An Effective Algorithm for Economic Dispatch of Power System with Prohibited Operating Zone

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Abstract. In the actual operation of the power system, some generating units may have physical limitations. For a unit with prohibited operating zone, its operation zone \([P_{min}, P_{max}]\) will be divided into several discrete sub feasible regions. In this paper, the influence of units with prohibited operating zone on the system is deeply studied, and the influence of units with prohibited operating zone on other units in the system, including the influence between units with prohibited operating zone, and the optimal solution state of economic dispatch problem for units with prohibited operating zone are further studied. Then the iterative algorithm for the above three problems is modified. At the same time, the economic law and physical essence of the economic dispatch problem for units with prohibited operating zone are explored. With high calculation efficiency, the algorithm proposed in this paper has its own engineering application value.

1. Introduction

The goal of economic dispatch of power system is to determine the optimal generation plan of generating units on the basis of satisfying various system constraints and generating unit constraints, so that the power system can meet the load demand with the minimum cost consumption. In the conventional economic dispatch problem, the unit combinations have been determined, and it is assumed that the output power of the generating unit is continuously adjustable between its lower limit and upper limit. In the actual operation of the power system, some generating units may have physical limitations. For example, in some operation zone, the vibration of the generator bearing will be amplified, in such condition, the prohibited operating zones of the generating units need to be set. For a unit with prohibited operating zone, its operation zone \([P_{min}, P_{max}]\) will be divided into several discrete sub feasible regions, and the output power of that unit can only be adjusted within the sub feasible region.

It can be seen that the economic dispatch problem with prohibited operating zone is a non-convex optimization problem. And the traditional optimization algorithms, such as Lagrange relaxation method and gradient method, will not be directly applied to solving economic dispatch problems. In view of such an optimization problem of discontinuous decision space, experts and scholars in many fields have conducted in-depth research. In the 1990s, Lee F.N. first proposed a model of economic dispatch for units with prohibited operating zone, and an economic dispatch method of classifying and decomposing the decision space was given [1]. The classified decision subspace is either infeasible or
can be directly solved by Lagrange relaxation method. The disadvantage is that the classification must be completed on the basis of determining the relationship curve between the optimal incremental rate of the system and the system load, while the acquisition of the discontinuous curve itself has certain complexity. When the system contains a large number of units with effective prohibited operating zone, the number of classification results is huge and twice iterations of calculation are required for each classification and decomposition except the first time. Fan J. Y. proposed a new algorithm [2] to divide the favorable decision space, and the most favorable decision space was selected by calculating the cost penalty term caused by each favorable decision space. Finally, the $\lambda$ iterative method was conducted on the most favorable decision space to obtain the optimal solution. However, the cost penalty term calculated in this paper ignores the situation that, in addition to the unit incumbent load with effective prohibited operating zone, the cost difference caused by the change of the system incremental rate $\lambda r$ and the multiple approximations in the calculation of the cost penalty term may lead to the generation of the suboptimal solution. Adhinarayanan T. studied the fast algorithm of economic dispatch problem for units with prohibited operating zone, and gave a fast algorithm [3] which only carried out twice $\lambda$ iterations, but it only got the suboptimal solution. The above literature studies the decision space deeply, so that the economic dispatch problem [4-7] for units with prohibited operating zone can still be solved by the traditional Lagrangian relaxation method, where $\lambda$ represents the marginal cost of unit power generation, which has a clear economic meaning.

In contrast, some intelligent algorithms, such as genetic algorithm [8-9], evolutionary algorithm [10-11], neural network algorithm [12] and particle swarm optimization algorithm [13-15], have been successfully applied to solve the non-convexity of the economic dispatch problem for units with prohibited operating zone and have achieved some results in the past two decades. Although the artificial intelligence algorithm can get the local or global optimal solution through more iterations, the calculation time is relatively long, which is not suitable for the economic dispatch decision of the actual power system.

In this paper, we deeply study the influence of units with prohibited operating zone on the system, and the influence of units with prohibited operating zone on other units in the system, including the influence between units with prohibited operating zone, and the optimal solution state of economic dispatch problem for units with prohibited operating zone are further studied. Then we modify the iterative algorithm for the above three problems. At the same time, the economic law and physical essence of the economic dispatch problem for units with prohibited operating zone are explored. With high calculation efficiency, the algorithm proposed in this paper has its own engineering application value.

2. Problem description
The prohibited operating zone of generating units divides the continuous operation zone of units into several discontinuous decision subspaces. The corresponding economic dispatch model can be described as follows:

The dispatch goal is to minimize the generation cost of the system:

$$\text{obj} = \min \sum_{i \in \Omega} F_i(P_i)$$

(1)

$$F_i(P_i) = a_i + b_i P_i + c_i P_i^2$$

(2)

In formula (1) and formula (2), $i$ is the generating unit number; is the set of all generating units in use that can be dispatched; $P_i$ is the output power of unit $i$; $F_i(P_i)$ is the fuel cost of unit $i$; $a_i, b_i, c_i$ is the cost characteristic coefficient of the generating unit $i$.

Formula (1) must meet the following constraints:

1) Power balance constraint:

$$\sum_{i \in \Omega} P_i = P_D$$

(3)

In formula (3), $P_D$ is the load value of system.

2) Upper and lower limits of unit output power:
In formula (4), \( P_{\text{max}} \) is the upper limit of the unit output power; \( P_{\text{min}} \) is the lower limit of the output power of unit \( i \); and \( \Omega \) is the set of all generating units in use with prohibited operating zone.

3) Output power constraint for units with prohibited operating zone

\[
P_{\text{min}} \leq P_i \leq P_{i,\text{max}}, \quad \forall i \in \Omega - \omega \quad (4)
\]

In formula (4), \( P_{\text{max}} \) is the upper limit of the unit output power; \( P_{\text{min}} \) is the lower limit of the output power of unit \( i \); and \( \omega \) is the set of all generating units in use with prohibited operating zone.

3) Output power constraint for units with prohibited operating zone

\[
P_{\text{min}} \leq P_i \leq P_{i,j}^{d} \quad \text{or} \\
P_{i,j}^{w} \leq P_i \leq P_{i,j}^{u} \quad \text{or} \\
P_{i,n}^{w} \leq P_i \leq P_{\text{max}} \quad \forall i \in \omega \quad (5)
\]

In formula (5), \( j \) is the prohibited operating zone number of the unit; \( n_i \) is the number of prohibited operating zone contained in unit \( i \); \( P_{i,j}^{d} \) is the lower bound of the prohibited operating zone \( j \) of unit \( i \); \( P_{i,j}^{u} \) is the upper bound of the prohibited operating zone \( j \) of unit \( i \).

It can be seen that if a unit \( i \) contains \( n_i \) prohibited operating zones, its operation zone will be divided into \( n_i + 1 \) discrete subregions, which together form a non-convex set. Therefore, the total number \( N \) of decision subspaces for a system containing \( \omega \) units with prohibited operating zone is:

\[
N = \prod_{n \in \omega} (n_i + 1) = \prod_{n \in \omega} (n_i + 1) \quad (6)
\]

In formula (6), \( \prod \) is the multiplication sign.

For each decision subspace, the output power of all generating units will be continuously adjustable in a certain region, so it can be solved by the classical Lagrangian relaxation method, and the global optimal solution is the minimum value of the solution results of all decision subspaces. However, for a practical system, when there are many units with prohibited operating zone, the total number \( N \) of decision subspaces will increase exponentially. Obviously, large scale calculation will not be conducive to the actual decision-making, indicating that this problem requires a more rapid and effective calculation method to solve.

3. Algorithm of solution

3.1. The impact of units with prohibited operating zone on the system

When solving the economic dispatch problem without considering the prohibited operating zone, the system power cost of the generating unit is the minimum according to the equal incremental rate criterion. Assuming that the optimal generation level of unit \( i \) is in the prohibited operating zone \([P_{i,j}^{d}, P_{i,j}^{u}]\), the prohibited operating zone \( j\{P_{i,j}^{d}, P_{i,j}^{u}\} \) of unit \( i \) is called the effective prohibited operating zone. At this time, no matter whether the output power of unit \( i \) is determined in the lower or the upper bound of the effective prohibited operating zone, it will increase the generation cost of the system. If the change of the incremental rate of other units in the system is ignored, the corresponding cost penalty for the increase is:

\[
P_{C_{i,j}}^{d} = \hat{\lambda}(\hat{P}_{i,j} - P_{i,j}^{d}) - [F_i(\hat{P}_{i,j}) - F_i(P_{i,j}^{d})] \quad (7)
\]

\[
P_{C_{i,j}}^{u} = [F_i(P_{i,j}^{u}) - F_i(\hat{P}_{i,j})] - \hat{\lambda}(P_{i,j}^{u} - \hat{P}_{i,j}) \quad (8)
\]

In formula (7) and formula (8), \( P_{C_{i,j}}^{d} \) is the cost increment when the output power of unit \( i \) is determined in the lower bound of the effective prohibited operating zone; \( P_{C_{i,j}}^{u} \) is the cost increment when the output power of unit \( i \) is determined in the upper bound of the effective prohibited operating zone; \( \hat{\lambda} \) is the optimal incremental rate of the system without considering the prohibited operating zone; \( \hat{P}_{i,j} \) is the optimal generation level of the unit \( i \) without considering the prohibited operating...
When the incremental rate is $\dot{\lambda}_{ij}$, $PC_{ij}$ is exactly equal to $PC_{ij}^u$, and $\dot{\lambda}_{ij}$ is defined as the average incremental rate of unit $i$ in the prohibited operating zone $j$. Combining formulas (7) and (8), with the elimination of intermediate variables, there is:

$$\dot{\lambda}_{ij} = \frac{F_i(u_{ij}^u) - F_i(u_{ij}^d)}{u_{ij}^u - u_{ij}^d}$$  \hspace{0.5cm} (9)

If $F_i(P_i)$ is a quadratic function, it can be proved that:

$$\begin{cases} 
\hat{\lambda} < \dot{\lambda}_{ij}, & PC_{ij}^d < PC_{ij}^u \\
\hat{\lambda} > \dot{\lambda}_{ij}, & PC_{ij}^d > PC_{ij}^u 
\end{cases}$$  \hspace{0.5cm} (10)

Substituting formula (2) into formula (9) can obtain:

$$\dot{\lambda}_{ij} = \frac{(a_i + b_i u_{ij}^u + c_i u_{ij}^{2u}) - (a_i + b_i u_{ij}^d + c_i u_{ij}^{2d})}{u_{ij}^u - u_{ij}^d}$$  \hspace{0.5cm} (11)

$$= \frac{b_i (u_{ij}^u - u_{ij}^d) + c_i (u_{ij}^{2u} - u_{ij}^{2d})}{u_{ij}^u - u_{ij}^d}$$

$$= b_i + 2c_i \left( \frac{u_{ij}^u + u_{ij}^d}{2} \right)$$

For units with quadratic cost function, there is:

$$\dot{\lambda}_i = \frac{dE_i(P_i)}{dP_i} = b_i + 2c_i P_i$$  \hspace{0.5cm} (12)

Comparing formula (11) and formula (12), if the output power corresponding to the average incremental rate of unit $i$ in the prohibited operating zone $j$ is the average output power of the prohibited operating zone, then the average output power of the prohibited operating zone is exactly equal to the output power at the midpoint of the corresponding prohibited operating zone. Therefore:

$$\begin{cases} 
\hat{P}_i < \frac{P_{ij}^u + P_{ij}^d}{2}, & PC_{ij}^d < PC_{ij}^u \\
\hat{P}_i > \frac{P_{ij}^u + P_{ij}^d}{2}, & PC_{ij}^d > PC_{ij}^u 
\end{cases}$$  \hspace{0.5cm} (13)

According to the above conclusion, the following solutions can be obtained:

1. Solve the economic dispatch problem without considering the prohibited operating zone of units, obtain the optimal output power for all units, and calculate the average output power of prohibited operating zone of all units.

2. If the output power of all units is not in the prohibited operating zone, the result obtained is the optimal solution, and the next step is (4). If the output power of a unit is in the prohibited operating zone, then compare the optimal output power $\hat{P}_i$ of the unit with the average output power $\frac{P_{ij}^u + P_{ij}^d}{2}$ of the corresponding prohibited operating zone. If $\hat{P}_i < \frac{P_{ij}^u + P_{ij}^d}{2}$, the output power $P_i$ of unit $i$ is determined as $P_{ij}^d$; if $\hat{P}_i > \frac{P_{ij}^u + P_{ij}^d}{2}$, the output power $P_i$ of unit $i$ is determined as $P_{ij}^u$. Keep the output power of other units with prohibited operating zone at their optimal output power.

3. Carry out economic dispatch calculation for the remaining load and determine the output power of the units without the prohibited operating zone.

4. Get the calculation result and stop the calculation.

The above algorithm can solve the economic dispatch problem of the units with prohibited...
operating zone by twice iterations with Lagrangian relaxation method, but it does not consider the
effect of the output power of the unit with effective prohibited operating zone on other units at its
prohibited zone boundary, so it can only get the suboptimal solution.

3.2. The impact of units with prohibited operating zone on other units in the system
Based on the equal incremental rate criterion of static economic dispatch, the incremental rate of
system is defined as the incremental rate of other units in the system except the units whose output
power is in the upper or lower bound of its prohibited zone and the units whose output power is in the
upper or lower limit of its output power.

Obviously, when the output power of the units with prohibited operating zone is determined at the
upper or lower bound of the prohibited operating zone, the average incremental rate corresponding to
this part of load will be increased or decreased, so the incremental rate corresponding to the optimal
solution of other loads in the system should also change, rather than remaining at the optimal
incremental rate $\lambda$ of the system. The above-mentioned algorithm is modified and Algorithm One is
obtained as follows:

1. Solve the economic dispatch problem without considering the prohibited operating zone of
units, obtain the optimal output power for units that have not determined their output power, and
calculate the average output power of prohibited operating zone of all units.

2. If the output power of all units is not in the prohibited operating zone, the result obtained is the
optimal solution, and the next step is (4). If the output power of a unit is in the prohibited operating
zone, then compare the optimal output power $P_i^{\lambda}$ of the unit with the average output power
$\frac{P_{i,j}^u + P_{i,j}^d}{2}$ of the corresponding prohibited operating zone. If $\hat{P}_i < \frac{P_{i,j}^u + P_{i,j}^d}{2}$, the output power $P_i$ of unit $i$ is
determined as $P_{i,j}^u$; if $\hat{P}_i > \frac{P_{i,j}^u + P_{i,j}^d}{2}$, the output power $P_i$ of unit $i$ is determined as $P_{i,j}^d$.

3. After correcting and determining the output power of the unit with the effective prohibited
operating zone, the next step is (1).

4. Get the calculation result and stop the calculation.

It can be seen that although Algorithm One needs to repeatedly correct the output power of the
units with prohibited operating zone but not in the effective prohibited operating zone, it can get more
accurate calculation results than the original algorithm, and the maximum number of iterations $M + 1$,
which makes the calculation of the problem change from exponential scale to linear scale, and $M$ is the
number of units in the prohibited operating zone.

3.3. The impact between units with prohibited operating zone
After the first $\lambda$ iterative calculation, if multiple units have effective prohibited operating zone, they
will affect each other. Assuming that the output power of a unit is determined at the upper or lower
bound of its prohibited operating zone, the optimal incremental rate corresponding to other loads in
the system will change correspondingly. Specifically, when the output power of a unit is determined at its
upper bound, the incremental rate will decrease correspondingly; when the output power of a unit is
determined at its lower bound, the incremental rate will increase correspondingly, and this change will
affect the determination of the output power of other units with the effective prohibited operating zone.
Physically, this is caused by the nonconvexity of multiple units in the system with discontinuous
operation region. When the system scale is small and the average output power of the effective
prohibited operating zone of a unit is close to its optimal output power, it will be more likely to have
an effect and make the calculation result deviate from the optimal solution.

In order to eliminate the above effects, if more than one unit is in the effective prohibited operating
zone after each iteration of step (1), it is necessary to determine the output power of one unit with the
effective prohibited operating zone to the upper or lower bound of the prohibited zone, and then carry out iterative calculation for all the remaining units. Therefore, it will be the key to choose which unit to the boundary of its prohibited operating zone.

The goal of economic dispatch is to minimize the cost of power generation. Therefore, in step (2), when the unit with the effective prohibited operating zone is selected for adjustment, the minimum impact on the economic dispatch results without considering the prohibited operating zone corresponding in step (1) must be considered. It can be proved that adjusting the output power of the unit with the minimum optimal output power difference $\Delta P^k_i$ between the average output power of the effective prohibited operating zone and the optimal output power of the corresponding unit in this iteration to the upper or lower bound of the prohibited operating zone will have the minimum impact on the generation cost of the system, where $k$ is the number of iterations, and $k \leq M$.

In fact, the unit's quadratic cost coefficient should also be taken into account when selecting the unit. However, since the impact of the corresponding adjustment on the system is proportional to the quadratic of $\Delta P^k_i$, selecting the unit with smallest $\Delta P^k_i$ as the unit to be adjusted during each iteration will be accurate enough.

### 3.4. Optimal solution state of economic dispatch problem of units with prohibited operating zone

As can be seen from the above research analysis, if a unit contains an effective prohibited operating zone in the iterative calculation process, then the output power of the unit will be determined at the boundary of its effective prohibited operating zone. This is consistent with the results of most cases of the economic dispatch problem of the units with the effective prohibited operating zone. However, there are a few cases where the optimal solution of the unit with the effective prohibited operating zone is not at the boundary of its effective prohibited operating zone, but in a small marginal domain. This is because when the output power of multiple units with prohibited operating zone is within their effective prohibited zone, their directions are inconsistent in the process of selecting its prohibited zone boundary, and the greater the power deviation in different directions, the greater the occurring possibility of this situation.

Therefore, it is necessary to adjust the direction of the calculation results once. The specific process is as follows: let $\theta$ be the set of units with effective prohibited operating zone in the iterative process. If the last iterative calculation result shows that the incremental rate of system is higher than the incremental rate of unit in the upper bound of the prohibited operating zone or lower than the incremental rate of unit in the lower bound of the prohibited operating zone in $\theta$, the iterative calculation should be carried out for the units in $\theta$ and the units without the effective prohibited operating zone. In fact, the above direction adjustment is carried out according to the criterion of equal incremental rate in economic dispatch, which is consistent with the objective of optimal dispatch.

### 4. Analysis of examples

In this paper, the validity of the above algorithm research is verified by 15-unit system and four-unit system respectively. The characteristic parameters of each unit in 15-unit system are consistent with those in [1], and the four-unit system has a different quadratic cost coefficient and prohibited operating region from those in [1]. The corresponding load values of the two calculation examples are 2650MW and 1386MW, respectively.

#### 4.1. Example analysis of 15-unit system

| Unit   | Space decomposition algorithm in [34] | Fast iterative algorithm in [36] | Algorithm One in this paper |
|--------|--------------------------------------|---------------------------------|-----------------------------|
| $P_1$/MW | 450                                  | 437.834                         | 450                         |
| $P_2$/MW | 450                                  | 455                             | 450                         |
It can be seen from Table 2 that compared with the method of decision space decomposition proposed in [1], Algorithm One in this paper does not need to preprocess the decision space and reduces the number of iteration times at the same time. Compared with the fast iterative algorithm in [3], the amount of calculation is increased, but better calculation results can be obtained.

In this example, when the iterative calculation is carried out for the first time without considering the prohibited operation zone of the unit, only unit five is in the effective prohibited operating zone. Therefore, the fast iterative algorithm in [3] keeps the output power of unit two, unit six and unit 12 as their optimal output power, whose corresponding incremental rate is higher than the incremental rate of other units in the system, only suboptimal solutions can be obtained. In fact, during the iterative calculation by Algorithm One, all the units in the case system with prohibited operating zone happen to have the effective prohibited operating zone, and only one unit in each calculation has the effective prohibited operating zone, so the maximum number of iterations of Algorithm One is $M+1=5$.

### 4.2. Example analysis of 4-unit system

#### Table 3 Comparison of output power of 4-unit system

| Unit  | Algorithm One in this paper | Algorithm Two in this paper | Algorithm Three in this paper |
|-------|-----------------------------|-----------------------------|-------------------------------|
| $P_1$/MW | 350                         | 350                         | 350.333                      |
| $P_2$/MW | 356                         | 335                         | 335                           |
| $P_3$/MW | 340                         | 350.5                       | 350.333                      |
| $P_4$/MW | 340                         | 350.5                       | 350.333                      |

#### Table 4 Comparison of generation cost and iteration times of 4-unit system

|       | Algorithm One in this paper | Algorithm Two in this paper | Algorithm Three in this paper |
|-------|-----------------------------|-----------------------------|-------------------------------|
| $obj$ | 17781.744                   | 17781.702                   | 17781.699                     |
| Iteration times | 2                          | 3                          | 4                            |
It can be seen from the example of four-unit system that the optimal output power of each unit is 1386/4 = 346.5, which is greater than the average output power of effective prohibited operating zone of unit one of 325 and that of unit two of 345.5, because the cost characteristics of four units are the same without taking into account the influence between the units containing the effective prohibited operating zone. Therefore, the average output power of unit one and unit two will be both at the upper bound of their effective prohibited operating zone.

After considering the influence between the units with the effective prohibited operating zone, the difference between the optimal output power of unit one and the upper bound power of the effective prohibited operating zone is small, so it is necessary to adjust the optimal output power of unit one to its upper bound of the effective prohibited zone will have a small impact on the system. At this time, the optimal output power of the remaining units two, three and four is (1386-350)/3 = 345.33, which is lower than the average output power of effective prohibited operating zone of unit two, so we adjust the output power of unit two to its lower bound of effective prohibited operating zone in the second iteration.

In the process of adjusting the output power of the units with the effective prohibited operating zone, because the directions of two adjustment are inconsistent, the system incremental rate is higher than the corresponding incremental rate of the upper bound of the effective prohibited operating zone of unit one. Therefore, a direction adjustment is needed, and the optimal solution is obtained through Algorithm Three in this paper.

5. Conclusion
In this paper, an efficient iterative algorithm is proposed to solve the economic dispatch problem for units with prohibited operating zone. For a unit with prohibited operating zone, its output power can only be adjusted in the discontinuous operation domain, which will result in the non-convex decision space of the economic dispatch problem, so it cannot be solved directly by the traditional Lagrangian relaxation method. Through the in-depth study of the characteristics of the economic dispatch problem of units with prohibited operating zone, this paper discusses and analyzes the influence of units with prohibited operating zone on other units in the system and the influence between units with prohibited operating zone and the optimal solution state of the economic dispatch problem of units with prohibited operating zone. Based on the above three aspects of research, the iterative algorithm is modified. While solving the calculating, the economic law and physical essence of the economic dispatch problem of units with prohibited operating zone are explored. The algorithm proposed in this paper has high calculation efficiency, and the maximum number of iterations of the algorithm is less than $M+2$, where $M$ is the number of units with prohibited operating zone in the iterative process. The validity of the above research is verified by the analysis of examples.

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