Bi-objective Optimization of Black Start Allocation for Regional Power Grid

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Abstract. Under the influence of extreme weather events, black start allocation is more and more important for regional power grids lack of hydroelectric units and pumped-storage aggregates. This paper proposes a bi-objective optimization model considering both the time of the whole restoration and the risk of line recovery, an improved TOPSIS method is employed to solve the problem based the non-inferior solution. The results of the Dongguan power grid verify the effectiveness of this method.

1. Introduction

More and more extreme weather events have caused frequent power outages in recent years, which makes black start play a crucial role in the first stage of the restoration after the blackout. All provinces belonged to China Southern Power Grid have been required to make their own black start schemes and areas vulnerable to natural disasters must have their own black start units [1]. Therefore, the research on the black resource allocation for regional network is of great importance. Most studies on black resource allocation are mainly about the investment of unit transformation [2]. Additionally, the reliability is often more important than the economy of the black start scheme [3]. Besides the reliability of the black start unit itself, it’s also important to strengthen the energizing path to the non-black start units [4].

This paper focuses on optimization of the black start allocation to minimize both time and risk of the restoration after power system black out, considering the unit’s starting characteristics, network topology, charging path and line failure. We employ a bi-objective programming method to provide a recommendation for decision-makers, aim to benefit the efficiency and reliability of power system restoration.

2. Black-start unit selection

Hydroelectric generating units, pumped storage hydroelectric plants, gas turbine generator sets, and FCB thermal power units are usually used as black start power sources. The first two are often considered to be the best black start units, but practically not every regional network owns hydropower plants due to the geographical constraints. Due to the high transformation cost of FCB units, gas turbine generators will be given priority in practical engineering applications.

Gas turbine generator set has the advantages of fast start-up speed, short transformation cycle and
low transformation cost, its practical applications in the field of black start is relatively mature. Gas turbine generator sets are generally divided into two types: combined cycle power plant (CCPP) units and internal combustion engines. This paper is mainly about the black start allocation of the CCPP units due to the higher proportion in the national grid.

3. Black-start allocation model

3.1 Feasibility study of CCPP units’ transformation
A CCPP unit is a complex system with a gas turbine, steam turbine and a heat recovery steam generator working together. It’s often required to be equipped with a diesel generator of sufficient capacity to drive the start motor. For example, a 9E-class CCPP unit can work as black start source with a 2MW diesel engine unit. In addition, enough fuel capacity is needed to avoid refueling interruptions after a blackout, pledging that the CCPP units possess the self-start ability.

3.2 Generator model
After the power outage, the unit will go through three stages: starting-up, grid-connection and ramping up, then the unit will be recovered to normal run state.

3.2.1 CCPP unit model. Since the CCPP unit can start up quickly without auxiliary power and the needed starting power is rather small, we make an assumption that it can start at zero and always have the highest ramp rate until the unit maximum output power. The model of black start units during the system restoration is shown in figure 1.

In figure 1, \( t_0 \) is the time when the CCPP unit start up, i.e. \( t_0 = 0 \). The unit then starts to ramp up at time \( t_c \) to reach its technical maximum output \( P_{\text{max}} \) at time \( t_m \); \( K_B \) is the unit ramp rate. The relationship among the variables is formulated as:

\[
t_m = t_c + \frac{P_{\text{max}}}{K_B}
\]

3.2.2 Non-black start unit model. The model of non-black start units during the system restoration is shown in figure 2. The unit need power \( P_{\text{st}} \) to be started; \( P_N \) is the units’ maximum power output; \( a \) is the ratio between the units’ minimum technical output and maximum power output.

The ramping up of the non-black start units can be roughly divided into two stages. In the first stage, the units’ ramp rate is assumed to be \( K_{N1} \). In the second stage, the units have stronger climbing capacity and the units’ ramp rate is \( K_{N2} \); \( K_N \) (the dotted line) is the average of the two stages for simplicity [5]. According to figure 2,

\[
t_m = t_{\text{st}} + \left( t_c - t_{\text{st}} \right) + \frac{P_{\text{max}} + P_{\text{st}}}{K_N}
\]
3.3 Unit start-up sequence model

Actually, the primary objective of the black start service is the restoration of the guaranteed network. Since the establishment of the guaranteed network is to satisfy consumers’ basic needs and ensure that the important load can stay alive, the scale of the guaranteed power grid accounts for a little of the whole power grid. Therefore, when the last unit starts up in sequence and reaches its technical maximum output, we can say that the restoration of the guaranteed network is approximately completed.

3.3.1 Restoration time. The time when a single unit reaches its maximum output is related with the unit’s starting time, grid-connected time, capacity and ramp rate, while the time when the last unit output reaches the top depends on the restoration sequence and the energizing path. Besides these, measured by statistics, the output of all generators can cover the power demand of the guaranteed network. Therefore, restoration time of the guaranteed network is determined as the time the last unit needed to reach its maximum output, which can reflect the efficiency of the regional power grid restoration. The restoration time of the black start scheme \( k \) can be represented as:

\[
T_k = \max \{ t_m^j \} \tag{3}
\]

\( t_m^j \) is the time when the unit \( j \in J \) reaches its technical maximum output.

3.3.2 Unit start-up sequence optimization. The unit start-up sequence is determined by objective (3) and the constraints are as follows:

\[
0 < t_{j,st} < t_{j,st,max} \tag{4}
\]

\[
t_{j,st,\min} < t_{j,st} \tag{5}
\]

\[
P_i(t_i) - P_{st,i} \geq 0 \tag{6}
\]

\[
t_{j,st} \geq t_{i,j} + t_{st} \tag{7}
\]

Constraints (4)- (5) are respectively about the units’ maximum critical hot-start time \( t_{j,st,max} \) and minimum critical cold-start time \( t_{j,st,\min} \). Constraint (6) makes sure that the total power provided by the energized system is bigger than the starting power needed by the units ready to start. \( P_i(t_i) \) is the power available for the generator de-energized at the current time and \( P_{st,i} \) is the starting power needed by unit \( j \). Constraint (7) on the transmission lines’ charging time is based on the assumption that the charging time of each line is the same. The shortest path from the bus \( i \) to unit \( j \) can be calculated by Dijkstra’s algorithm, \( t_{i,j} \) is the charging time.
3.4 Risk of line recovery

Blackout accident caused by the extreme weather events is often accompanied by line trip, then the automatic reclosing will work to make the transmission line re-energized. However, this method can be useless and we call it’s a permanent fault, in this case the risk of the black start will be greatly increased, hence we should select the path with the lowest risk in the black start.

This paper defines the risk of line recovery based on the probability of permanent line fault and network topology. The risk of the scheme \( k \) is as follows:

\[
R_k = \sum_{i=1}^{L} \sum_{j=N_{total}}^{P_i} (N_i + \frac{B_j}{B_{total}})
\]  

(8)

\( R_k \) represents the risk of the black start scheme; \( L \) is the number of lines \( (i \in L) \); \( P_i \) is the probability of permanent line fault under the influence of extreme weather events, which can be obtained by the formula in [6]; \( N_i \) is the number of substations that cannot be re-energized due to permanent line fault; \( B_i \) is the sum of the capacity of units that fail to be started; \( N_{total} \) is the number of substations in the guaranteed grid; \( B_{total} \) is the sum of the capacity of all generator sets.

3.5 Optimization model of black start unit’s location

Considering the different dimensions of the time and the risk, we adopt the min-max normalization to simplify the subsequent calculation. Then the black start allocation problem can be modeled as a bi-objective optimization, which considers both reliability and rapidity of the black start allocation:

\[
\min \begin{cases} 
T_k = \frac{T_k}{\max T_k} \\
R_k = \frac{R_k}{\max R_k}
\end{cases}
\]  

(9)

4. Method to solve the bi-objective optimization model

4.1 Pareto non-inferior solution

For this bi-objective optimization problem, if a limited number of \( K \) solutions can be listed, the objective values of them are as shown in figure 3.

As figure 3 illustrates, scheme 3 is better than 4 for the objective 1, scheme 4 is better than 3 for the objective 2, so we cannot say which one is better. The same as to the scheme 1 and 5, but the scheme 1 and 5 are better than 3 and 4 for the both two objectives. Except for the scheme 1, 2 and 5 which cannot be compared with each other, the other schemes are all worse than them. The scheme 1, 2 and 5 are called non-inferior solutions ultimately [7].

![Figure 3. The illustration of non-inferior solution.](image)

4.2 The improved TOPSIS method

After obtaining the non-inferior solutions, this paper proposes an improved TOPSIS method to transform the bi-objective optimization model into a single objective optimization problem. For a multi-objective
problem, we want to find a solution that can enable every objective to attain to the optimum. Yet, such optimal solution doesn't exist in most cases. To solve this, the TOPSIS defines a ‘distance’ between the feasible solutions and the ideal point corresponding to the optimal solution, if we can find a nearest feasible one and this solution is called the best compromise solution \[8\]. In two-dimensional space, the ‘distance’ between two coordinate points is defined as (\(p=2\)):

\[
d_p = \left[ (x_1 - x_2)^p + (y_1 - y_2)^p \right]^{\frac{1}{p}}, \quad p \geq 1
\]

Considering the priority weights of targets are different, the improved TOPSIS introduces a weighted distance combined with formula (8) to set up a single objective optimization model:

\[
\min \sqrt{\alpha (T_k - T_0)^2 + \beta (R_k - R_0)^2}
\]

\((T_0, R_0)\) is the coordinate of the ideal point; \(\alpha\) and \(\beta\) are weighting coefficients of the two targets which can be determined by the specific requirements of the regional power grid.

5. Case study

In order to prove the effectiveness of this method, the guaranteed network of Dongguan power system is studied. As shown in figure 4, there are 24 transmission lines, 18 substations, and 7 power plants in the guaranteed network. The line voltage of 5, 8, 15, 18, and 24 are 110kV, and the others are 220kV.

![Figure 4. The guaranteed power grid of Dongguan.](image)

From table 1 we know that Dong Tang is a thermal power plant which is too hard to be transformed, we can only consider the other 6 plants, i.e. \(K=6\). The restoration time and risk of each black start allocation are calculated and normalized in table 2.

| Station     | Total Capacity (MW) | Unit Capacity (MW) | Type       |
|-------------|---------------------|--------------------|------------|
| Zhang Yang  | 360                 | 180×2              | CCPP       |
| Tong Ming   | 360                 | 180×2              | CCPP       |
| Dong Xing   | 360                 | 180×2              | CCPP       |
| Hu Men      | 180                 | 180                | CCPP       |
| Gao Bu      | 360                 | 180×2              | CCPP       |
| Dong Tang   | 285                 | 150+135            | thermal    |
| Dong Xing B | 940                 | 470×2              | CCPP       |

Figure 5 is based on table 2 to find the non-inferior solutions. As we can see, schemes 3 and 6 are the non-inferior solutions. And then we set the coordinate origin as the ideal point since the restoration time and risk should be as small as possible. Considering reliability is often more important than rapidity in the process of black start, the value of \(\alpha\) is 0.35 while \(\beta\) is 0.65.

| k | Black Start Source | \(T_i\) | \(R_i\) |
|---|-------------------|--------|--------|
| 1 | Zhang Yang        | 1      | 1      |
| 2 | Tong Ming         | 0.85   | 0.617  |
| 3 | Dong Xing         | 0.73   | 0.578  |
6 Dong Xing B is the best option to be transformed as the black start unit from table 3, this solution can successfully minimize the restoration time of the guaranteed network and the risk of line recovery simultaneously.

Table 3. The result of the optimal allocation.

| k  | Black Start Source | $T_k^*$ | $R_k$ | $\sqrt{\alpha (T_k - T_{k^*}) + \beta (R_k - R_{k^*})}$ |
|----|--------------------|---------|------|------------------------------------------------|
| 3  | Dong Xing          | 0.73    | 0.578| 0.635                                             |
| 6  | Dong Xing B        | 0.85    | 0.471| 0.630                                             |

6. Conclusion
To find the optimum scheme of black start allocation for regional power grids under the extreme weather events, this paper proposes a bi-objective optimization model considering both the time and risk of the restoration. An improved TOPSIS is employed to solve the problem and the results show that the black start allocation can ensure the efficiency and reliability at the same time.

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