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[1]; [2]; [3]; [4]; [5]; [6]; [7]; [8]; [9]Coordinated Generation Cost Optimization Considering the Marginal Costs

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Abstract

In conventional power system, multiple generators commonly coexist. In the meantime, each of the generators has different characteristics in terms of generation cost. Hence, it is necessary to consider them coordinately and achieve the rational power generation mix. Furthermore, in modern smart grids, the characteristics of the generators become even complex, which requires further considerations of different generation cost factors in order to fulfill the requirements of system optimal operation. In this paper, different types of generation costs are analyzed in detail, including starting cost, minimum power generation cost, marginal cost, etc. At the same time, the simplified optimization model is proposed to accelerate the solving rate and ensure that the solution is a global optimal one. Numerical experiments are conducted to validate the proposed method.

Keywords : Generator mix, marginal cost, generation cost minimization

1. 1.Introduction

In order to meet the requirements of ever growing electricity demands, the coordinated characteristics of multiple generators should be considered simultaneously so that coordination among various generation units can be achieved and generation costs can be thereby reduced [1]-[4]. Meanwhile, the overall system reliability can be also enhanced by coordinating multiple generators in the same electric grids. Conventional optimization approach and cost analysis are more suitable for studying the characteristics of small-scale power systems. However, for larger-scale power systems with large numbers of synchronous generators (especially for modern smart grids with various generation mix), the legacy approach may not be effective and the corresponding cost optimization could be infeasible. The deployment of microgrids could be a good solution to consolidate the dispersed generations into a single unit with relatively larger generation capacity [5]-[8]. However, microgrids themselves may also induce operational issues regarding power dispatch, electricity transactions, resource allocation, etc. Additional discussions are needed to fully leverage the benefits of microgrids in cost analysis and economic dispatch in modern electric grids.

Economic operation is one of the critical requirements and criteria in the operation and management of modern power systems. Especially for today's electric grids, the particular requirements can be detailed in the following aspects:

1) The generation costs follow the basic hourly generation cost rate, which determines the particular hourly generation cost of each individual generator;

2) Frequency start-up and shut-down procedures should be avoided, so that the additional cost during the start process can be eliminated, which thereby reduced the overall generation cost;

3) The minimum output power of each generator should be taken into account during the analysis, which is induced by the physical limit of each generator.

4) When the output power of each generator is controlled to be larger than its minimum limit, an additional hourly rate should be considered, which is called marginal cost. Marginal cost is used to represent the overall cost increase induced by the additional power generation of each particular generator.

In order to optimally combine the generation costs from multiple generators (i.e., to minimize the overall system cost), the above cost categories should be comprehensively considered. Hence, the overall cost equation can be derived. Meanwhile, various operational constraints should be considered during the combination of multiple generators, including system topology constraints, maximum power generation constraints, minimum power generation constraints, etc.

For unit commitment and combination of multiple generators, the computational efficiency should be always taken care of. It is necessary to ensure the required computational efficiency and minimize model complexity. In order to solve the above issues, the conventional way of solving the problem is focused on the solving mode, i.e., to improve the original problem solving efficiency and accuracy by altering the solving modes. Particularly, the traditional approaches mainly focus on heuristic methods [9], which is relied on continuously changing the decision variables and gradually approaching the optimal solution. These methods feature lower complexity and less model dependency. However, there could still be some issues regarding convergence. In other words, the algorithm may not converge at the desired and optimal operation points due to the continuous changing and perturbation in the system. In some cases, the optimization problem may lead to sub-optimal other than global optimal due to the inherent issues of heuristic methods.

In this paper, we focus on the improvement of original models, rather than changing the solving methods. In particular, we first adjust the decision variables based on the understanding of physical systems. The purpose of this step is to reduce the numbers of decision variables. Meanwhile, by involving sign signals, the unnecessary procedures or unrealistic unit commitment can be eliminated. Hence, the feasible range is simplified and minimized, and the solving efficiency is thereby enhanced.

Based on the practical and given system model, all the generation costs are listed and analyzed, and the overall cost equation is derived based on the coordination among multiple generation units. After that, in order to minimize the overall generation cost, the optimization model is simplified and the modified model is presented for following analysis. The proposed model can be used to enhance the solving efficiency of the corresponding optimization problem, and the computational efficiency can be enhanced. Meanwhile, it can be guaranteed that the obtained results are the global optimal other than sub-optimal. Finally, the proposed mathematical model is derived in numerical experiment and the proposed optimization problem is thereby analyzed. The related results are given to validate the proposed model and method.

2.Problem Formulation

In order to diversify the generation requirements, four types of generators with different parameters are considered in this study. These four types of generators feature different generation cost and operation characteristics. Particularly, each type of generator features maximum output power constraints. When being connected into the grid, their output power features various minimum power level. Meanwhile, each generator features a starting cost, which is used to limit the on/off times. When each generator is operated with minimum output power, each of them features a fixed hourly rate. When the output power is higher than the minimum output power, the marginal cost should be considered, as introduced above.

In order to simplify the proposed problem to some extent, it is assumed that the start point appears at the beginning of each time interval. Meanwhile, compared to the generation cost of each generator, the shut-down cost is much lower. Hence, the shutting down cost is eliminated here. In order to ensure the reliable operation of generators, sufficient generation margin should be guaranteed with respect to the maximum allowable generation power. Here, it is set that the surplus generation cost is set to 30% of the maximum demand requirements. This is involved to avoid the reliability and stability issues induced by sudden load change.

It is assumed that the load demand follows the chart in Fig. 1. The detailed load data is shown in Table 1. Meanwhile, the generation parameters of each generator are summarized in Table 2. The data shown in Table 1 and Table 2 will be used in the following analysis. Meanwhile, system parameters are listed in Table 3.

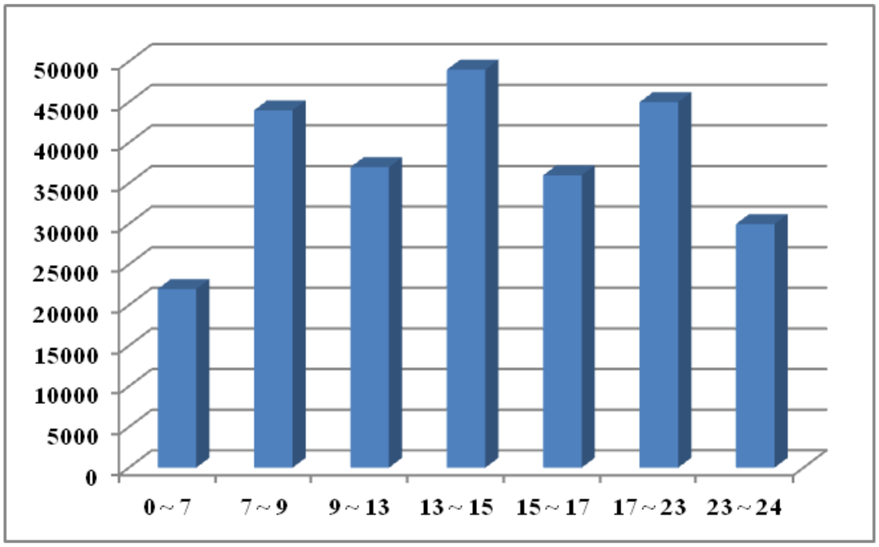

Figure 1: Couldn't find a caption, edit here to supply one.

Figure 1: Load data

Table 1. Load Data

Time	0 ˜ 7	7 ˜ 9	9 ˜ 13	13 ˜ 15	15 ˜ 17	17 ˜ 23	23 ˜ 24
Load /MW	12000	32000	25000	36000	25000	30000	18000

Table 2. Generation Costs

	# of Gen.	Minimum Power (MW)	Maximum Power (MW)	Fix Cost ($k/hour)	Marginal Cost ($k/(hour[?]W))	Starting Cost ($k)
Unit #1	10	750	1750	2250	2.7	5000
Unit #2	4	1000	1500	1800	2.2	1600
Unit #3	8	1200	2000	3750	1.8	2400
Unit #4	3	1800	3500	4800	3.8	1200

Table 3. System Parameters

Symbol	Range of the Subscript	Indication
$N_{\mathrm{ij}}+N_{\mathrm{ij}}^{'}$	$i\in\mathbf{A},j\in\mathbf{B}$	Number of Type #i generators in the jth interval
N_{sij}	$i\in\mathbf{A},j\in\mathbf{B}$	Sum of Type #i generators in the jth interval
P_{sij}	$i\in\mathbf{A},j\in\mathbf{B},k\in\left\{\mathbf{1},\mathbf{2},\ldots,N_{\mathrm{ij}}+N_{\mathrm{ij}}^{'}\right\}$	Power of the kth Type #i generator in the jth interval
P_{ij}	$i\in\mathbf{A},j\in\mathbf{B}$	Total power of Type #i generator in the jth interval
$P_{i\,\mathrm{min}}$	$i\in\mathbf{A}$	Minimum output power of Type #i generator
$P_{i\,\mathrm{max}}$	$i\in\mathbf{A}$	Maximum output power of Type #i generator
$N_{i\,\mathrm{max}}$	$i\in\mathbf{A}$	Maximum number of available Type #i generators
P_{dj}	$i\in\mathbf{B}$	Total load power in the jth time interval
F_{1i}	$i\in\mathbf{A}$	Fixed generation cost of Type #i generator
F_{2i}	$i\in\mathbf{A}$	Marginal generator cost of Type #i generator
F_{si}	$i\in\mathbf{A}$	Start up cost of Type #i generator
T_j	$i\in\mathbf{B}$	Time duration in the jth time interval

3.Model Implementation

The constraints in the above problem formulation are comprised of the following aspects: 1) Maximum and minimum constraints of generator output power; 2) Number of particular type of generators in each given time interval; 3) Load power is satisfied in each given time interval; 4) The maximum output power is no less than 120% of the power rating. Meanwhile, the total generation cost is comprised of: 1) Total starting cost of all the generators; 2) Total fixed cost of all the generators; 3) Total marginal cost of all the generators.

The constraints and objective in this optimization formulation are detailed as follows:

Define that and.

The upper and lower limits of output power of each generator is shown as:

$P_{i\,\mathrm{min}} \le P_{ijk} \le P_{i\,\mathrm{max}}$(1)

The total number of Type #i generator is limited by:

$0 \le N_{ij} + N'_{ij} \le N_{i\,\mathrm{max}}$(2)

In the given time interval, the total output power of all the generators should meet the load requirements, which is shown as:

$\sum_{i=1}^{4}\sum_{k=1}^{N_{ij}+N_{ij}{'}} P_{ijk}{=}P_{dj}$(3)

The maximum output power should not be lower than 120% of the load requirements:

$\sum_{i=1}^{4} P_{imax}(N_{ij}+N_{ij}{'}){\ge}1.2P_{dj}$(4)

The daily starting cost is shown as:

$\sum_{j=1}^{7}\sum_{i=1}^{4}F_{si}N_{ij}{'}$(5)

The fixed generation cost can be represented as:

$\sum_{j=1}^{7}\sum_{i=1}^{4}F_{1i}T_j(N_{ij}+N_{ij}{'})$(6)

Meanwhile, the marginal cost can be derived as:

$$\sum_{j=1}^{7}\sum_{i=1}^{4}\sum_{k=1}^{N_{ij}+N_{ij}'} F_{2i}(P_{ijk}-P_{i\min})T_j (7)$$

Therefore, the system model can be formulated as:

$$minW=\sum_{j=1}^{7}\sum_{i=1}^{4}F_{si}N_{ij}'+\sum_{j=1}^{7}\sum_{i=1}^{4}F_{1i}T_j(N_{ij}+N_{ij}') + \sum_{j=1}^{7}\sum_{i=1}^{4}\sum_{k=1}^{N_{ij}+N_{ij}'} F_{2i}(P_{ijk}-P_{i\min})T_j$$

s.t. (8)

$$P_{i\min}\le P_{ijk}\le P_{i\max}$$

$$0\le N_{ij}+N_{ij}'\le N_{i\max}$$

$$\sum_{i=1}^{4}\sum_{k=1}^{N_{ij}+N_{ij}'} P_{ijk}=P_{dj}$$

$$\sum_{i=1}^{4} P_{imax}(N_{ij}+N_{ij}')\ge 1.2P_{dj}$$

As it can be seen from (8), the derived model is complicated with multiple decision variables. Meanwhile, since only the number of generators is needed to be confirmed with minimum daily generation cost and the detailed generation power of each generator is not needed, the above model in (8) can be simplified. By setting the total output power as the decision variables, it can be derived as follows. First, the upper and lower limits of the generator output power can be obtained as:

$$P_{i\min}(N_{ij}+N_{ij}')\le P_{ij}\le P_{i\max}(N_{ij}+N_{ij}')(9)$$

The total number of generators in each given time interval is also limited as:

$$0\le N_{ij}+N_{ij}'\le N_{i\max}(10)$$

Meanwhile, the total generation power should satisfy the load power,

$$\sum_{i=1}^{4} P_{ij}=P_{dj}(11)$$

The total generation power should be less than 120% of the total load power, which yields that:

$$\sum_{i=1}^{4} P_{i\max}(N_{ij}+N_{ij}')\ge 1.2P_{dj}(12)$$

The start cost in each daily cost is shown as:

$$\sum_{j=1}^{7}\sum_{i=1}^{4}F_{si}N_{ij}'(13)$$

The fixed cost is shown as:

$$\sum_{j=1}^{7}\sum_{i=1}^{4} F_{1i}T_j(N_{ij}+N_{ij}')(14)$$

Meanwhile, the marginal cost is represented as:

$$\sum_{j=1}^{7}\sum_{i=1}^{4}F_{2i}[P_{ij}-P_{i\min}(N_{ij}+N_{ij}')]T_j(15)$$

Therefore, the final model can be obtained:

$$minW = \sum_{j=1}^{7}\sum_{i=1}^{4} F_{si} {N_{ij}}' + \sum_{j=1}^{7}\sum_{i=1}^{4} F_{1i} T_j (N_{ij} + {N_{ij}}') + \sum_{j=1}^{7}\sum_{i=1}^{4} F_{2i} T_j [P_{ij} - P_{i\min}(N_{ij} + {N_{ij}}')]$$

s.t. (16)

$P_{i\min}(N_{ij} + {N_{ij}}') \le P_{ij} \le P_{i\max}(N_{ij} + {N_{ij}}')$

$0 \le N_{ij} + {N_{ij}}' \le N_{i\max}$

$\sum_{i=1}^{4} P_{ij} = P_{dj}$

$\sum_{i=1}^{4} P_{i\max}(N_{ij} + {N_{ij}}') \ge 1.2 P_{dj}$

In the model shown in (16), since no detailed output power of each generator is included, the complexity of the model is reduced. In order to further simplify the model, it is assumed that when new generator is started, there is no generators being shut down in the same time interval. In other words, it is not the case to start some generators and shut them down in the same time interval. Based on this assumption, the mathematical description with the number of generators can be simplified in further using a single variable$N$ sij, which represents the number of Type #i generators running in the jth time interval.

It should be noted that the newly started generators in the jth time interval is shown as:

$\frac{sign(N_{sij} - N_{si,j-1}) + 1}{2}(N_{sij} - N_{si,j-1})(17)$

Here, sign([?]) is a sign function. When x is larger than zero, sign([?]) equals 1; when x is smaller than zero, sign([?]) equals -1.

When j = 1, (17) can be rewritten as:

$\frac{sign(N_{si1} - N_{si7}) + 1}{2}(N_{si1} - N_{si7})(18)$

Similar to the second model derived above, the upper and lower constraints of output power of a generator is defined as:

$P_{i\min} N_{sij} \le P_{ij} \le P_{i\max} N_{sij}(19)$

The number of generators running in the given time interval is limited as:

$0 \le N_{sij} \le N_{i\max}(20)$

In order to satisfy the load requirements, it yields that:

$\sum_{i=1}^{4} P_{ij} = P_{dj}(21)$

Given that the maximum output power should be no less than 120% of the power rating:

$\sum_{i=1}^{4} P_{i\max} N_{sij} \ge 1.2 P_{dj}(22)$

Therefore, the starting cost in the daily generation cost can be shown as:

$$\sum_{j=2}^{7}\sum_{i=1}^{4}\left[F_{si} \cdot \frac{sign(N_{sij} - N_{si,j-1}) + 1}{2}(N_{sij} - N_{si,j-1})\right] + \sum_{i=1}^{4}\left[F_{si} \cdot \frac{sign(N_{si1} - N_{si7}) + 1}{2}(N_{si1} - N_{si7})\right] \quad (23)$$

The fixed and marginal costs are shown as:

$\sum_{j=1}^{7}\sum_{i=1}^{4} F_{1i}T_jN_{sij}(24)$

$\sum_{j=1}^{7}\sum_{i=1}^{4} F_{2i}(P_{ij}-P_{i\min}N_{sij})T_j(25)$

Hence, the final derived model can be shown as:

$$
\begin{aligned}
\min W = \sum_{j=2}^{7}\sum_{i=1}^{4} & [F_{si}\cdot \tfrac{sign(N_{sij}-N_{si,j-1})+1}{2}(N_{sij}-N_{si,j-1})] \\
& + \sum_{i=1}^{4}[F_{si}\cdot \tfrac{sign(N_{si1}-N_{si7})+1}{2}(N_{si1}-N_{si7})] \\
& + \sum_{j=1}^{7}\sum_{i=1}^{4} F_{1i}T_j(N_{ij}+N_{ij}{'}) \\
& + \sum_{j=1}^{7}\sum_{i=1}^{4} F_{2i}T_j[P_{ij}-P_{i\min}(N_{ij}+N_{ij}{'})]
\end{aligned}
$$

s.t. (26)

$P_{i\min}N_{sij} \le P_{ij} \le P_{i\max}N_{sij}$

$0 \le N_{sij} \le N_{i\max}$

$\sum_{i=1}^{4} P_{ij}{=}P_{dj}$

$\sum_{i=1}^{4} P_{i\max}N_{sij} \ge 1.2P_{dj}$

Therefore, the derived model in (26) is linear and much simplified, which can be used to enhance the computational efficiency.

4.Numerical Experiment

Based on the data shown in Table 1 and Table 2, the derived optimization problem is solved in order to validate the accuracy of the obtained model. The three optimization problems all give the same optimal. By using MATLAB m-scripts, the results can be obtained and summarized in Table 4 and Table 5. Meanwhile, the time stamps during numerical tests can be extracted, as shown in Table 6, where is can be seen that the simplified model features higher computational efficiency.

Table 4. Output power of each type of generators in each time interval.

	Interval 1	Interval 2	Interval 3	Interval 4	Interval 5	Interval 6	Interval 7
Unit#1	4	4	5	7	5	4	4
Unit #2	4	4	4	4	4	4	4
Unit #3	2	8	8	8	8	8	5
Unit #4	0	3	0	3	0	2	0

Table 5. Number of generators participating into power generation in each time internal.

Table 6. Solving Time for Each Type of Model

	Original Model/s	Type I: Model/s	Type II: Model /s
Solving Time	2.36	1.24	0.96

5.Conclusions

In this paper, based on the analysis of different generation costs, the marginal costs are included in the conventional unit commitment problem. Meanwhile, in order to enhance the computational efficiency, the simplified models are derived based on the reasonable assumptions in generation mix. By using the simplified models, the model accuracy and the computational efficiency can be enhanced, as demonstrated in the numerical experiment.

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