of unexpected outages. However, the shutdown of the DG could definitely affect the expected returns for the generation company (GenCo) [1-4], which would be caused by the lack of capacity [5-7]. Therefore, in planning the GMS, both the system reserve (SR) [8-10] and GenCO's financial return should be considered, simultaneously and effectively.

In general, the problem of the GMS can be divided into three categories: (i) In terms of cost, most of them would examine how to maintain the generation system at the minimized system costs [3, 4], (ii) in terms of reliability, most of the research has focused on two types of considerations: system reliability in the reserve (unrelated to the failure rate) [8, 10] and system reliability related to the failure rate [9, 11], and (iii) in terms of emission [12]. Nonetheless, the above-mentioned terms might be regarded simultaneously, i.e., reliability and cost [13, 14]. However, several studies have proposed GMS models depending on the priorities of the three factors with a difference of objectives, mathematical methods, system constraints, and network topologies, as discussed previously.

For the brief description, the profit of the GenCo would be maximized by taking into account the ageing impact of the components. To solve the problem, the operating hour method would be modified [15]. To maximize the benefit, a multiple-leader-common follower game would be used to organize several GenCos [16]. To optimize the GenCo's profit, the GMS model would be proposed. This would be based on the DG's failure rate (FR) and would be solved using a genetic algorithm and linear programming method [17]. The GMS problems would be organized in a competitive market to maximize the profit of the various GenCos. The results would be run using a Nash equilibrium and energy efficient plants [18]. In [19], the cost of the unsupplied energy was offered and a sequential Monte Carlo simulation was used to validate the results; consequently, the issue would be neutralized using the accelerated quantum particle swarm optimization process to maximize the GenCo's profit. The unsupplied energy would be taken into consideration [20], whereas the GMS plan would be solved using bender decomposition. The GMS model would be based on transmission line and generation maintenance costs along with the risk to minimize the cost [21]. To solve the results, the Lagrangian relaxation and bender decomposition was modified. In [22], the relaxation induced approach was used to measure the GMS model based on the GenCo's maximum profit and the system reliability index. In [12], a lexicographic technique with fixed coefficient search space value was used as a tool for the GMS model to minimize the cost, maximize the average net reserve value with demand response, and minimize the emission. In [23], a dominance-based multi-objective, the SA process, was used to model the exchange between minimizing the maintenance costs and maximizing the system reliability. A penalty cost was applied to the model to optimize the GenCo's profit while minimizing the financial uncertainty, and the results were analyzed using a risk-based analysis [24]. The GMS model was based on a multi-objective problem and evaluated by adapting the global criterion to maximize the return of the GenCo and the SR [7]. In [18], the profit of several GenCos and the SR was satisfactory. The Nash equilibrium and non-cooperative game theory were used to solve the model. In [25], the midterm and short-term load forecast uncertainties were simulated using a multiscale multiresolution GMS model executed in the form of a stochastic affinely stretchable robust optimization method. The model coordinated the preventive maintenance of the generating units, which was a non-linear stochastic optimization problem that was effectively handled using the particle swarm optimization and genetic algorithms methods to minimize the risk of the load probability loss [26].

1.2 Model and contribution

According to the literature review, there are studies employing valuable mathematical techniques, which are the global criterion and lexicographic methods, to solve the GMS problems as multi-objective models [7, 12, 27, 28]. Both methods have been demonstrated as effective solutions for GMS problems. However, no previous work has compared the efficiency of these two approaches, aiming to determine which yields better results for the GenCo. These methods are applied separately, considering different systems, objectives, and scenarios. This paper addresses the gap in the literature by comparing the results generated using global and criterion methods to provide the GenCo with optimal GMS indices. A multi objective problem, as presented in published work [30], is formulated with two main objectives to evaluate the outcomes. Additionally, while the lexicographic technique [12] traditionally employs a constant search space, this work introduces variations in the search space to identify improved outcomes and conduct a comprehensive analysis. In comparison with existing models in the literature, this paper makes the following main contributions:

- While the global criterion and a lexicographic method are employed separately in individual studies, this paper addresses the GMS problem by utilizing both methods under the same objectives, test systems, and conditions. This enables an effective comparison and analysis of the results from the two approaches.
- To enhance the efficiency assessment of the lexicographic method, the coefficient search space is varied across several values. Additionally, the GMS problem is executed with two case studies to validate the robustness of the results. The tendencies of the appropriate method are depicted and analyzed to facilitate the GenCo in extending the application of GMS results to other objective functions.

1.3 Paper organization

This paper is organized as follows: The problem formulations and constraints are formulated in Section 2. The proposed multi-objective optimization method is described in Section 3, while numerical studies are demonstrated in Section 4. The conclusions are provided in Section 5.

2. Problem formulation

This section describes the objective functions and constraints related to the GenCo's annual return and PnF.

2.1 Objective function

The first objective was to maximize the annual return of the GenCO. In Eq. (2.1), for the total number of the time interim (T), the annual return was expressed as the difference between the revenue and cost.

$$Max\ return = \sum_{t=1}^{T}\left(Revenue_t - Cost_t\right). \quad (2.1)$$

Revenue is defined in Eq. (2.2) as follows:

$$Revenue_t = mp_t\left[\sum_{s=1}^{ND}\left(P_{s,t}\right) + \sum_{mg=1}^{MG}\left(F_{mg,t}^{LMP} \times P_{mg,t}^{smg}\right)\right] \times h. \quad (2.2)$$

In Eq. (2.3), the cost [29] is denoted by the following expenditure factors:

$$Cost_t = \left\{\sum_{mg=1}^{MG}\left(F_{mg,t}^{LMP} \times mp_t \times P_{mg,t}^{smg}\right) \times h + \sum_{s=1}^{ND}\left[\left(Cp_s P_{s,t} + Cf_s u_{s,t} + Cm_s P_{MAX,s} x_{s,t}\right) \times h + Csu_s y_{s,t}^{U}\right]\right\}. \quad (2.3)$$

The second objective was to maximize the PnF. The PnF was determined by using the FR, the duration between the previous and current maintenance periods, and the DG's capacity [8] (Eq. (2.4)). Since negative results could appear to be counteractive, the equation was modified to be in the form of minimizing the terms (Eqs. (2.5)-(2.6)) to make them easier to understand. Finally, in Eqs. (2.7)-(2.8), the natural logarithm was used to linearize the equation.

$$Max\ PnF = \prod_{s=1}^{ND}\left[\frac{1}{\exp\left(-FR_s\left(w_s^t - w_s'\right)\right)}\right]^{\frac{P_{MAX,n}}{P_{Largest}}}, \quad (2.4)$$

$$Max\ PnF = Min\ Y, \quad (2.5)$$

$$MinY = \prod_{s=1}^{ND}\left(-FR_s\left(w_s^t - w_s'\right)\right)^{\frac{P_{MAX,n}}{P_{Largest}}}, \quad (2.6)$$

$$MinY = \sum_{s=1}^{ND} -\frac{P_{MAX,n}}{P_{Largest}} \ln\left[\exp\left(-FR_s\left(w_s^t - w_s'\right)\right)\right], \quad (2.7)$$

$$MinY = \sum_{s=1}^{ND} -\frac{P_{MAX,n}}{P_{Largest}}\left(FR_s\left(w_s^t - w_s'\right)\right), \quad (2.8)$$

2.2 Constraints

The constraints were classified into two main categories as follows:

2.2.1 System reserve constraints

These constraints took into consideration the power generation, loss, load, and load power that were exchanged with the main grid for the system reserve (SR) and minimized system reserve (MSR) determined by the ISO (Eqs. (2.9)-(2.10), respectively) to satisfy the system reserve constraints.

$$SR_t(\%) = \frac{\left[\sum_{s=1}^{ND} P_{MAX,s} x_{s,t} - P_{t,Loss} - \sum_{l=1}^{NL} L_{l,t} - \sum_{mg=1}^{MG} P_{mg,t}^{smg}\right]}{\sum_{l=1}^{NL} L_{l,t}} \times 100, \quad (2.9)$$

$$SR_t(\%) = MSR. \quad (2.10)$$

Because this study was conducted in response to the virtual power plant system, the electricity that exceeded the minimum limit was sold back to the main grid. (In this study, the minimum was 15 %).

2.2.2 Operational constraints

Most of the operational constraints were related to the operation of the DG and system security [29, 30], which could be defined using the equations below.

The duration period when the DG was required for maintenance is shown in Eq. (2.11), and outage continuity is shown in Eq. (2.12).

$$\sum_t^T x_{s,t} = d_s, \quad (2.11)$$

$$x_{s,t} - x_{s,t-1} \le x_{s,t+d_s-1}. \quad (2.12)$$

The start-up, shutdown, and maintenance states were determined by Eqs. (2.13)-(2.15), respectively.

$$y_{s,t}^U - y_{x,t}^D = u_{s,t} - u_{s,t-1}, \quad (2.13)$$

$$y_{s,t}^U - y_{x,t}^D \le 1, \quad (2.14)$$

$$u_{s,t} - u_{s,t} \le 1, \quad (2.15)$$

The output of DG and power flow are limited as (2.16) and (2.17), respectively.

$$u_{s,t} P_{MIN,s} \le P_{s,t} \le u_{s,t} P_{MAX,s}, \quad (2.16)$$

$$\left|F_L^{a,b,t}\right| \le F_{a-b}^{MAX}. \quad (2.17)$$

3. Methods of Multi-Objective Optimization

For the purposes of this study, the multi-objective optimization approaches were classified into two categories: (i) Global criterion method and (ii) lexicographic method.

3.1 Global criterion method

The GMS model investigated by the global criterion method is often simulated as a scalar optimization [31] with each objective's function being solved simultaneously in a single stage. The optimal value is derived from the combination of the objectives, as demonstrated in Eqs. (3.1)-(3.2), respectively.

$$\min Z = \sum_{obj=1}^{NF}\left(CF_{obj}\right)^n, \quad (3.1)$$

$$CF_{obj} = \begin{cases} \left(\dfrac{OF_{obj}^{*} - OF_{obj}^{CV}}{OF_{f}^{*} - OF_{f}'} \right), & \text{for maximising } CF_{obj}, \\ \left(\dfrac{OF_{obj}^{CV} - OF_{obj}^{*}}{OF_{obj}' - OF_{obj}^{*}} \right), & \text{for minimising } CF_{obj}. \end{cases} \quad (3.2)$$

The global criterion method was applied to the proposed GMS model. The mathematical equation [27] is shown as Eq. (3.3).

$$\min Z = \left(\frac{reGen^{*} - reGen^{CV}}{reGen^{*} - reGen'} \right)^{n} + \left(\frac{PnF^{CV} - PnF^{*}}{PnF' - PnF^{*}} \right)^{n}. \quad (3.3)$$

Incidentally, the compromised values of the annual return and PnF of the GenCo were between the reGen* and reGen' Pair and those of the PnF* and PnF' Pair.

3.2 Lexicographic method

The lexicographic method [31, 32] is used to solve the GMS model in several stages depending on the number of objective functions. In this technique, the first objective, which was the most significant, had to be identified [33], and the optimal value obtained in the first stage was provided with a constraint, which was then multiplied by the coefficient search space (δ_{obj}) in the next stage, where $(\delta_{obj}) \in [0,1]$ [12] was used to adjust the coefficient search space.

For the mathematical description, if the first stage was to optimize the objective function, as displayed in Eqs (3.4)-(3.5), the obtained optimal value would be set as a constraint for the next stage. However, if the first step, as shown in Eq. (3.6), was to solve the minimum value, the constraint for the next stage would be shown as Eq. (3.7).

$$\max OF_{obj}^{*} \quad ; \text{ for first stage,} \quad (3.4)$$

$$OF_{obj}^{*} \geq (1 - \delta_{obj}) OF_{obj}^{*} \quad ; \text{ constaint for the nest stage,} \quad (3.5)$$

$$\min OF_{obj}^{*} \quad ; \text{ for first stage,} \quad (3.6)$$

$$OF_{obj}^{*} \leq (1 + \delta_{obj}) OF_{obj}^{*} \quad ; \text{ constaint for the nest stage,} \quad (3.7)$$

In which case, combining Eqs. (3.5)-(3.7) would yield an optimal value range, as shown in Eq. (3.8).

$$(1 - \delta_{obj}) OF_{obj}^{*} \leq OF_{obj}^{*} \leq (1 + \delta_{obj}) OF_{obj}^{*}. \quad (3.8)$$

4. Numerical Example

The numerical examples demonstrated the effectiveness of the mathematical approaches. In each case, the results were solved in nine scenarios, which were as follows:

Scenario 1: The GMS plan was based on maximizing the annual return.

Scenario 2: The GMS plan was based on minimizing *Y*.

Scenario 3: The MOGMS model was based on the global criterion method.

Scenario 4: The MOGMS model was based on the lexicographic method. (The first objective was minimizing *Y*.)

SC4.1 $\delta_{obj} = 0.02$,

SC4.2 $\delta_{obj} = 0.04$,

SC4.3 $\delta_{obj} = 0.06$,

SC 4.4 $\delta_{obj} = 0.08$,

SC 4.5 $\delta_{obj} = 0.1$.

Scenario 5: The MOGMS model was based on the lexicographic method. (The first objective was maximizing the GenCo's return.)

SC5.1 $\delta_{obj} = 0.02$

SC5.2 $\delta_{obj} = 0.04$

SC5.3 $\delta_{obj} = 0.06$

SC5.4 $\delta_{obj} = 0.08$

SC5.5 $\delta_{obj} = 0.1$

4.1 Case I: the IEEE 6-bus test system

In this section, the modified IEEE 6-bus test system (Fig. 1) was utilized to solve the results. The input data from Table 1 presented a 52-week study. FR_i was estimated from [8] using the linear regression method. All DG's

w_i' values were based on the postulation that the previous maintenance was performed during the low market price. Figs. 2-3 illustrate the total load and market price with the MSR set at 15% [27].

Table 2 demonstrates the GMS plans in Columns 2-6, while the compared values of the objective functions are shown in Columns 7-8. Finally, the minimum system reserves were satisfied, as seen in Column 9.

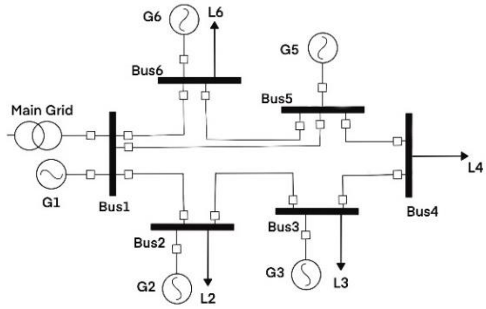

Fig. 1. The adapted IEEE 6-bus test system.

Table 1. Parameter of DG case I.

Units	$P_{MAX,s}$ (MW)	$P_{MIN,s}$ (MW)	Cp_s ($/MWh)	Cf_s ($/h)	Cm_s ($/MWh)	Csu_s ($)	FR_s	w_s'
DG1	7	4	47	61	90	98	0.13887	-13
DG2	5	3	69	72	100	111	0.19301	-12
DG3	5	3	57	57	80	103	0.13901	-42
DG4	6	4	55	65	90	103	0.13894	-37
DG5	5	2	69	72	95	111	0.13901	-39

Table 2. The GMS result of Case I Scenario 1-5.

case	Maintenance interim in the t^{th} week DG 1	DG 2	DG 3	DG 4	DG 5	The annual returns compared with maximum value (%)	The Y compared with minimum value (%)	The MSR (%)
Scenario 1	38	11	36	13	15	0	17.642	15
Scenario 2	4	5	2	1	3	1.767	0	15
Scenario 3	11	12	13	9	10	0.189	6.879	15
Scenario 4	13	12	15	11	10	0.136	8.002	15
Scenario 5	4	5	2	1	3	1.767	0	15

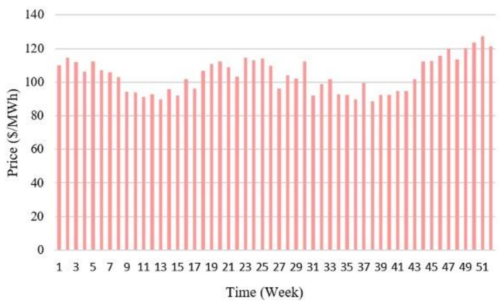

Fig. 2. Market price of IEEE 6-bus.

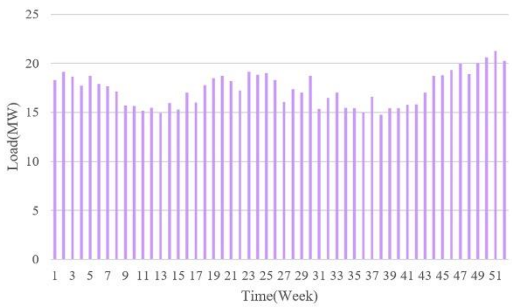

Fig. 3. Total load of IEEE 6-bus.

The zeros in Columns 7-8 indicate that the optimal value of each scenario was the same as the optimal value of all the GMS plans. In contrast, the value 1.767 in Column 7 indicates that the return was 1.767% lower than the maximum value. In addition, the number 17.642 in Column 8 indicates that the inverse of the PnF was more than the 17.642% minimum value.

From Table 2, in Scenario 1, DGs 1-5 were closed for maintenance in the 38th, 11th, 36th, 13th, and 15th weeks. As shown in Figs. 2-3, it can be seen that the GMS plan of Scenario 1 occurred in a low market price and load intervals. This was consistent with the result of previous studies [8, 12, 27] because the GenCo could have the capacity to completely generate the power in the peak load time. In Scenario 2, all the DGs were maintained at the start of the year to reduce the risk of an unexpected outage. In Scenarios 3 and 4, they were based on the MO problems; thus, all the DGs were maintained at both the low market price and beginning of the year. When comparing the result of the global criterion method with that of the lexicographic approach, the GMS plan of the global criterion method provided a lower return and higher Y of 0.053% and y%, respectively. On the other hand, the GMS plan of the lexicographic method provided a higher return and lower Y. Consequently, the selection of the maintenance plan should be determined by the amount the GenCo expected, e.g., if the GenCo was concerned about the return, Scenario 4 would be preferred. The results in Scenario 5 were the same as Scenario 2 because the 10% of the coefficient search space was higher than the worst case of the lowest return of 1.767%, which was not appropriate for the objective.

Tables 3 and 4 show the δ_{obj} adjustment of the lexicographic method for 10%, 8%, 6%, 4%, and 2%, respectively to find the δ_{obj} value that would be appropriate for the first objective of each scenario. This was conducted in order to decrease the discrepancy of the result and GMS plan that was caused by the inappropriateness of the δ_{obj} value.

Table 3 shows a comparison of the results obtained by selecting the first objective to minimize Y that showed the results from SC4.1 (δ_{obj} = 2%) to be similar to the best results from Table 2 with a value of 1.864%.

Table 3. Scenario 4: Result of the lexicographic method is based on the MOGMS model. (The first objective is to minimize Y adjusting δ_{obj} Case I).

case	Maintenance interim in the t^{th} week					The annual returns compared with maximum value (%)	The Y compared with minimum value (%)	The MSR (%)
	DG 1	DG 2	DG 3	DG 4	DG 5			
SC4.1 = 0.02	4	9	11	1	2	1.153	1.864	15
SC4.2 = 0.04	11	12	13	1	4	0.687	4.000	15
SC4.3 = 0.06	11	12	13	9	4	0.377	5.950	15
SC4.4 = 0.08	13	12	15	11	10	0.136	8.002	15
SC4.5 = 0.1	13	12	15	11	10	0.136	8.002	15

Table 4. Scenario 5: Result of the lexicographic method is based on the MOGMS model. (The first objective is to maximize GenCo return adjusting Case I)

case	Maintenance interim in the t^{th} week					The annual returns compared with maximum value (%)	The Y compared with minimum value (%)	The MSR (%)
	DG 1	DG 2	DG 3	DG 4	DG 5			
5.1 = 0.02	4	5	2	1	3	1.767	0	15
5.2 = 0.04	4	5	2	1	3	1.767	0	15
5.3 = 0.06	4	5	2	1	3	1.767	0	15
5.4 = 0.08	4	5	2	1	3	1.767	0	15
5.5 = 0.1	4	5	2	1	3	1.767	0	15

The results differed from SC4.5 (Scenario 4 from Table 3), where most research utilized δ_{obj} = 10%, which was 6.138 %. When the percentage of dependability was adjusted for the increase of δ_{obj}, this was shown to decrease over time. Aside from the results of the secondary objectives, such as, annual returns, the larger the δ_{obj} value, the greater the profit percentage when comparing SC4.1 and SC4.5 with a profit difference of 1.017 %. Table 3 clearly demonstrates that adjusting the δ_{obj} values provided a result that was more appropriate for the main objective.

To compare the lexicographic results the first objective was to maximize the GenCo's return in Table 4, which indicated that all the results from SC5.1-SC5.5 had the same results and were still identical to

Table 5. Parameter of DG case II.

Units	$P_{MAX,s}$ (MW)	Cp_s (\$/MWh)	Cf_s (\$/h)	Cm_s (\$/MWh)	Csu_s (\$)	FR_s
DG 1	15	37	61	25	20	0.1383
DG 2-7	20	45	57	15	50	0.1379

Scenario 2 since the δ_{obj} values were incompatible with the selection of the first objective. As a result, δ_{obj}= 2%, which was still more than the worst-case scenario of the lowest return was presented in Scenario 2. As a consequence, if the outcome was more consistent with the first objective, δ_{obj} should be optimized for the objective, which was less than 2% in this study. To compare the calculation methods, the global criterion method was more appropriate than the lexicographic method if the GMS was based on a small system, a few objective functions, and the DGs. Moreover, the δ_{obj} value should not be fixed because the result was not actually acceptable for the first objective.

4.2 Case II: the IEEE 18-bus test system

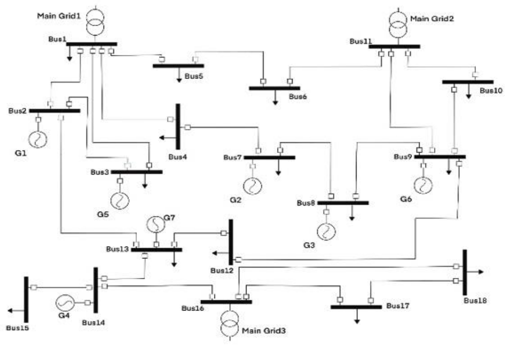

Fig. 4. The adapted IEEE 18-bus test system.

The IEEE 18-bus test system is shown in Fig. 4. The market price and total load are illustrated in Figs. 5-6, respectively. Similar to Case I, the input data are shown in Table 5 [27].

Table 6 shows that Scenario 1 had the objective min*Y* that was 26.738% lower than Scenario 2. Alternatively, Scenario 2 gave benefits to the GenCo in terms of the PnF. When the results of Scenarios 3 and 4 were examined, it was noticeable that Scenario 3 outperformed Scenario 4.

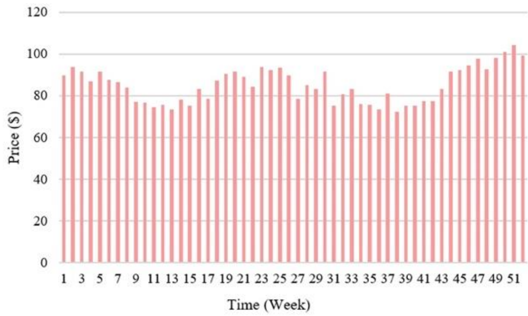

Fig. 5. Market price of IEEE 18 bus.

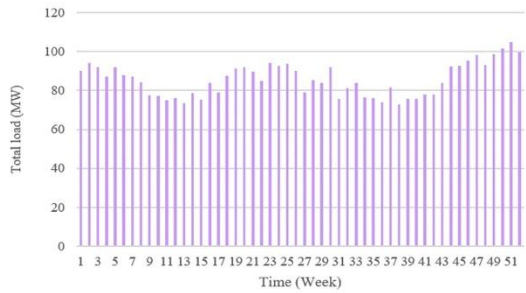

Fig. 6. Total load of IEEE 18 bus.

The results for Scenario 5 were extremely close to those of Scenario 2 because the 10% coefficient search space was quite large, which was similar to Scenario 5 of Case 1.

Tables 7 and 8 show the results of the adjustment of δ_{obj} with the first objective described in Table 7 as min*Y*. The results were similar to Case 1 in that the resultant percentages were close to the optimal δ_{obj} value results. Except for SC4.1, where the δ_{obj} = 2%, the result could not be shown because the δ_{obj} = 0.02 constraint was not satisfactory.

For this case, the N/A at δ_{obj} = 2% could indicate the flexible region of the δ_{obj} for the primary objective.

Table 6. The GMS result of Case II Scenario 1-5.

case	Maintenance interim in the t^{th} week DG 1	DG 2	DG 3	DG 4	DG 5	DG 6	DG 7	The annual returns compared with maximum value (%)	The Y compared with minimum value (%)	The MSR (%)
Scenario 1	40	36	31	15	38	13	11	0	26.738	15
Scenario 2	7	2	6	3	5	1	4	1.076	0	15
Scenario 3	14	15	9	10	13	11	12	0.107	9.809	15
Scenario 4	14	12	1	9	13	11	10	0.257	9.91	15
Scenario 5	7	3	5	4	1	2	6	1.076	2.625	15

Table 7. Scenario 4: Result of the lexicographic method is based on the MOGMS model. (The first objective is to minimize Y adjusting δ_{obj} (Case II).

case	Maintenance interim in the t^{th} week DG 1	DG 2	DG 3	DG 4	DG 5	DG 6	DG 7	The annual returns compared with maximum value (%)	The Y compared with minimum value (%)	The MSR (%)
4.1 = 0.02	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
4.2 = 0.04	6	4	3	2	10	9	1	0.82	3.937	15
4.3 = 0.06	2	9	4	1	11	10	8	0.594	5.925	15
4.4 = 0.08	1	10	8	4	13	11	9	0.398	7.96	15
4.5 = 0.1	14	12	1	9	13	11	10	0.257	9.91	15

Table 8. Scenario 5: Result of the lexicographic method is based on the MOGMS model. (The first objective is to maximize GenCo return adjusting δ_{obj} (Case II).

case	Maintenance interim in the t^{th} week DG 1	DG 2	DG 3	DG 4	DG 5	DG 6	DG 7	The annual returns compared with maximum value (%)	The Y compared with minimum value (%)	The MSR (%)
5.1 = 0.02	7	3	5	4	1	2	6	1.076	2.625	15
5.2 = 0.04	7	3	5	4	1	2	6	1.076	2.625	15
5.3 = 0.06	7	3	5	4	1	2	6	1.076	2.625	15
5.4 = 0.08	7	3	5	4	1	2	6	1.076	2.625	15
5.5 = 0.1	7	3	5	4	1	2	6	1.076	2.625	15

The results of Table 8 are similar to Case 1 in which the δ_{obj} values had been determined to be unsuitable for the selection of the first objective. The results show that the two case studies produced practically identical results, thus indicating that both mathematical methods were immensely effective for the GMS model.

5. Conclusion

In this study, the GMS models considered the GenCo's financial return and the DGs' PnF that were solved as single and multi-objective problems. One of the most important constraints was the minimum system reserve. The results were achieved by using the global criterion and lexicographic methods. The IEEE 6-bus and IEEE 18-bus test systems were used to analyze the numerical example. The results demonstrate that the global criterion and lexicographic methods could produce unique GMS plans. Therefore, the GenCo had the opportunity to select which GMS to use for their power system. In addition, when the calculation approaches were taken into consideration, the global criterion was stable for the system with few DGs and objective functions. The lexicographic solution, on the other hand, was appropriate for the GMS model, which had several objectives and a large network. Furthermore, the coefficient of the lexicographic method should not be fixed but should take on various values depending on the scenario.

Nomenclature

Obj	The indicator of the objectives
mg	The indicator of the main grids

MG	The overall amount of the main grids
ND	The overall amount of the DGs
NF	The overall amount of the objectives
s	The indicator of the DGs
t	The indicator of the time interim
Cf_s	The *s*th DG's fixed cost ($/h)
Cm_s	The *s*th DG's maintenance cost ($/MWh)
Cp_s	The *s*th DG's production cost ($/MWh)
Csu_s	The *s*th DG's start-up cost ($)
F_{a-b}^{MAX}	the line a-b's maximum capacity (MW)
FR_s	The *s*th DG's failure rate
F_{mg}^{LMP}	The locational marginal pricing factor for the *mg*th main grid
$L_{l,t}$	The value of the *t*th interim's lth load (MW)
$P_{Largest}$	The maximum capacity of any DG. (MW)
$P_{MAX,s}$	The *s*th DG's maximum capacity (MW)
$P_{MIN,s}$	The minimum power that could be generated from the *s*th DG (MW)
d_s	The *s*th DG's maintenance duration (h)
w_s'	The amount of the interim between when the *s*th DG was reinstalled during prior maintenance and the last interim of the preceding maintenance window
mp_t	The *t*th interim's market price. ($/MWh)
h	The amount of hours allocated to the maintenance schedule (hr)
δ_{obj}	Coefficient search space in the lexicographic method (its value ranged from 0 to 1.)
CF_{obj}	The compromised function
$F_L^{a,b,t}$	The power flow during the *t*th interim on the line a-b (MW)
OF_{obj}'	The *obj*th objective's non-optimal value
OF_{obj}^{*}	The *obj*th objective's optimal value.
OF_{obj}^{CV}	The *obj*th objective's compromised value
$P_{mg,t}^{pmg}$	In the *t*th interim, the power supplied by the *mg*th main grid (MW)
$P_{mg,t}^{smg}$	In the *t*th interim, the GenCo sold to the *mg*th main grid (MW) (depending on the power purchase agreement)
$P_{s,t}$	In the *t*th interim, the power generated by the *s*th DG (MW)
$P_{t,Loss}$	In the *t*th interim, there was a power loss (MW)
SR_t	In the *t*th interim, there was a system reserve (%)
w_s^t	Under the current scheduling window, the *t*th interim that the *s*th DG was scheduled to be maintained
$u_{s,t}$	The on/off status of the *s*th DG in the *t*th interim (1 when the DG was during the normal state and 0 otherwise)
$x_{s,t}$	The operational status of the sth DG in the *t*th interim (1 when the DG was during maintenance and 0 otherwise)
$y_{x,t}^{D}$	The shutdown status of the *s*th DG in the *t*th interim
$y_{s,t}^{U}$	The start-up status of the *s*th DG in the *t*th interim (1 when the DG was commenced after completing the maintenance and 0 otherwise)

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