Optimization of the Composition of Operating Units in Power Plants by Genetic Algorithm

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Abstract: One of the main tasks to be solved during planning the short-term modes of power systems is the optimization of compositions of operating units in power plants. In general case, it is a complex problem of nonlinear mathematical programming. Its solution, in essence, comes down to determining for each time interval of the planning period the composition of units to be put into operation or to be stopped. Currently, there are many methods and algorithms for solving of this problem. On the powers obtained at this stage and generalized energy characteristics, the optimal compositions of operating units in power plants are determined. The effectiveness of proposed algorithm is researched on the examples of power systems mode optimization with determination the composition of operating units in power plants. The high accuracy of results of optimization and the reliability of convergence of iterative process is ensured due to direct use in calculations the real, obtained in tabular form, energy characteristics of power plants with effective consideration of functional constraints by penalty functions, as well as due to the ability of genetic algorithm to solve multi-extremal problems without any simplifications.

1 INTRODUCTION

In problems of optimal planning of short-term modes of power system, the unevenness of consumers load schedules sets the conditions for changing the composition of operating units in power plants. In order to reliably provide consumers with high-quality electricity at minimal economic costs, it is advisable to use the optimal composition of operating units in power plants in each time interval of the planning period. Thus, here the task is to determine for each time interval of planning period the composition of units to be put into operation or to be stopped in power plants participating in optimization in accordance with the changing of load schedule,.

Currently, in the existing literature there are many methods and algorithms for solving the problem under consideration [1-13].

Due to the simplicity and ease of using, the most widely used algorithm is based on the preliminary construction of energy characteristics for all the possible combinations of operating units [1, 2]. According to this algorithm, stopping of the unit when the load decreases begins from that one, turning off which provides the greatest savings in fuel costs. By analogy with this in the intervals of increasing the consumer loads, the start-up of the next units begins from that one, in which the maximum savings of fuel costs is ensured.

Thus, the use of such algorithm provides for the multiple solution of the optimization problem to build a series of dependencies for each interval of the power system load change. In addition, the calculation of fuel costs using a simplified method, as well as considering the possibility of successively turning off (or turning on) the units when the load changes, introduces additional errors that reduce the effect of optimization.

The algorithms proposed in [3, 4, 9], which are based on the use of mixed integer linear programming, have also become quite widespread. However, they allow us to obtain the approximate solutions of the problem only.

In [5, 6], the use of classical Lagrange relaxation methods and the selection of options by priority for solving the problem under consideration are proposed. Despite the simplicity of the algorithm, these methods are characterized by problems associated with obtaining a solution with sufficient accuracy and a rather long duration of the calculation process. In [10], an algorithm for choosing the composition of units in power plants and determining their optimal capacities based on the differential assessment method is described. However, this algorithm has not found wide application for solving practical problems due to some computational difficulties.

In [7, 8], particle swarm optimization algorithms are proposed for solving the problem under consideration. They are based on the use of quadratic energy characteristics of plants, which are obtained by approximation the real characteristics of power plants, usually given in tabular form. These algorithms have good computational qualities and, in most cases, allow us to obtain the optimal solution of the problem with sufficient accuracy. Along with this, in some cases, they encounter difficulties associated with taking into account functional constraints in the form of inequalities, as well as decreasing the accuracy of the results due to the use of quadratic approximation functions of energy characteristics of power plants.

In connection with the indicated shortcomings, which have place for existing methods and algorithms for solving the problem under consideration, the problem of their improvement to overcome the above mentioned difficulties remains an urgent task. The urgency of the problem is also associated with the need to frequently solving of this problem for modern power systems, which include solar and wind power plants with significant capacity [12-14].

Over the past few years, a number of works on the use of artificial intelligence methods, in particular, a genetic algorithm, in solving the problems of optimization of modes of power systems, such as [7, 8, 15-17] have appeared. The positive features of the genetic algorithm, determined by the ability to work with objective functions that have discontinuities, determine the global extremum of multiextremal problems without simplifying them, creates a good conditions for their effective use in solving the problem under consideration.

This paper proposes an effective genetic algorithm for optimization of composition of operating units in power plants, taking into account regime and technological constraints, where many of the difficulties typical for existing algorithms are successfully overcome.

2 METHODS AND MATERIALS

To present the essence of the proposed algorithm, consider a power system containing only thermal power plants (TPPs) which are involved in optimization. Since if there are hydro power plants (HPPs) participating in optimization, they are taken into account using indefinite Lagrange multipliers, which physically represent the equivalents of the fuel costs of water consumption in them. Accordingly, at known values of these multipliers, multiplying them by the energy characteristics of the corresponding HPPs, we obtain equivalent fictitious TPPs (in calculation sense). Further optimization is carried out as for a power system containing only TPPs involved in optimization. The values of these multipliers can be determined as in [18,19]. The proposed algorithm provides for accounting for other types of power plants using existing methods that do not affect its efficiency.

Thus, the objective function, which is a function of the total fuel costs in the TPP of power system for the planning period T, has the following form (1):

$$F = \sum_{t=1}^{n_T} \sum_{i=1}^{n} \left[B_{it}(P_{it}, c_{it}) + B_{it}^{\mathrm{S}}(\tau_{it}, c_{it}) \right], \qquad (1)$$

where n, n_T are the number of TPPs involved in optimization and time intervals in considered period of planning the power system mode T, respectively; P_{it}, B_{it} – active power and fuel costs of i-th TPP in t-th time interval of the planning period; c_{it} is a combination of operating units in i-th TPP in t-th interval; τ_{it} is idle time of the i-th TPP unit after shuting down and start-up it in the t-th time interval; B_{it}^{S} - fuel costs associated with the start-up of the unit of i-th TPP (start-up consumption), left in the off state for a while τ_{it}. It also takes into account the costs associated with a reduction the service life of the unit as a result of the next start.

The dependence of the starting fuel consumption on the idle time of the unit is non-linear. However, it has been proven that when the idle time of the unit does not exceed 20 hours, the dependence is approximately linear and it passes through the origins of the coordinate axes. In this case, this function can be represented as $\tau \cdot B_{oi}^{\mathrm{S}}(c_i)$ and, in accordance with this, the optimization problem for the planning period can be reduced to the problem of interval optimization, when it is solved separately for each time interval. In this case the objective function for any interval is represented as follows:

$$F=\sum_{i=1}^{n}\left[B_i(P_i,c_i)+B_{oi}^{S}(c_i)\right], \qquad (2)$$

where $B_{0i}^{S}=\dfrac{B_i^{S}}{\tau_i}$.

Minimization of (2) by optimization the composition of operating units in TPPs and their respective capacities is carried out taking into account constraints on: the number of simultaneously started (or stopped) units, the balance of active power in power system (3)

$$W=\sum_{i=1}^{n}P_i-P_D-\pi=0 \qquad (3)$$

the minimum and maximum allowable powers of power plants (4)

$$P_i^{\min}\le P_i\le P_i^{\max}, \qquad (4)$$

the minimum and maximum power flows in controlled power transmission lines (PTL) (5)

$$P_l^{\min}\le P_l\le P_l^{\max}, \quad l\in L, \qquad (5)$$

where W is the function of unbalance of active power in power system; P_D is the total active load in power system; π is the total losses of active power in electrical networks of power system; P_i, P_i^{min}, P_i^{max} are calculated and maximum allowable powers of TPP; L is the set of PTL in which the active power flows are controlled; P_l, $P_l^{\min}$, $P_l^{\max}$ are calculated and specified limit values of the active power flow along the l-th controlled PTL.

In the proposed algorithm, the considered problem of integer programming is solved by methods of continuous mathematical programming. The calculations are carried out in two stages. At the first stage, for each TPP, according to the given energy characteristics of the units and all possible combinations of jointly operating units, a generalized energy characteristic is built. At the second stage, the optimization of the power system mode is carried out according to the generalized energy characteristics of TPP obtained at the first stage, taking into account all regime and technological constraints.

If the relative increments of fuel costs for units in TPP are given, then such characteristic for any particular combination of them is constructed by summing the abscissas of the units included in it by the equality of the relative increments in them.

Let is explain the methodology for construction the generalized energy characteristics of power plants using the example of TPP that has two possible combinations of operating units with the corresponding characteristics of relative increments (CRI) (Figure 1 a) and consumption characteristics (Figure 1 b) of fuel costs. Analyzing these CRIs, we can draw the following conclusions: at plant capacities in P_1^{min}–P_2^{min} range, the single possible composition of operating units is the composition corresponding to the characteristic 1, and in the range of P_1^{max}–P_2^{max} is the composition corresponding to the characteristic 2. To determine the power of the plant, at which it is necessary to switch from one composition of units to another one in range of P_2^{min}–P_1^{max} we should compare the fuel costs B_1 and B_2, determined for the operating conditions of combinations the units with characteristics 1 and 2, respectively. Let's assume that combination of units 2 differs from combination 1 by one included unit. In this case, B_2 should include in its composition the starting consumption of the newly switched on unit B^{S}_{o2}. For example, if at power P_2^{min} $B_1 > B_2$, then at the same point the transition to the composition with combination 2 is carried out. Otherwise, the transition point is searched in specified range P_2^{min}–P_1^{max}, at which the condition $B_1 = B_2$ is provided. At the transition point from composition of unit 1 to 2 the following equality is carried out (6):

$$\int_{P_1^{min}}^{P_{12}} b_1(P_1)dP_1=\int_{P_2^{min}}^{P_{12}} b_2(P_2)\cdot dP_2+B_{02}^{S}, \qquad (6)$$

where P_{12} is the power of the plant at the transition point; B_{02}^{S} is the starting consumption of fuel costs for the next unit to composition 1.

If $B_1<B_2$ remains within the range P_2^{min}–P_1^{max}, then the power at which the forced transition to the composition with combination 2 is carried out is P_1^{max}.

Figure 1 shows the generalized CRI obtained on the basis of the calculation according to the described algorithm (Figure 1 a) and the corresponding consumption characteristics of fuel costs (Figure 1 b) for the example under consideration.

In general case, in modern power plants there can be many combinations of compositions of operating units. Accordingly, obtaining a generalized energy characteristic for the plant by the described algorithm becomes a time-consuming, but solvable task. On the other hand, in many plants the simultaneous start-up of more than one unit is not allowed because technical reasons. In such cases, the construction of a generalized characteristic based on the determination of transition points to the next compositions of units is simplified by reducing the number of compared variants of combinations.

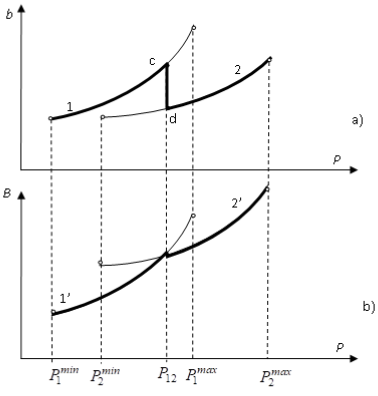

Figure 1: Construction of generalized characteristics of relative increments - a) and consumption characteristics of fuel costs - b) of TPP.

Thus, for the entire control range of each power plant, all transition points from one composition to another are determined. As a result, usually, sawtooth similar CRIs for plants are obtained (Figure 1 a). Accordingly, the resulting problem of optimization of mode of power system with such CRI of plants becomes multi-extremal.

After obtaining the generalized energy characteristics of power plants, the second stage of calculation is performed. Where the objective function which is the sum of the generalized consumption functions of TPPs involved in optimization is minimized (7):

$$F = \sum_{i-1}^{n} B_i(P_i) \to \min \qquad (7)$$

subject to all the above presented constraints.

The proposed algorithm provides for solving the last optimization problem by genetic algorithm. At the same time, to improve the convergence of the iteration process, the constraint on the balance of active power in power system (2) is taken into account by the allocation of a balancing plant. In this case, the power of this plant goes into the number of dependent variables. Therefore, the constraints on its maximum and minimum allowable values are taken into account using penalty functions in exponential form (8), (9):

$$P_1 = P_н + \pi - \sum_{i=2}^{n} P_i \, , \qquad (8)$$

$$G_{\max} = \alpha e^{\beta\left(P_1 - P_1^{\max}\right)}, \; G_{\min} = \alpha e^{\beta\left(-P_1 + P_1^{\min}\right)}, \qquad (9)$$

where α, β are weight (penalty) coefficients.

Accounting of functional constraints in the form of inequalities is also carried out by exponential penalty functions (10):

$$G_{l.\max} = \alpha_l e^{\beta_l\left(P_l - P_l^{\max}\right)} \; G_{l.\min} = \alpha_{l.} e^{\beta_{l.}\left(-P_l + P_l^{\min}\right)} \qquad (10)$$

The generalized objective function, which is minimized by the genetic algorithm, taking into account constraints (4), has the following form (11):

$$F = \sum_{i=1}^{n} B_i(P_i) + G_{\max} + G_{\min} + \sum_{l=1}^{L_P} G_{l.\max} + \sum_{l=1}^{L_P} G_{l.\min} \to \min \qquad (11)$$

According to the optimal capacities of powers and generalized energy characteristics obtained as a result of solving the last problem, the optimal compositions of the operating units in them are determined.

Due to the performance of optimization using the real, usually given in tabular form, energy characteristics of plants, their powers obtained at the second stage of calculation are automatically optimal for certain already optimal compositions of operating units in them. Unlike many existing algorithms for solving of this problem, it is not required to perform additional optimization of power system mode using energy characteristics for the selected optimal compositions of units in plants.

Thus, the calculations according to the proposed algorithm are performed in the following order:

1) construction of the generalized energy characteristics of power plants based on the determination of transition points in the CRI of individual combinations of units;
2) optimization of power system mode using the generalized energy characteristics of plants and taking into account all the constraints by genetic algorithm;
3) determination of the optimal compositions of operating units in power plants according to the corresponding ones obtained as a result of implementation of Section 2, plants capacities.

3 RESULTS AND DISCUSSION

The efficiency of the proposed algorithm was researched on the example of optimization the composition of operating units in the problem of optimal distribution of power system load of 800 MW between three TPPs with two units of the same type. The CRI of fuel equivalent consumption of one unit and reference fuel equivalent consumption at its minimum load are shown in Table 1.

Table 1: The characteristics of relative increments of fuel equivalent consumption of TPP units.

TPP – 1 B_0=35,2 t.f.e./h.	P_1, MW	100	108	115	130	159	188	210
	b_1, $\frac{t.f.e.}{MW \cdot h.}$	0.301	0.303	0.305	0.307	0.309	0.330	0.332
TPP – 2 B_0=28,5 t.f.e./h.	P_2, MW	80	96	109	110	160		
	b_2, $\frac{t.f.e.}{MW \cdot h.}$	0.316	0.317	0.319	0.334	0.3341		
TPP – 3 B_0=50,0 t.f.e./h.	P_3, MW	150	240	270	271	300		
	b_3, $\frac{t.f.e.}{MW \cdot h.}$	0.295	0.296	0.297	0.300	0.3001		

To compare the calculation results, Table 2 shows the results of optimal distribution of power system load at all the possible compositions of operating units in TPPs.

Table 2: The results of the optimal distribution of power system load between TPPs at various possible compositions of operating units.

TPP-1		TPP-2		TPP-3		Total fuel consumption, t.f.e./h.
Number of operating units	P_1, MW	Number of operating units	P_2, MW	Number of operating units	P_3, MW	
1	120.0	1	80.0	2	600.0	258.75
1	210.0	2	290.0	1	300.0	263.73
1	100.0	2	160.0	2	540.0	263.18
2	390.22	1	109.78	1	300.0	262.41
2	200.0	1	80.0	2	520.0	263.94
2	337.54	2	162.46	1	300.0	264.91
2	200.0	2	160.0	2	440.0	268.75

Comparing the results given in Table 2, we determine the mode in which the total consumption of fuel equivalent in TPPs is minimum 258.75 t.f.e./h. and the optimal compositions of operating units in them are 1, 1, 2, respectively. Table 3 shows the results of solving of the problem under consideration by the algorithm proposed here.

Comparing the results obtained in Table 3 with the reference one given in Table 2, we can verify the high accuracy of the proposed algorithm.

The effectiveness of the proposed algorithm was also studied in more complex example, where it is required to determine the optimal compositions of operating units in three TPPs with 5, 12 and 7 units of the same type, respectively, during the day with optimal coverage of the daily load schedule of power system shown in Table 4.

Table 3: The results of optimizing the composition of operating units by the proposed algorithm.

TPP-1		TPP-2		TPP-3		Total fuel consumption, t.f.e./h.
Number of operating units	P_1, MW	Number of operating units	P_2, MW	Number of operating units	P_3, MW	
1	120.0	1	80.0	2	600.0	258.75

Table 4: Daily load schedule of power system.

t, h. P_{Dt}, MW	1 3650	2 3500	3 3450	4 3550	5 3650	6 3800
t, h. P_{Dt}, MW	7 3900	8 4000	9 4100	10 4200	11 4150	12 4050
t, h. P_{Dt}, MW	13 3950	14 3900	15 3960	16 4000	17 4100	18 4200
t, h. P_{Dt}, MW	19 4400	20 4550	21 4590	22 4500	23 4200	24 3900

Table 5 shows the results of optimization the composition of operating units in TPPs, by the proposed algorithm for several hours of the day with total loads of 3500 MW, 4000 MW, 4500 MW and 4200 MW.

Table 5: The results of optimization the composition of operating units in TPPs.

t, h.	TPP -1		TPP-2		TPP-3		Total fuel consumption for the t-th interval, t.f.e./h.
	Number of operating units	P, MW	Number of operating units	P, MW	Number of operating units	P, MW	
1	5	1050	3	350	7	2100	1131.3
2	5	1050	6	850	7	2100	1302.1
3	5	1050	9	1350	7	2100	1473.0
4	5	1050	7	1050	7	2100	1370.2

In order to evaluate the effectiveness of the proposed algorithm, reference results are also obtained based on a simple selection and comparison of them for all possible combinations of operating units in power plants. Comparing them with the results shown in Table 5 showed their complete agreement.

Thus, the proposed algorithm for optimization the composition of operating units in power plants based on genetic algorithm allows us to reliably obtain the solution of the problem with high accuracy. A characteristic feature of genetic algorithm makes it possible to directly use the generalized energy characteristics of plants without their correction in order to reduce them to a convex programming problem. This ensures an increase the accuracy of optimization and, accordingly, the effect of optimization.

4 CONCLUSION

The paper has accomplished the following:

1) A new algorithm for optimization the composition of operating units in power plants of power system based on genetic algorithm, which allows us to obtain the optimal solution of the problem, taking into account regime and technological constraints in the form of equalities and inequalities with sufficient reliability and accuracy is proposed.
2) An increase the accuracy of the results when using the proposed algorithm is ensured by optimization with the direct use the real energy characteristics of power plants, which are usually specified in tabular form.
3) To implement the described algorithm for optimization the composition of operating units in power plants with direct use of their energy characteristics specified in tabular form, it is advisable to apply a genetic algorithm with real coding of variables.

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