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Generation maintenance scheduling based on multiple objectives and their relationship analysis*

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Abstract: In a market environment of power systems, each producer pursues its maximal profit while the independent system operator is in charge of the system reliability and the minimization of the total generation cost when generating the generation maintenance scheduling (GMS). Thus, the GMS is inherently a multi-objective optimization problem as its objectives usually conflict with each other. This paper proposes a multi-objective GMS model in a market environment which includes three types of objectives, i.e., each producer's profit, the system reliability, and the total generation cost. The GMS model has been solved by the group search optimizer with multiple producers (GSOMP) on two test systems. The simulation results show that the model is well solved by the GSOMP with a set of evenly distributed Pareto-optimal solutions obtained. The simulation results also illustrate that one producer's profit conflicts with another one's, that the total generation cost does not conflict with the profit of the producer possessing the cheapest units while the total generation cost conflicts with the other producers' profits, and that the reliability objective conflicts with the other objectives.

Key words: Generation maintenance scheduling, Market environment, Multi-objective optimization
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1 Nomenclature

The terminologies used in this paper are listed as follows:

$I(t,s)$	Reliability index in period t and subperiod s
$P_{\mathrm{G}_{ij}}(t,s)$	Power generated by unit j of producer i in period t and subperiod s
$v_{ij}(t,s)$	Online status for unit j of producer i in period t and subperiod s (1 if unit j is on in subperiod s of period t and 0 otherwise)
x_{ij}	Start week for maintenance of unit j of producer i
$y_{ij}(t,s)$	Start-up status for unit j of producer i in period t and subperiod s (1 if unit j is started up at the beginning of subperiod s of period t and 0 otherwise)
C_{kij}	The coefficients of the generation cost of unit j of producer i, (k=0, 1, 2)
C_{ij}^{M}	Maintenance cost ($/MW) of unit j of producer i
C_{ij}^{SU}	Start-up cost ($) of unit j of producer i
D_{ij}	Duration (number of time weeks) of the maintenance outage of unit j of producer i

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$P_{\mathrm{D}}(t,s)$	Power demand (MW) in period t and subperiod s
$P_{\mathrm{G}_{ij}}^{\max}$	Capacity (MW) of unit j of producer i
$P_{\mathrm{G}_{ij}}^{\min}$	Minimum power output (MW) of unit j of producer i
$R^{\min}(t,s)$	Net minimum reserve (MW) in period t and subperiod s
$\lambda(t,s)$	Energy price estimate (\$/MWh) for period t and subperiod s
N_i	Number of producers
$N_i(t)$	Maximum number of units in maintenance for producer i in period t
N_{t}	Number of time periods
N_{s}	Number of sub-periods in a time period
$T(t,s)$	Duration (number of hours) of subperiod s in period t
G_i	Set of indices of generation units owned by producer i
G	Set of G_i
d_{ij}	Continuous maintenance duration

2 Introduction

Maintenance scheduling (MS) is an important work in the operations of power systems. It is to reduce the total operation cost and maintain the reliability of the system while satisfying both maintenance and network constraints (Shahidehpour and Marwali, 2000). The MS is a complex, high-dimensional, non-linear, and mixed integer optimization problem. There are mainly two types of facility maintenance scheduling in power systems, i.e., the generation MS (GMS) and the transmission line MS, which could be studied independently. This paper focuses on the GMS, which has been studied in much literature (Christiaanse and Palmer, 1972; Kralj and Petrović, 1988; Marwali and Shahidehpour, 1998; Burke and Smith, 2000; Lu *et al.*, 2008; Yare *et al.*, 2008; Feng *et al.*, 2009; Yang and Chang, 2009b; Zhan *et al.*, 2011; Pandzic *et al.*, 2013; Schlünz and van Vuuren, 2013; El-Sharkh, 2014). A comprehensive overview of the GMS in the market environment is provided in Shahidehpour and Marwali (2000).

In the traditional power system, an appropriate GMS is generated by the system operator and imposed on producers. Christiaanse and Palmer (1972) proposed an automated scheduling of the maintenance of generating facilities, which is an early work on the GMS. Dopazo and Merrill (1975) proposed a fast and accurate method to solve the problem, in which the GMS was formulated as a 0-1 integer linear program problem. A survey of the GMS and its solution method was presented in Kralj and Petrović (1988). In Chen and Toyoda (1991), a decomposition technique based on virtual load was proposed for the GMS considering the network constraints. A decomposition method based on duality theory was proposed for GMS by Yellen *et al.* (1992). The heuristic methods, e.g., the memetic algorithm (Burke and Smith, 2000), the simulated annealing method (Saraiva *et al.*, 2011; Schlünz and van Vuuren, 2013), the group search optimizer (Zhan *et al.*, 2011), and the clonal selection algorithm (El-Sharkh, 2014) have been applied to solve the GMS.

In the market environment of the power system, the independent system operator (ISO) is in charge of maintaining the system reliability while the producers are pursuing their own profits (Conejo *et al.*, 2005). In fact, the ISO hopes that the units are maintained in low demand periods in order to increase the system reliability. However, every producer hopes to maintain its own units in low price periods in order to reduce the opportunity cost for maintenance outage and consequently maximize its own profit (Conejo *et al.*, 2005). Usually, the low demand periods and the low price periods do not match together exactly. Therefore, the ISO's objective and each producer's objective are clearly conflicting. Thus, the GMS is inherent a multi-objective optimization problem (MOP).

The MOP could be transformed into a single-objective optimization problem (SOP) using a weighted sum method (Deb, 2001; Heo *et al.*, 2011) or converting an objective into a constraint (Marwali and Shahidehpour, 1999; 2000; Wu L *et al.*, 2008; Pandzic *et al.*, 2012). The SOP transformed is then solved by a single-objective optimization method. In Marwali and Shahidehpour (1999; 2000), the system emission was treated as a constraint and then the GMS problem was solved by a Benders decomposition method. In Wu L *et al.* (2008), the coordination of the midterm generation maintenance outage schedule and the hourly price-based unit commitment was proposed for price-based GMS in restructured power systems. The control of both emission and risk was treated as constraints. In Heo *et al.* (2011), the reliability losses were transformed into the outage costs and different types of costs were added together as the total expected cost, which can be seen as a weighted sum method. The total cost was then minimized by the genetic algorithm to find the optimal maintenance strategy.

To obtain a coordinating GMS satisfying both the ISO and the producers, an interaction scheme between ISO and producers has been developed to generate and modify the maintenance schedule (Conejo *et al.*, 2005; Barot and Bhattacharya, 2008; Feng and Wang, 2010). In Conejo *et al.* (2005), a coordinating mechanism based on incentives/disincentives among producers and the ISO was proposed to encourage producers to modify their maintenance schedules in order to obtain an acceptable solution for both. In Barot and Bhattacharya (2008), the security coordinated MS in restructured power systems was solved by an iteration scheme, in which the generation companies (GENCOs) altered their maintenance plans in specific periods according to the corrective signals generated by the ISO until a maintenance plan with no unserved energy was achieved. In Feng and Wang (2010), based on its resultant costs/benefits, each producer submitted the maintenance bidding costs for its owned units to ISO. Then the ISO scheduled the units' outage periods to attain a fine balance among the bidding costs, the satisfactory degrees of units, and the possible load curtailment. At last, the ISO generated an appropriate cost settlement to determine the eventual expenditure or compensation for each producer. In Pandzic *et al.* (2013), the GMS was formulated as an equilibrium problem with equilibrium constraints corresponding to a multiple-leader-common-follower game, which could be recast as a mixed integer linear programming problem.

However, the conflicting relationship between the ISO and each producer has not been clearly analyzed. For example, are every two objectives conflicting with each other? What are the characteristics of the Pareto fronts between each two objectives? What is the cause for the conflicting relationship? In this paper, the conflicting relationship between different objectives is further analyzed. The analysis provided is expected to help to understand the objectives' relationship more comprehensively, help to choose objective functions better, and help to make a more reasonable decision.

Recently, multi-objective evolutionary algorithms (MOEAs) have received great attention (Wu QH *et al.*, 2008; Yang *et al.*, 2008; Mendoza *et al.*, 2009; Yang and Chang, 2009a; Guo *et al.*, 2012; Niknam and Doagou-Mojarrad, 2012). MOEAs could solve an MOP by simultaneously optimizing each objective, without using weights to sum up all the objective functions. Thus, MOEAs could obtain multiple Pareto-optimal solutions in a single run using no a priori knowledge. In Yang and Chang (2009a), an MS in composite power system in the centralized electric power system was solved by an MOEA, in which the conflicting relationship among the overall operation cost, the failure cost, and the reliability of the power system was analyzed. Wang and Pham (2011) studied a multi-objective optimization of imperfect preventive maintenance policy for dependent competing risk systems, in which both the system availability and system cost objectives were simultaneously optimized by the nondominated sorting genetic algorithm-II (NSGA-II).

The multi-objective GMS model can be transformed into a single-objective GMS through the weighted sum method, which is then solved by a mixed integer programming based method. The disadvantage of this method is that the weight values are not easy to obtain and they need to be finely tuned in different runs of the mixed integer programming based method in order to obtain a Pareto front. Another disadvantage of the mixed integer programming based methods is that the computational burden increases exponentially as the dimension of variables increases.

The presented GMS model employs an encoding technique for the variables, which makes the model suitable to be solved by MOEAs which use real number encoding, including the NSGA-II (Chen *et al.*, 2014), multi-objective particle swarm optimization (MOPSO) (Tripathi *et al.*, 2007), and group search optimizer with multiple producers (GSOMP) (Guo *et al.*, 2012). In our previous work (He *et al.*, 2009; Guo *et al.*, 2012), it has been proved that GSOMP has better performance than NSGA-II and MOPSO, especially on complex high-dimensional multi-objective optimization problems. Thus, the GSOMP presented in Guo *et al.* (2012) is employed in this paper to solve the GMS in the market environment.

Similar to the interaction scheme, the aim of our research presented in this paper is also to generate a coordinating GMS which satisfies both the

ISO and each producer. Instead of the interaction scheme, we include both the ISO and each producer's objectives in a multi-objective optimization model, which is then solved by GSOMP. Each producer's profit adopted as a separate objective in the multi-objective optimization model is to make sure that each producer is satisfied with the obtained coordinating GMS. The objectives, including each producer's profit, the reliability of the power system, and the total generation cost of all the producers, are optimized simultaneously and the conflicting relationship among them is analyzed. The advantage of solving the GMS using the GSOMP lies in that it is simple and can provide a holistic view of the conflicting relationship. Besides, GMS can be easily extended to consider more objectives, e.g., the pollutant emission, as the GMS with a few more objectives to be optimized is approximately the same problem for the GSOMP in terms of the resolution complexity.

It should be noted that the solution obtained in the interaction scheme is one of the Pareto-optimal solutions obtained by GSOMP. Obtaining a set of Pareto-optimal solutions instead of one single optimal solution provides the decision maker with more comprehensive understanding of all the feasible solutions to make a satisfactory final plan of GMS. If the decision maker is not satisfied with the current solution, it just needs to select another solution from the Pareto-optimal solutions obtained. However, the interaction scheme needs to run again in order to obtain a different solution. Besides, the GSOMP can be used to investigate the conflicting relationship between different objectives.

The multi-objective optimization can be executed by the ISO and the producers are to implement the decision obtained. The unified marginal price is adopted instead of the locational marginal price. The uncertainties involved in the GMS, including the load uncertainty, the price uncertainty, and the generating unit reliability are not considered in this paper. In other words, forecasts of load demand and market clearing prices are considered known and forced outage rates of units are considered to be zero. This assumption simplifies the solving of the GMS without any loss of generality, which was also adopted by other researchers as well (Chattopadhyay *et al.*, 1995; Conejo *et al.*, 2005; Barot and Bhattacharya, 2008). The novelty of our work focuses on the analysis of the relationship between the multiple objectives adopted in the paper and the cause of the relationship.

3 Encoding technique for generation maintenance scheduling

In a GMS model, there are four types of variables, i.e., the generation variable, the maintenance variable, the online status, and the start-up status. In this paper, the generation variable $P_{\mathrm{G}_{ij}}(t,s)$ is encoded into the real number (Chen *et al.*, 2014).

3.1 Maintenance variable

Traditionally, the maintenance variable is encoded into the binary number. For example, if a generator is continuously maintained in the 3rd and the 4th time periods, the maintenance variable is represented as $(0\ 0\ 1\ 1\ 0\ \cdots\ 0)$. In this paper, the maintenance variable is represented by two integer numbers: the start week of the generator x_{ij} and the continuous maintenance duration d_{ij}. Then the maintenance variable of the generator can be represented by: $x_{ij}=3$ and $d_{ij}=2$. The advantage of this encoding technique is that the maintenance outage duration constraint and the continuous maintenance constraint are automatically satisfied, which will reduce the number of constraints and consequently decrease the complexity of solving the GMS.

3.2 Online status

Traditionally, the online status $v_{ij}(t,s)$ is encoded into the binary number. In this paper, the online status is treated as the intermediate variable represented by generation variables, which will dramatically decrease the number of binary variables and consequently solve the GMS in an easier way:

$$v_{ij}(t,s)=\begin{cases}0, & P_{\mathrm{G}_{ij}}(t,s)<P_{\mathrm{G}_{ij}}^{\min},\\ 1, & P_{\mathrm{G}_{ij}}^{\min}\le P_{\mathrm{G}_{ij}}(t,s)\le P_{\mathrm{G}_{ij}}^{\max}.\end{cases} \tag{1}$$

The $P_{\mathrm{G}_{ij}}^{\min}$ of some generation units is greater than 0. In the implementation of GSOMP, the value of $P_{\mathrm{G}_{ij}}(t,s)$ is modified at random and it might be between 0 and $P_{\mathrm{G}_{ij}}^{\min}$. The online status is set to be 0 if its power output is smaller than $P_{\mathrm{G}_{ij}}^{\min}$.

3.3 Start-up status

To further decrease the number of variables in the model, the start-up status $y_{ij}(t,s)$ is treated as intermediate variables represented by the online status:

$$\begin{cases} y_{ij}(t+1,1)=\max\{v_{ij}(t+1,1)-v_{ij}(t,N_\mathrm{s}),\ 0\}, \\ y_{ij}(t,s+1)=\max\{v_{ij}(t,s+1)-v_{ij}(t,s),\ 0\}, \end{cases} \tag{2}$$

where $\max\{a,b\}$ means the maximal one of a and b.

Using the techniques given in this section, there are no binary variables, which dramatically decreases the dimension of the variables and makes the GMS very suitable to be solved by GSOMP. Besides, the GMS is also suitable to be solved by other MOEAs, e.g., NSGA-II (Chen *et al.*, 2014) and MOPSO.

4 Generation maintenance scheduling model

In this section, the GMS problem in the market environment of the power system is formulated as a multi-objective optimization model, in which each producer's profit, the system reliability, and the total generation cost are to be optimized simultaneously subjective to the maintenance constraints and the network constraints. The GMS model in which the maintenance status is encoded as the binary number can be obtained in Conejo *et al.* (2005). In this section, the maintenance variable of the GMS model is encoded into the integer number as described in Section 3.1.

4.1 Objectives

4.1.1 Producers' profit objective

In the market environment of a power system, each producer seeks for the maximization of its own profit. The profit can be calculated by subtracting the fuel cost, the start-up cost, and the maintenance cost from the revenue:

$$\begin{aligned} \text{Maximize}: F_i = &\sum_{j\in G_i}\sum_{t=1}^{N_\mathrm{t}}\Bigg\{\sum_{s=1}^{N_\mathrm{s}}\big\{\big[\lambda(t,s)P_{\mathrm{G}_{ij}}(t,s) \\ &-\big(C_{0ij}+C_{1ij}P_{\mathrm{G}_{ij}}(t,s)+C_{2ij}P_{\mathrm{G}_{ij}}^2(t,s)\big)\big]T(t,s)\big\} \\ &-C_{ij}^{\mathrm{SU}}y_{ij}(t,s)\Bigg\}-\sum_{j\in G_i}\sum_{t=1}^{N_\mathrm{t}}\Big[C_{ij}^{\mathrm{M}}P_{\mathrm{G}_{ij}}^{\max} \\ &\vee_{m=0}^{D_{ij}-1}\left(x_{ij}=(t-m)\right)\Big], \end{aligned} \tag{3}$$

where F_i $(i=1,2,3)$ represents the profit objective of producer i, and $\vee$ denotes the logic OR. The $(x{=}y)$ is equal to logic one if x is equal to y and logic zero otherwise.

4.1.2 System reliability objective

The system reliability objective is defined to be the minimization of the standard deviation of the reliability index defined in Eq. (5):

$$\begin{aligned} &\text{Minimize}: F_4=\mathrm{std}(I(t,s)), \\ &\qquad t=1,2,\cdots,N_t;\ s=1,2,\cdots,N_\mathrm{s}. \end{aligned} \tag{4}$$

$$\begin{aligned} I(t,s)=&\left[\sum_{i=1}^{N_i}\sum_{j\in G_i}P_{\mathrm{G}_{ij}}^{\max}\big(1-\vee_{m=0}^{D_{ij}-1}\big(x_{ij}=(t-m)\big)\big)\right. \\ &\left.-P_\mathrm{D}(t,s)\right]\Bigg/\left[\sum_{i=1}^{N_i}\sum_{j\in G_i}P_{\mathrm{G}_{ij}}^{\max}-P_\mathrm{D}(t,s)\right]. \end{aligned} \tag{5}$$

Objective (4) is to guarantee similar reserve capacity in each subperiod, no matter in high demand or in low demand subperiod. The reliability index $I(t,s)$ for period t and subperiod s is defined to be the net reserve divided by the gross reserve as shown in Eq. (5). The gross reserve in any subperiod is calculated as the difference between the sum of the capacity of all units and the power demand. The net reserve is calculated as the difference between the gross reserve and the power capacity in maintenance.

4.1.3 Total generation cost

The total generation cost of all the producers consists of the fuel cost, the start-up cost, and the maintenance cost, which is to be minimized as a maintenance scheduling is better with lower generation cost:

$$\begin{aligned} \text{Minimize}: F_5=&\sum_{j\in G}\sum_{t=1}^{N_\mathrm{t}}\Bigg\{\sum_{s=1}^{N_\mathrm{s}}\big[\big(C_{0ij}+C_{1ij}P_{\mathrm{G}_{ij}}(t,s) \\ &+C_{2ij}P_{\mathrm{G}_{ij}}^2(t,s)\big)T(t,s)\big]+C_{ij}^{\mathrm{SU}}y_{ij}(t,s)\Bigg\} \\ &+\sum_{j\in G}\sum_{t=1}^{N_\mathrm{t}}\Big[C_{ij}^{\mathrm{M}}P_{\mathrm{G}_{ij}}^{\max}\vee_{m=0}^{D_{ij}-1}\left(x_{ij}=(t-m)\right)\Big]. \end{aligned} \tag{6}$$

In this paper, there are five objectives in the GMS model which are optimized simultaneously by the GSOMP:

$$\text{Minimize} : F = [-F_1, -F_2, -F_3, F_4, F_5]. \quad (7)$$

4.2 Constraints

4.2.1 Minimum net reserve

Constraint (8) ensures a net reserve above a specified threshold for all periods and subperiods:

$$\sum_{i=1}^{N_i} \sum_{j \in G_i} P_{\mathrm{G}_{ij}}^{\max} \Big(1 - \vee_{m=0}^{D_{ij}-1} \big(x_{ij} = (t-m)\big)\Big) \\ - P_{\mathrm{D}}(t,s) \geq R^{\min}(t,s), \quad \forall t, \forall s. \quad (8)$$

4.2.2 Maximum number of units simultaneously in maintenance

Due to the limited resources, only a certain number of units can be maintained at the same time:

$$\sum_{j \in G_i} \vee_{m=0}^{D_{ij}-1} \big(x_{ij} = (t-m)\big) \leq N_i(t), \quad \forall i,\ \forall t. \quad (9)$$

4.2.3 Capacity and minimum power output

The power output of each online unit should keep between its minimum and maximum capacities:

$$v_{ij}(t,s) P_{\mathrm{G}_{ij}}^{\min} \leq P_{\mathrm{G}_{ij}}(t,s) \leq v_{ij}(t,s) P_{\mathrm{G}_{ij}}^{\max}. \quad (10)$$

4.2.4 Maintenance and online status

This constraint enforces that a unit cannot be online and in maintenance simultaneously:

$$\vee_{m=0}^{D_{ij}-1} \big(x_{ij} = (t-m)\big) + v_{ij}(t,s) \leq 1, \\ \forall j \in G_i, \forall t, \forall s. \quad (11)$$

4.2.5 Power balance

This constraint ensures a balance between the generation and the load demand:

$$\sum_{i=1}^{N_i} \sum_{j \in G_i} P_{\mathrm{G}_{ij}}(t,s) v_{ij}(t) = P_{\mathrm{D}}(t,s), \quad \forall t, \forall s. \quad (12)$$

The proposed model can satisfy the maintenance outage duration constraint and the continuous maintenance constraint automatically, which simplifies its resolving and thus increases the solution accuracy. The binary variables, including the online status and the start-up status, are treated as intermediate variables. Thus, there is no binary variable in the proposed model, which dramatically decreases the dimension of the variables and consequently reduces the computational complexity. In the meantime, the reduced number of constraints and variables can also reduce the computational burden.

5 Simulation results

To verify the effectiveness of the proposed GMS model, it has been solved by GSOMP on two test systems:

Case 1: A system with three generators and three producers.

Case 2: The IEEE reliability test system with 32 generators and three producers.

In GSOMP, the population size and the maximum iteration number in case 1 are set to be 400 and 800 respectively, and those in case 2 are set to be 800 and 800 respectively. Considering hourly subperiods requires hourly load and price data, which will cause a great increase of uncertainty and computation complexity. In this paper, the subperiod is set as one day, which is the trade-off of the accuracy and the computational complexity. The continuous maintenance duration d_{ij} of each generation is set to be two weeks. The generators' parameters used in cases 1 and 2 are tabulated in Tables 1 and 2 (Subcommittee, 1979), respectively. The generators in case 2 are divided into three producers such that their maximum generation capacities vary slightly. The load demand and the market price in cases 1 and 2 are taken from Subcommittee (1979) and a Spain Electric Energy Market (http://www.omel.es/frames/en/resultados/resultados_index.htm), and are plotted in Figs. 4 and 5, respectively.

Table 1 Generators' parameters used in case 1

Generator	C_{2ij}	C_{1ij}	C_{0ij}	$P_{\mathrm{G}_{ij}}^{\max}$	$P_{\mathrm{G}_{ij}}^{\min}$
1	0.010 59	8.3391	64.160	800	10
2	0.003 00	10.7600	32.960	700	0
3	0.010 88	12.8875	6.780	500	0

5.1 Relationship among the objectives of generation maintenance scheduling model

In this section, the encoding techniques presented in Section 3 are used when solving the GMS

Table 2 Generators' parameters used in case 2

P	G	C_{2ij}	C_{1ij}	C_{0ij}	$P_{\mathrm{G}_{ij}}^{\max}$	$P_{\mathrm{G}_{ij}}^{\min}$	$\dfrac{f\left(P_{\mathrm{G}_{ij}}^{\max}\right)}{P_{\mathrm{G}_{ij}}^{\max}}$
1	1	0.069 66	26.244	31.67	20	0	29.2206
1	2	0.069 66	26.244	31.67	20	0	29.2206
1	3	0.012 80	17.820	10.15	76	0	18.9264
1	4	0.012 80	17.820	10.15	76	0	18.9264
1	5	0.069 66	26.244	31.67	20	0	29.2206
1	6	0.069 66	26.244	31.67	20	0	29.2206
1	7	0.012 80	17.820	10.15	76	0	18.9264
1	8	0.012 80	17.820	10.15	76	0	18.9264
1	9	0.004 40	13.290	39.00	100	0	14.1200
1	10	0.004 40	13.290	39.00	100	0	14.1200
1	11	0.004 40	13.290	39.00	100	0	14.1200
1	12	0.010 87	12.887	6.78	197	0	15.0643
1	13	0.010 87	12.887	6.78	197	0	15.0643
1	14	0.010 87	12.887	6.78	197	0	15.0643
2	15	0.069 66	26.244	31.67	12	0	29.7189
2	16	0.069 66	26.244	31.67	12	0	29.7189
2	17	0.069 66	26.244	31.67	12	0	29.7189
2	18	0.069 66	26.244	31.67	12	0	29.7189
2	19	0.069 66	26.244	31.67	12	0	29.7189
2	20	0.002 40	12.330	28.00	155	0	12.8828
2	21	0.002 40	12.330	28.00	155	0	12.8828
2	22	0.002 40	12.330	28.00	155	0	12.8828
2	23	0.002 40	12.330	28.00	155	0	12.8828
2	24	0.003 00	10.760	32.96	350	0	11.9042
3	25	0.010 59	8.339	64.16	400	10	12.7357
3	26	0.010 59	8.339	64.16	400	10	12.7357
3	27	0.012 80	17.820	10.15	50	0	18.6630
3	28	0.012 80	17.820	10.15	50	0	18.6630
3	29	0.012 80	17.820	10.15	50	0	18.6630
3	30	0.012 80	17.820	10.15	50	0	18.6630
3	31	0.012 80	17.820	10.15	50	0	18.6630
3	32	0.012 80	17.820	10.15	50	0	18.6630

P: producer; G: generator; $f(P_{G_{ij}}^{\max})$: the generation cost of unit G_{ij} when its power output is at the maximum

by GSOMP in both cases 1 and 2. The bigger value of the profit objective of each producer is the better. Thus, the coordinates correspondent to these profit objectives are reversed to make the Pareto fronts always lie on the bottom left side (Figs. 1–3). It should be noted that the Pareto front of two, three, and more conflicting objectives is a curve, a three-dimensional curved face, and a high-dimensional curved face, respectively. To show the high-dimensional curved face on the two-dimensional paper, we give out the views from each two objectives as shown in Figs. 1–3.

The result of GMS obtained by GSOMP in case 1 is shown in Fig. 1, from which we can obtain the following relationship:

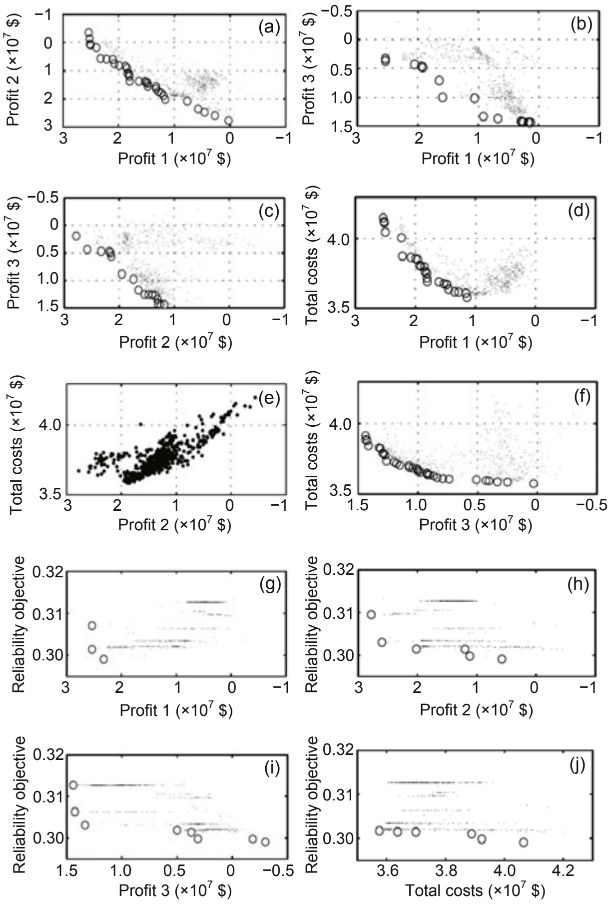

Fig. 1 Pareto fronts of GMS obtained by GSOMP in case 1: Pareto front viewed from objectives 1 and 2 (a); 1 and 3 (b); 2 and 3 (c); 1 and 5 (d); 2 and 5 (e); 3 and 5 (f); 1 and 4 (g); 2 and 4 (h); 3 and 4 (i); and 5 and 4 (j). Light-black points represent the Pareto fronts considering all the objectives; Dark-black circles represent the Pareto fronts considering only two objectives ((e) excluded)

1. One producer's profit and another one's profit have a conflicting relationship as shown in Figs. 1a–1c.

2. The profit of producer 1 conflicts with the total generation costs as shown in Fig. 1d.

3. The profit of producer 3 conflicts with the total generation costs as shown in Fig. 1f.

4. The profit of producer 2 and the total generation costs have a positive correlation relationship as shown in Fig. 1e. In other words, a solution with bigger profit of producer 2 has smaller value of total generation costs. The reason is that the units owned by producer 2 have the cheapest generation costs. The profit of producer 2 will increase as the generation of its units increases. At the same time, the total generation costs will decrease as the

proportion of the generation of units owned by producer 2 increases.

5. Figs. 1g–1j show that the reliability objective also conflicts with the other objectives. It should be noted that there are 800 Pareto-optimal solutions. However, there is only 48 different reliability objective values. The reason is that the reliability objective value is determined by the maintenance schedule solution and the load demand but not affected by the generation output values. However, the same maintenance schedule solution with a different generation output value is associated with a different Pareto solution. Thus, it is not curious to see that the Pareto fronts shown in Figs. 1g–1j locate in different straight lines.

The result of GMS obtained by GSOMP in case 2 is shown in Fig. 2, from which we can see that the relationship between each two objectives is similar to what is shown in Fig. 1. In case 2, 32 generators are maintained in 52 weeks and therefore there are a large number of maintenance schedule solutions. Thus, the straight-line shaped Pareto front in Fig. 1 does not appear in Fig. 2.

The generation units' data in case 2 have been provided in Table 2. It can be seen that generators 20–26 are the cheapest and generators 20–24 belong to producer 2. If we wish to obtain a GMS with low generation cost, generators 20–26 should generate power as much as possible which will simultaneously maximize the profit of producer 2. If the power generated by producer 2 decreases, the decreased power needs to be compensated by some more expensive generators, which will increase the total generation cost. Thus, the minimization of the total generation cost and the maximization of the profit of producer 2 have a positive correlation relationship. This supports the relationship between the profit of producer 2 and the total generation cost shown in Fig. 2e.

The conflicting relationship between each producer's profit objective in case 1 is further analyzed with the results shown in Fig. 3. It can be seen clearly from Fig. 3 that Pareto front 'P12' has small values of the 3rd objective, that Pareto front 'P13' has small values of the 2nd objective, and that Pareto front 'P23' has small values of the 1st objective. It should be noted that small value means bad value for each producer's profit objective. Thus, all the producers' profit objective should be optimized to ensure each producer's profit.

The analysis given above can help to select objective functions more reasonably. For instance, the objective function of the total generation cost and the profit objective function of the producer possessing the cheapest units have a positive correlation. Then we can simply adopt only one of these two objectives in the GMS model and consequently simplify the resolution of the model.

5.2 The cause for the conflicting relationship

The capacities in maintenance of each producer over each week in cases 1 and 2 are shown in Figs. 4 and 5. Figs. 4a–4c show the maintenance scheduling of the solutions with the maximal profit of producers 1, 2, and 3, respectively. It is shown in Fig. 4a

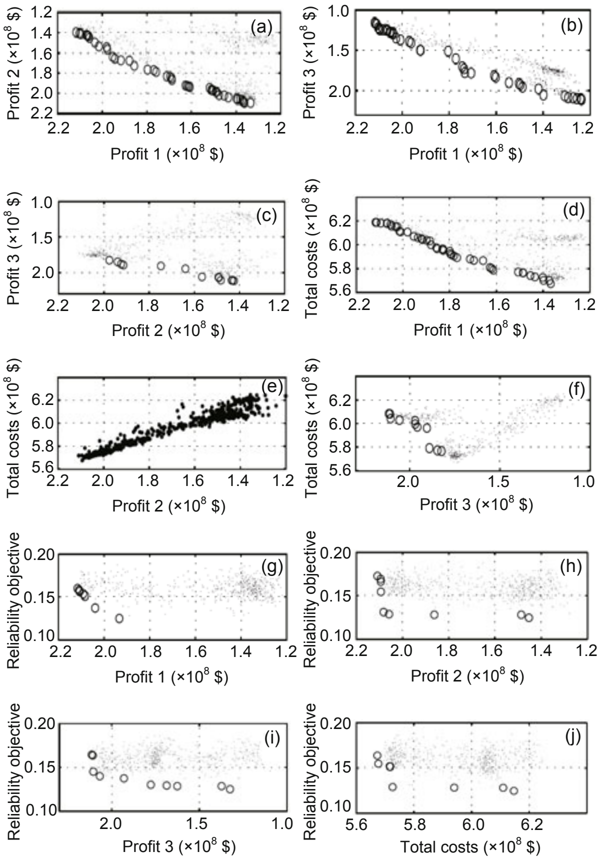

Fig. 2 Pareto fronts of GMS obtained by GSOMP in case 2: Pareto front viewed from objectives 1 and 2 (a); 1 and 3 (b); 2 and 3 (c); 1 and 5 (d); 2 and 5 (e); 3 and 5 (f); 1 and 4 (g); 2 and 4 (h); 3 and 4 (i); and 5 and 4 (j). Light-black points represent the Pareto fronts considering all the objectives; Dark-black circles represent the Pareto fronts considering only two objectives ((e) excluded)

that the units owned by producer 1 are maintained in the lowest-price weeks, i.e., the 7th and 8th weeks. In Fig. 4b, the units owned by producer 2 are also maintained in these lowest-price weeks. Similarly, the units owned by producer 3 are also maintained in these weeks as shown in Fig. 4c.

Figs. 5a.1–5a.3, 5b.1–5b.3, and 5c.1–5c.3 show the maintenance scheduling of the solutions with the maximal profit of producers 1, 2, and 3, respectively. Sub-figures (*.1), (*.2), and (*.3) show the maintenance scheduling of producers 1, 2, and 3, respectively (* represents a, b, or c). It is clearly shown in Fig. 5a.1 that units owned by producer 1 are maintained in the lowest-price weeks, i.e., the 46th–52nd, the 33rd and 34th, and the 13th and 14th weeks. Similarly, units owned by producers 2 and 3 are also maintained in these lowest-price weeks as shown in Figs. 5b.2 and 5c.3, respectively. In summary, the units owned by a producer are maintained in the lowest-price weeks in the solution with the biggest profit of that producer. The maintenance scheduling characteristics shown in Figs. 4 and 5 can be explained considering that the opportunity cost for maintenance is low when a unit is maintained in low-price weeks.

In addition to the maintenance scheduling, the power generation of each producer is also an important factor of its profit. The power generation of the solution with the biggest profit of producers 1, 2, and 3 is shown in Figs. 6a–6c, respectively. It should be noted that sub-figure (x) (x=a, b, or c) in Fig. 6 and sub-figures (x.1)–(x.3) in Fig. 5 come from the same solution, i.e., the solution with the biggest profit of producer y (y=1 if x=a, y=2 if x=b, and y=3 if x=c). In Fig. 6a, producer 1 almost always keeps generating the maximal capacities except the weeks in which its units are maintained. Similarly, producers 2 and 3 also have the maximal generation as shown in Figs. 6b and 6c, respectively. In a word, a producer's power generation reaches its maximum

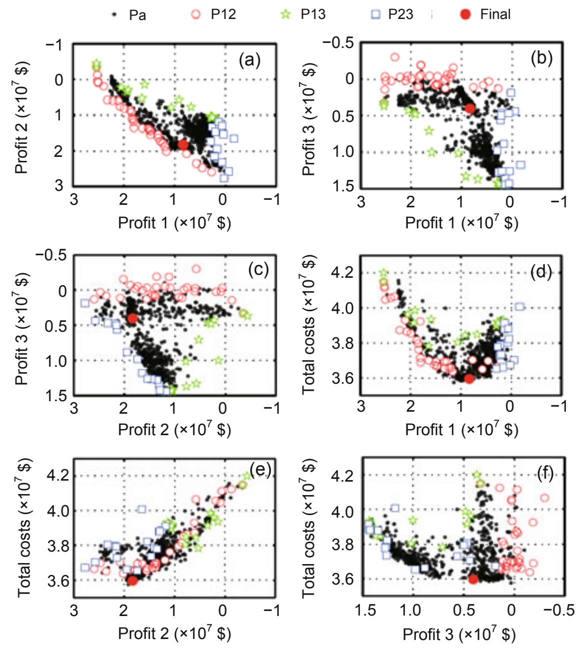

Fig. 3 Pareto fronts of each two producers and the final solution of GMS obtained by GSOMP in case 1: Pareto front viewed from objectives 1 and 2 (a); 1 and 3 (b); 2 and 3 (c); 1 and 5 (d); 2 and 5 (e); 3 and 5 (f). 'Pa', 'P12', 'P13', and 'P23' represent the Pareto fronts considering all the objectives, only the 1st and 2nd objectives, only the 1st and 3rd objectives, and only the 2nd and 3rd objectives respectively, and 'Final' represents the final solution. References to color refer to the online version of this figure

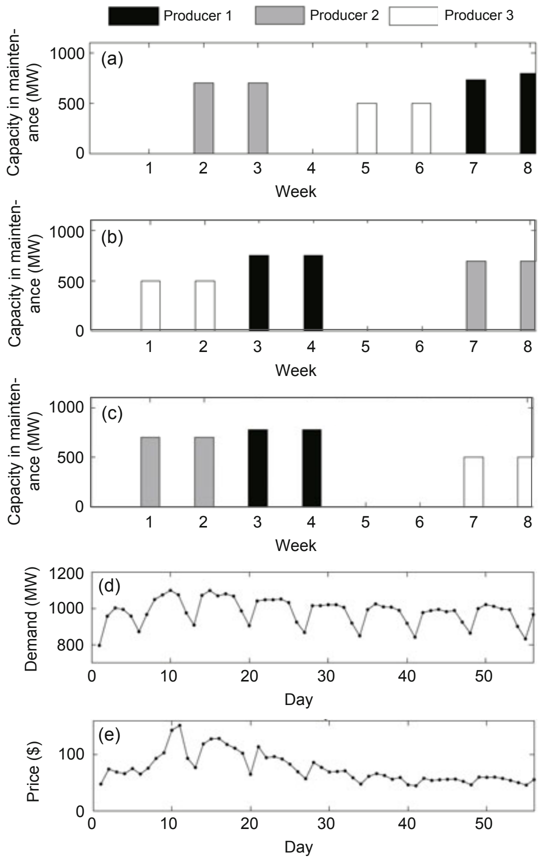

Fig. 4 Different maintenance scheduling in case 1: solutions with the maximal profit of producer 1 (a), producer 2 (b), and producer 3 (c); (d) load demand in each day; (e) price in each day

in the solution with the biggest profit.

Thus, we can come to the conclusion that a producer's profit is mainly affected by the maintenance scheduling and the power generation of its own units and that a producer tends to maintain its own units in the lowest-price weeks and generate as much power as possible to pursue the maximization of its profit. These are the reasons for the conflicting relationship among the three producers.

To show the effect of the reliability objective in the GMS, the capacity available in each day of the solution with the minimal reliability objective is given in Fig. 7. Due to the limited size of the paper, only the analysis of the solution in case 2 is given. Two types of reliability objectives are adopted in the GMS respectively for the sake of comparison: (1) The reliability is set to be the average of the reliability index I introduced by Conejo *et al.* (2005), and the corresponding result is shown in Fig. 7a; (2) The reliability objective is set to be the standard deviation of the reliability index I as shown in Eq. (4) and the corresponding result is shown in Fig. 7b. The price of each day is shown in Fig. 7c. It can be seen from Fig. 7b that a certain amount of gross reserve is guaranteed in each subperiod, no matter the high-demand subperiod or the low-demand subperiod. However, in Fig. 7a, in days 218–231, 323–336, and 352–358, the reserve capacity is relatively low. Thus, it is reasonable to set the reliability objective

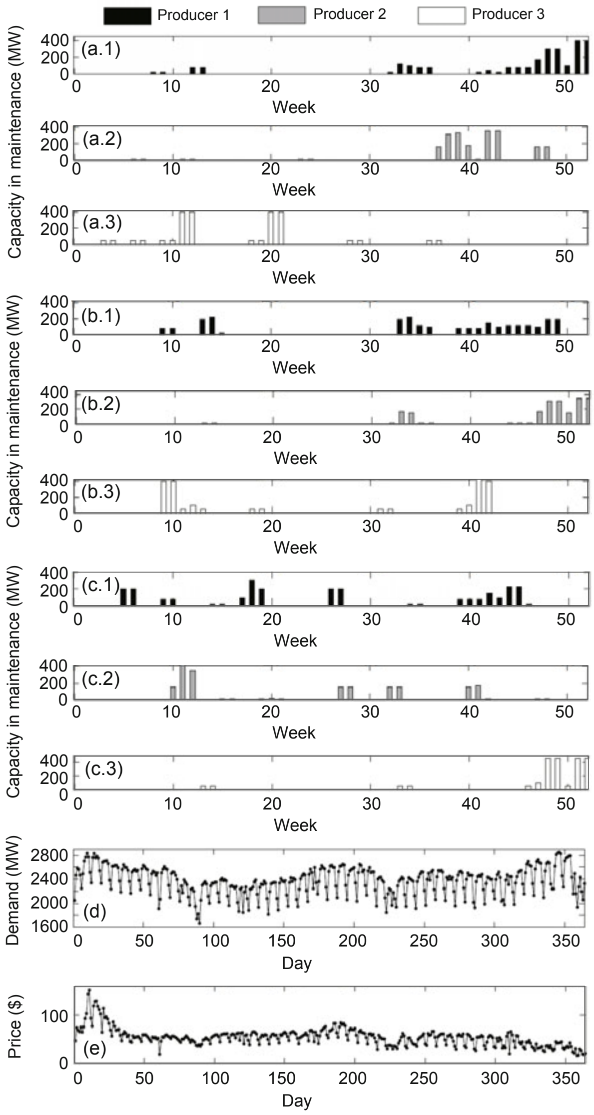

Fig. 5 Different maintenance scheduling in case 2: solutions with the maximal profit of producer 1 (a.1–a.3), producer 2 (b.1–b.3), and producer 3 (c.1–c.3); (d) load demand in each day; (e) price in each day

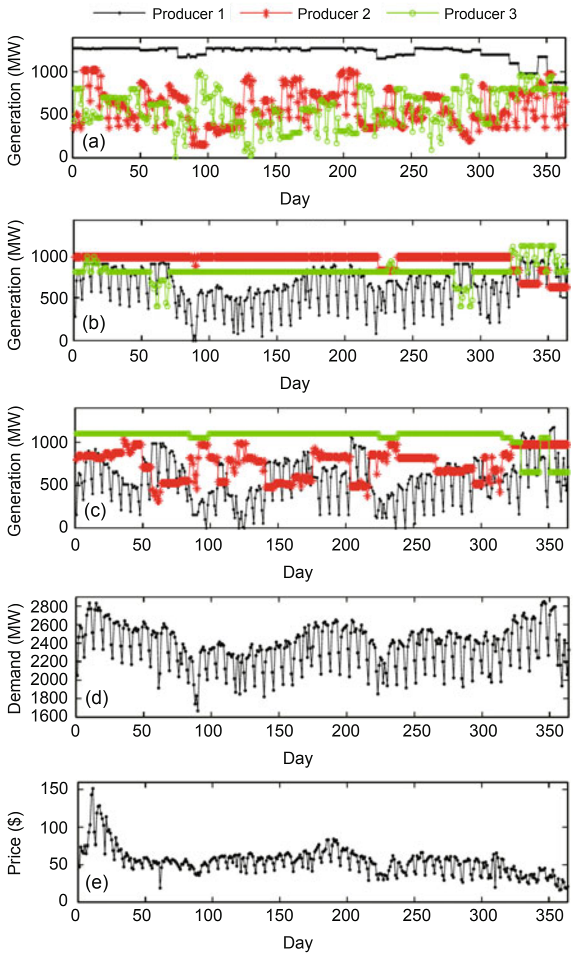

Fig. 6 Each producer's total power generation in case 2: solution with the maximal profit of producer 1 (a), producer 2 (b), and producer 3 (c); (d) load demand in each day; (e) price in each day

as the standard deviation instead of the average of the reliability index.

5.3 Determination of the final solution

The GSOMP has obtained a set of Pareto-optimal solutions above. Then the decision maker is to select one of them as the final solution. The advantage of solving GMS using GSOMP is that if the decision maker is not satisfied with the current final solution, he/she can simply select another one without solving the GMS again. In the following, the technique for order preference similar to an ideal solution (TOPSIS) (Hwang and Yoon, 1981), which is a practical and efficient multi-criterion decision making method, is employed to determine the final solution from the Pareto-optimal solutions obtained by GSOMP. This is a simple attempt to make a decision and is to be further researched.

The details of the TOPSIS can be obtained in Guo *et al.* (2012). Suppose that each objective has the same importance and then the final solution obtained in GMS in case 1 can be determined by TOPSIS, which is marked as the red-solid point in Fig. 3.

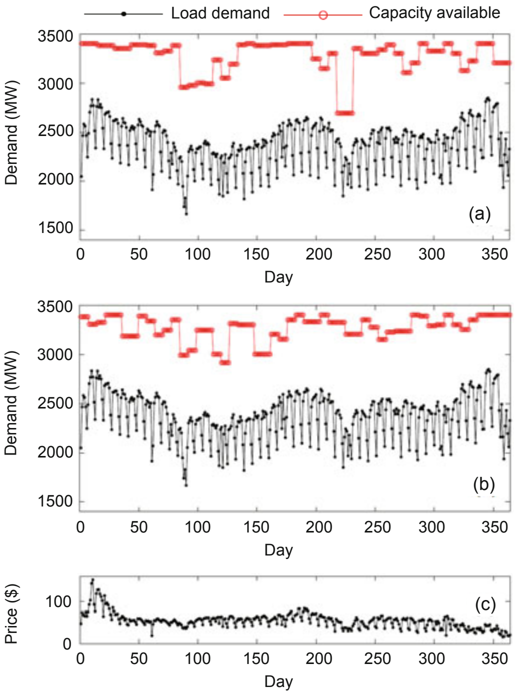

Fig. 7 The available capacity of the solutions of GMS with different types of reliability objective in case 2: reliability objective set as the average (a) and standard deviation (b) of the reliability index; (c) price in each day

It can be seen from Fig. 3 that the final solution does not lie on the Pareto front 'P12'. The reason is that the solutions on 'P12' have bad (small) value of profit of producer 3 and the final solution should have relative good value of each objective. Similarly, the final solution lies on neither of Pareto fronts 'P13' and 'P23'. It should be noted that for an objective which is to be maximized, a good (bad) value means a big (small) value. The final solution is a trade-off of all the objectives and can satisfy all the producers and the ISO as it has relatively good value of each objective.

6 Conclusions

This paper has presented a GMS in the market environment of power systems which is suitable to be solved by GSOMP. In the market environment, the system operator is in charge of maintaining an adequate level of reliability and the minimization of the total generation cost while each producer is pursuing the maximization of its own profits, which conflicts with the reliability and the total cost objectives. Thus, the GMS is inherent an MOP.

To solve the GMS by GSOMP, the maintenance status of generators is encoded into integer variables and both the online status and start-up status are treated as intermediate variables represented by the generation variables. The simulation results show that the GMS is well solved by GSOMP.

The simulation results illustrate that one producer's profit conflicts with another one's profit for the reasons that (1) each producer tends to maintain its own units in the lowest-price weeks but the maximal capacity in maintenance in each week is limited, and that (2) each producer tends to generate more power but the load in each day is fixed. The simulation results also indicate that the profit of the producer with the cheapest units does not conflict with the total generation costs while the other producers' profits conflict with the total generation costs. The proposed reliability objective also conflicts with the other objectives and can help to obtain a certain amount of reserve capacity in both high-demand and low-demand periods. At last, a practical and efficient multi-criterion decision making method, TOPSIS, is employed to determine the final solution from the multiple Pareto-optimal solutions.

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