Reactive power compensation optimization configuration method to reduce the risk of multi-circuit DC commutation failure

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Abstract. Aiming at the risk of simultaneous commutation failure of multiple DCs in multi-infeed DC areas, a reactive power compensation optimization configuration method to reduce the risk of multiple DC commutation failures is proposed, and the type, location and capacity of reactive power compensation devices are configured. Firstly, the type of reactive power compensation devices is determined by comparing SVC and STATCOM simulation; Secondly, the weak voltage area through typical faults in multi-infeed DC areas is found, and then the best reactive power compensation site is determined according to the concept of node relative transient voltage drop area RTVDAI index; The aim is to reduce the effect index of commutation failure risk and project economy, the best installation plan is determined by controlling the investment cost and reducing the risk of commutation failure. The closeness in the entropy method is used to evaluate the advantages and disadvantages of each capacity configuration plan, and then CFTOOL toolbox in MATLAB is used to fit the comprehensive analysis index of nearness. The optimal installation capacity is determined by analyzing the fitting curve of the closeness comprehensive analysis index. Finally, the engineering applicability of the configuration scheme was verified through simulation.

1. Introduction

With the increasing number of DC transmission lines put into operation in my country Southern Power Grid and East China Power Grid, multiple DC feeds into the AC grid have formed a complex multi-infeed DC system. AC system failures often cause the DC system converter bus voltage to drop, which in turn leads to DC System commutation failed [1-4]. If the simultaneous commutation failure, it will have a greater power impact on the receiving end system [5,6], and seriously threaten the safe and stable operation of the multi-infeed DC system [7, 8].

Improving the reactive voltage support capability of the receiving end system is an important means to reduce the risk of commutation failure. In addition to the system's own means such as adjusting the grid structure and optimizing the operation mode of the system, additional reactive power compensation equipment is usually considered to improve the dynamic reactive power support capacity after a failure. Therefore, a lot of research has been carried out on reactive power compensation devices [9-12] in AC power grids, mainly including two key issues of reactive power compensation device location selection and optimal configuration.
Existing research [13-15] mostly focuses on the location of reactive power compensation devices. Due to the large scale of the power grid, it is not efficient and unnecessary to use the entire power grid as the research object. Therefore, it is usually necessary to determine the corresponding weak area of voltage stability to reduce the search space and determine the optimal installation location. Most literatures rely on electrical distance to quickly determine the weak area, but the accuracy is not high. Therefore, literature [14] is based on simulation analysis to find the weak area, but the selection of the fault set is not typical. In the research of determining the best installation site of reactive power compensation device, literature [15] determines the installation site based on the reactive power compensation installation effect evaluation index of voltage sensitivity, which fails to reflect the impact on other nodes of the system.

There are relatively few studies on the optimal configuration of reactive power compensation device capacity. Literature [15] uses the cyclic point method to determine the installation capacity, but fails to optimize the installation capacity in detail. Literature [16] determines the commutation failure of reactive power compensation capacity. In the risk reduction effect index, the DC power is used to measure the supporting capacity of the receiving end grid to the DC system, and the interaction between AC and DC hybrid systems is not considered.

Therefore, this paper considers the reactive power interaction between the DC systems, and proposes an optimized configuration method for reactive power compensation devices to reduce the risk of multi-circuit DC commutation failure. This method uses the analysis of the typical fault set near the DC drop point and performs fault scanning to more accurately determine the voltage weak area, and then determine the best reactive power compensation device installation site. In order to reduce the risk of multi-circuit DC commutation failure with the best effect and minimize the cost of reactive power compensation, the reactive power optimization configuration [17,18] is carried out. Compared with the existing literature, the transient power impact of the DC system and its impact on the overall reactive power interaction characteristics are considered more carefully, so that the impact of the DC system on the receiving end power grid, Thus, the influence degree of the DC system on the power grid is obtained. The entropy method [19] is used to evaluate the configuration plan and obtain the comprehensive analysis index of fit. The CFTOOL curve fitting toolbox in MATLAB is used to fit the discretized closeness comprehensive analysis index data in order to determine the reactive power compensation capacity. Finally, the validity of the scheme is verified by simulation of the typical operation mode of East China Power Grid.

2. Analysis of key issues in reactive power optimal allocation

The optimal configuration of reactive power in multiple DC feed-in areas is particularly important for maintaining the stability of the grid voltage and improving economy. In the reactive power optimization configuration, choosing the best installation site can maximize the impact of the reactive power compensation device on the stability of the system. The reasonable configuration of the reactive power compensation device capacity is related to the stable operation of the system and the economics of the project. In the case of poor quality and system instability, the capacity configuration of the reactive power compensation device is analyzed.

In order to select reactive power compensation sites accurately and efficiently, the weak area is generally determined based on typical faults. The effectiveness of dynamic reactive power compensation in this area is higher than other areas, and then the installation site is determined in the weak area. With the goal of reducing the risk of commutation failure and the lowest cost, the capacity configuration of the reactive power compensation device is carried out, so as to take into account the stable operation of the multi-infeed DC regional system and the economy of the power grid.

The idea of solving the dynamic reactive voltage problem in this paper is in Figure 1:
Reactive power optimization configuration

- Determine reactive power compensation site
- Determine reactive power compensation capacity
- Objective function: \( \min f(u) = \{ f_1(u), f_2(u) \} \)
  - \( f_1(u) \) means cost
  - \( f_2(u) \) means reduce the commutation failure effect index
- Use entropy method to evaluate it and obtain comprehensive analysis index of closeness
- Use the CFTOOL toolbox for fitting, analyze the fitting curve to get the best configuration capacity

**Figure 1.** Idea map to solve the problem of dynamic reactive voltage.

### 3. Determination method of reactive power optimal allocation location

#### 3.1. AC/DC hybrid receiving end grid voltage weak area

Before and after the failure of the receiving end AC system, the configuration of the same capacity reactive power equipment at different locations has different support effects on the system. After the system fault is cleared, the area in the system where the voltage recovers the slowest or is the first to lose stability is the area with the lowest voltage in the whole network—the weak voltage area. There is a weak voltage area in the multi-infeed DC grid, and the effectiveness of installing dynamic reactive power compensation in this area is higher than that in other areas. Therefore, in order to be able to correctly excavate the weak voltage area, it is necessary to consider simulating multiple faults in different areas. Some typical faults are selected in the proposed area for simulation analysis. By scanning various faults, the system voltage stability under various conditions can be roughly divided into 3 categories in Table 1:

| Case 1 | All N-1 faults and DC unipolar blocking faults and AC N-2 faults |
|------|-------------------------------------------------------------|
| Case 2 | AC N-2 fault in DC bipolar blocking and partial maintenance mode |
| Case 3 | N-2 fault with partial maintenance mode |

As the tide increases, the main faults affecting the stability of the system are the DC bipolar blocking and the N-2 fault during the AC channel maintenance.

Through the simulation analysis of the typical faults affecting the voltage stability of the system, when the faults happen in the areas where multiple DCs are concentrated feed, the areas with the most serious voltage drops, as the weak areas of voltage stability in the power grid, are discovered.

#### 3.2. Reactive power compensation candidate site

In order to select the best dynamic reactive power compensation node in the weak voltage area, the concept of node relative transient voltage drop area index RTVDAI[20] is introduced. After a three-phase permanent short-circuit fault occurs at a certain node, the degree of voltage fluctuation at the remaining nodes in the system indicates the level of impact of the faulty node on their transient voltage.
The RTVDAI value is defined as:

\[
I_{RTVDAI,i} = \begin{cases} 
\frac{\sum_{j=1}^{N} (t_{end} - t_{start}) (u_{j,0} - u_{j,min})}{N} & u_{j,min} \leq 0.7u_{j,N} \\
0 & u_{j,min} > 0.7u_{j,N}
\end{cases}
\] (1)

Where: \(I_{RTVDAI,i}\) is the RTVDAI value of the remaining nodes with respect to node i after the failure of node i; N is the number of nodes other than node i; \(t_{start}\) is the moment when the voltage of node j drops to 70% of the rated value for the first time; \(t_{end}\) is the time when the voltage of node j returns higher than 70% of the rated value from it below; \(u_{j,0}\) is the voltage at node j when the system is operating stably before the fault; \(u_{j,min}\) is the lowest voltage at node j after the fault; \(u_{j,N}\) is the rated voltage at node j.

Through time domain simulation calculation, the best dynamic reactive power compensation DC line drop point and the RTVDAI of the primary and secondary cross-section nodes of the outgoing line are obtained. After sorting, the best dynamic reactive power compensation site location can be determined.

4. Optimized configuration scheme to reduce the risk of multi-circuit DC commutation failure

4.1. Selection of reactive power compensation device type

The simulation results of the positive sequence voltage and reactive power of STATCOM and SVC under the three-phase short-circuit N-1 fault are given as follows.

![Simulation of STATCOM and SVC](image)

*Figure 2. Simulation of STATCOM and SVC positive sequence voltage and reactive power.*

It can be seen from Figure 2 that STATCOM can provide more capacitive power than SVC during a fault, and STATCOM generally exhibits a faster response than SVC. Therefore, the reactive power balance and voltage stability can be maintained to a greater extent, which is beneficial to reduce the influence of voltage fluctuations, thereby reducing the risk of DC commutation failure. At the same time, because the reactive power generated by the SVC device is affected by the system voltage, the installation capacity of SVC is 2 to 3 times that of STATCOM and the installation area of SVC is greatly reduced under the same effect. Therefore, this article uses STATCOM as the reactive power compensation device in the DC feed area.
4.2. Economic cost analysis of reactive power compensation

At present, the static synchronous compensator (STATCOM) is a relatively common reactive power compensation device used in the power system, and is an important part of the flexible AC system. The role of STATCOM in the power system is to perform reactive power compensation, improve the voltage stability of the system, and improve the stable performance and dynamic performance of the system, but the operating and reactive power compensation costs are relatively high. Among them, \( f_1 \) represents the cost of the dynamic reactive power compensation device, and the calculation formula is:

\[
 f_1 = \sum_{i} C_{\text{pur}} Q_i
\]

where \( C_{\text{pur}} \) indicates the unit price of STATCOM reactive power compensation (ten thousand yuan/MVar); \( Q_i \) indicates the compensation capacity; \( H \) is the candidate node set.

According to the literature [7], the typical parameters of STATCOM that have been put into operation are \( C_{\text{pur}} = 84.8 \) Ten thousand yuan /MVar;

4.3. Commutation failure risk of multi-circuit DC

In the multi-fed DC system, the commutation failure recovery process will cause a large amount of loss of active power and increase the demand for reactive power. The longer the duration of the commutation failure, the more likely it is to cause system instability. Dynamic reactive power compensation can quickly provide reactive power after a fault, improve the recovery characteristics of the arc extinguishing angle, and shorten the duration of commutation failure. In order to analyze the role of reactive power compensation in reducing the risk of DC commutation failure, the commutation failure risk reduction effect index is proposed from the perspective of the root cause of commutation failure. The risk of commutation failure is defined as the product of the probability of failure and the duration of DC commutation failure. The calculation formula of the commutation failure risk reduction effect index is

\[
 E_s = \sum_{k=1}^{w} \rho_k \left( \sum_{i=1}^{\xi} / \sum_{j=1}^{\xi} \Delta T \right)
\]

where \( w \) is the total number of key faults; \( \rho_k \) is the probability of occurrence of fault \( k \). This article considers that the probability of occurrence of all faults is equal, which is \( 1/w \); \( \xi / \sum_{j=1}^{\xi} \) is the weighting coefficient of DC \( v \), where, \( \xi_v \) and \( \xi_j \) are the influence of DC \( v \) and \( j \) on the power impact of the receiving end system respectively. The larger the value \( \xi_v / \sum_{j=1}^{\xi} \), the greater the power loss after commutation failure, and the greater the DC weighting coefficient. \( \Delta T \) is the duration of commutation failure. After installing reactive power compensation, the duration of commutation failure will usually decrease, so \( E_s \) is generally a negative value. The smaller \( E_s \), it means that the reactive power compensation according to this scheme can minimize the duration of commutation failure and can reduce the risk of DC commutation failure more effectively.

4.4. How to determine the best plan

In order to improve the stability of the AC/DC hybrid system operation and the interests of the grid company, the goal is to reduce the risk of multi-DC commutation failure and the cost of reactive power compensation. Therefore, the objective function of this paper can be expressed as:

\[
 \min f(u) = \{ f_1(u), f_2(u) \}
\]

where the installed capacity \( u \) of the reactive power compensation device is the control variable, \( f_1 \) represents the cost of the dynamic reactive power compensation device; \( f_2 \) represents the difference in the risk of DC commutation failure before and after the installation of the dynamic reactive power compensation. Among them, \( f_2 \) is expressed by the commutation failure risk reduction effect index.
There are dimensional differences in the evaluation of cost and commutation failure risk reduction indicators. In order to eliminate the dimensional differences between different indicators and provide decision-makers with a certain decision-making basis, this paper adopts a multi-objective decision-making scheme based on an entropy weight evaluation method, when there is only a judgement matrix but no expert weights. This method is used to evaluate a scheme with multiple evaluation indicators through the entropy calculation of the multi-object evaluation matrix with respect to multiple indicators, and perform optimal evaluation of multiple reasonable schemes, the preferred scheme with higher reliability is obtained.

This paper selects the entropy method [19] to standardize the investment cost and the commutation failure risk reduction effect index, so that it is no longer affected by the data level and dimension. The steps for solving the evaluation problem with two evaluation indicators of investment cost and commutation failure risk reduction effect index and t schemes as evaluation objects are as follows:

1) Standardize the non-fuzzy evaluation matrix \( R' = [r_{ij}]_{2\times t} \) through formula (5) to obtain the standardized evaluation matrix \( R = [r_{ij}]_{2\times t} \). The standardized index value is
\[
r'_{ij} = \frac{\max(r_{ij}) - r_{ij}}{\max(r_{ij}) - \min(r_{ij})}, i = 1, 2; j = 1, 2, \ldots, t
\]
where \( r_{ij}' \) is the calculated index value.

2) The entropy of the i-th evaluation index is defined as
\[
H_i = -\frac{1}{\ln t} \sum_{j=1}^{s} f_i \ln f_i
\]
where \( f_i = r_{ij} / \sum_{j=1}^{s} r_{ij} \) and suppose: when \( f_i = 0 \), \( f_i \ln f_i = 0 \).

3) The entropy weight of the i-th evaluation index is \( k_i \), which is defined as
\[
k_i = \frac{1 - H_i}{\sum_{i=1}^{s} H_i}
\]

4) Use the entropy weight \( k_i \) to normalize the matrix \( R \) to obtain the attribute matrix \( B = [b_{ij}]_{2\times s} = [k r_{ij}]_{2\times s} \), \( b_{ij} \) is the index value with entropy weight.

5) Find the ideal point \( P^* = [p_1^*, p_2^*, \ldots, p_t^*] \), \( i = 1, 2, \ldots, t \). The negative ideal point is \([0, 0, \ldots, 0]^T \). Find the closeness \( T_j \) between the jth scheme and the ideal point, the formula is
\[
T_j = 1 - \frac{\sum_{i=1}^{s} (b_{ij} p_i^*)}{\sum_{i=1}^{s} (p_i^*)}
\]
Sort \( T_j \) from small to large. The smaller the value of \( T_j \), the closer to the ideal point, and the better the solution.

The specific steps are as follows. The candidate points for reactive power compensation are determined through typical faults, and then the best installation node is determined according to the RTVDAI value. After finding the best compensation site, the capacity configuration should be carried out under the lowest investment cost plan. The steps for capacity configuration are as follows:

1) In order to allocate resources reasonably, at the determined optimal compensation site, under certain investment cost conditions, reactive power compensation devices installed at several or all of the sites and set up k groups of plans. In the case of power compensation device, the degree of commutation failure reduction effect index determines the best installation plan.

2) According to the best installation plan determined above and referring to the principle of reactive power configuration of the power system, on the premise of ensuring the safe and stable operation of the system, The STATCOM maximum dynamic reactive power compensation rated capacity of the best compensation install site to be setted as ±1800MVar, the reactive power compensation capacity is divided into m grades with an accuracy value of ±100MVar. With the help of PSD-BPA software, the fault scan is performed under the typical fault in the weak voltage area, and
the DC power level before and after the STATCOM is installed under each capacity level and typical fault set is recorded.

3) Calculate STATCOM’s investment cost and commutation failure risk reduction effect index under different installation capacities according to formulas (2) and (3).

4) Using the entropy-weighted multi-objective decision-making method of program evaluation, standardize the investment cost and commutation failure risk reduction effect indicators, and obtain a standardized evaluation matrix that eliminates the dimensional difference between different indicators, and normalize it Constraint to obtain the index value of the entropy weight, and finally calculate the closeness T of each scheme to the ideal point according to the entropy weight value. The smaller the closeness degree, the closer the closeness degree is to the ideal value, that is, an optimal solution with higher reliability is obtained.

5) According to the obtained STATCOM, the comprehensive closeness analysis index is obtained under different compensation capacities. With the help of the CFTOOL curve fitting toolbox in MATLAB, the discretized closeness comprehensive analysis index data is fitted to obtain the comprehensive closeness analysis index. The relationship between the closeness comprehensive analysis index and the STATCOM dynamic reactive power compensation capacity function of the site is established. Then, their corresponding relationship curve can be drawn, by which the optimal dynamic reactive power compensation capacity of the established site STATCOM is obtained based on the minimum value of the comprehensive analysis index of the closeness.

5. Example analysis

Taking Suzhou Southern Power Grid as an example, the method in this paper is researched and verified. The grid has two DC feeds, including Longzheng DC and Jinsu DC, forming a typical multi-feed DC system. Considering the calculation amount and representativeness of the example, this paper considers 4 dynamic reactive power compensation candidate nodes, namely H=4. The DC model uses detailed models and measured parameters. The HVDC line information and the calculated DC weight coefficients are shown in Table 2.

| DC          | $\xi_j / \sum_{j=1}^{\infty} \xi_j$ |
|-------------|-----------------------------------|
| Longzheng DC| 1.6659                            |
| Jinsu DC    | 0.6134                            |

5.1. Reactive power compensation candidate node

This paper plans to study the feeding of Jinsu DC and Longzheng DC into the central area of the power grid and its vicinity, and conduct simulation calculations to determine the weak areas. In a typical operation mode, the two-circuit DC line receiving end drop point and the surrounding 230kV node are selected by simulation, and the Jinsu DC and Longzheng DC bipolar blocking and the AC channel are checked and repaired in the case of N-2 failure. The degree of voltage drops, as shown in Figure 3, plots the weak voltage areas of multiple DC feed-in areas, as shown in Figure 4.

In order to determine the best compensation site in a weak voltage area, and take into account the interaction between the nodes, this article uses the concept of node RTVDAI to determine the best reactive power compensation site. Select 230KV nodes in the voltage weak area from Figure 4 as the installation node inspection object, and calculate and sort the relative RTVDAI index of the nodes according to formula (1). Through calculation, it can be known that Su chefang, Su wujiang, Su Jinshan, and Su Gaoxin have the largest relative RTVDAI value, which can be selected as installation The best position of dynamic reactive power compensation device.
5.2. Reactive power compensation configuration scheme

According to the method for determining the optimal plan in 3.4, under certain conditions of investment cost, Reactive power compensation devices are installed in Su chefang, Su wujiang, Su jinshan, and Su gaoxin. Among them, point a, point b, point c, point d in sequence represent four reactive power compensation sites. Name the schemes according to the order of the installation sites. Set 11 groups of installation schemes, as shown in Figure 5. According to Figure 5, the commutation failure reduction effect index shows that under the condition of a certain investment cost, the scheme bcd commutation The failure reduction effect is the best, that is, the installation of reactive power compensation devices in Gaoxin, Wujiang and Jinshan is the best installation plan.

Refer to the principle of power system reactive power configuration, under the premise of ensuring the safe and stable operation of the system, set the maximum dynamic reactive power compensation

Figure 3. 230kV nodes are sorted in descending order of voltage drop.

Figure 4. Map of weak voltage areas in multiple DC feed-in areas.
rated capacity of STATCOM to be installed as the best compensation site to be ±1800MVar, and set the reactive power compensation capacity with an accuracy value of ±100MVar Divided into 18 gears. Then follow the steps 2, 3, and 4 of the capacity configuration in the previous section to obtain Table 3 System closeness index under different installation capacity, and draw the fitting curves in Figure 6 and Figure 7 using the CFTOOL curve fitting toolbox in MATLAB.

![Figure 5. Commutation failure reduction effect index under different schemes.](image)

**Table 3.** System closeness index under different installation capacity.

| Program | GaoXin | WuJiang | JinShan | Cost | Es  | Closeness |
|---------|--------|---------|---------|------|-----|-----------|
| 1       | 100    | 100     | 100     | 2.55 | -1.083 | 0.505     |
| 2       | 200    | 200     | 200     | 5.1  | -1.354 | 0.488     |
| 3       | 300    | 300     | 300     | 7.65 | -1.242 | 0.4666    |
| 4       | 400    | 400     | 400     | 10.2 | -1.97  | 0.4415    |
| 5       | 500    | 500     | 500     | 12.75| -2.231 | 0.4267    |
| 6       | 600    | 600     | 600     | 15.3 | -2.21  | 0.4594    |
| 7       | 700    | 700     | 700     | 17.85| -2.419 | 0.453     |
| 8       | 800    | 800     | 800     | 20.4 | -2.546 | 0.461     |
| 9       | 900    | 900     | 900     | 22.95| -2.909 | 0.428     |
| 10      | 1000   | 1000    | 1000    | 25.5 | -3.109 | 0.423     |
| 11      | 1100   | 1100    | 1100    | 28.05| -3.245 | 0.429     |
| 12      | 1200   | 1200    | 1200    | 30.6 | -3.397 | 0.4325    |
| 13      | 1300   | 1300    | 1300    | 33.15| -3.499 | 0.444     |
| 14      | 1400   | 1400    | 1400    | 35.7 | -3.78  | 0.426     |
| 15      | 1500   | 1500    | 1500    | 38.25| -3.9497| 0.427     |
| 16      | 1600   | 1600    | 1600    | 40.8 | -3.882 | 0.4666    |
| 17      | 1700   | 1700    | 1700    | 43.35| -3.691 | 0.5282    |
| 18      | 1800   | 1800    | 1800    | 45.9 | -4.059 | 0.495     |
The Fourier regression curve function obtained from Figure 6 shows that when the reactive power compensation capacity is 900Mvar-1000Mvar, the comprehensive analysis index value of closeness is at a low point. It can be seen from the regression curve function of the interpolation function obtained in Figure 7 that when the dynamic reactive power compensation capacity of each station is about 956.4MVar, the comprehensive analysis index value of the closeness is the smallest, that is, the sum of the multi-infeed DC commutation failure risk and reactive power compensation costs is the smallest.

Using STATCOM to reduce the risk of commutation failure is the best solution for dynamic reactive power compensation, and perform simulation analysis on the effect of reducing the risk of commutation failure to verify the engineering practicability and effectiveness of the program.

With repairing the Sushunan-Sushipai and Suhuasu-Sushipai communication channels, an example on the three-phase permanent N-2 faults in Sumudu-Sushipai and Suwunan-Suminzhu is taken to make a simulation comparison under no STATCOM installation conditions and the best STATCOM installation scheme.

From Figure 8, 9, 10 and 11 that in the case of AC line failure at the DC receiving end, the time for the two DC transmission power to recover to 90% of the rated power after the installation of STATCOM is reduced to varying degrees, which greatly reduces the system commutation failure. The degree of loss improves the stability of the AC and DC system. Under the AC line failure of the DC receiving end, the effect of the reduce commutation failure risk is significantly improved, which verifies the engineering practicality of the reactive power compensation configuration scheme proposed in this paper that uses STATCOM to the effect of reduce the commutation failure risk at the lowest cost.
6. Conclusions
1) Find the voltage weak area under typical faults, and determine the best dynamic reactive power compensation site in the voltage weak area through the node relative transient voltage drop area index RTVDAI. This method of arrangement pays more attention to the wrong index of actual engineering parameters, the concept is clear, and it is easy to implement.

2) The objective function of reactive power optimization configuration is established by reducing the commutation failure risk effect index and reactive power compensation cost, which not only comprehensively considers the influence of the commutation failure power impact and the reactive power impact of the DC system in reducing the commutation failure risk effect. It also reflects the requirements of power grid economy.

3) According to the objective function of reactive power optimization configuration, the entropy weight method is used to evaluate the reactive power optimization configuration plan to provide decision-makers with a basis for decision-making. According to the posted progress obtained in the entropy weight method, a continuous curve is obtained based on the discrete closeness data by using the CFTOOL toolbox in matlab. Then the best dynamic reactive power compensation capacity is obtained, and the installation capacity is accurately optimized.

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