Reliability and power supply capability evaluation of active distribution networks with four-terminal soft open points

Feng Yan1, Xiangyan Chen2, Wensheng Tang3, Ri Yan4, Hao Wu5

1State Grid Jiangxi Electric Power Company, Nanchang, Jiangxi, People’s Republic of China
2State Grid Jiangxi Electric Power Company Gaoan Power Supply Company, Gaoan, Jiangxi, People’s Republic of China
3State Grid Jiangxi Electric Power Company Yingtan Power Supply Company, Yingtan, Jiangxi, People’s Republic of China
4State Grid Jiangxi Electric Power Company Pingxiang Power Supply Company, Pingxiang, Jiangxi, People’s Republic of China
5State Grid Jiangxi Electric Power Company Jingdezhen Power Supply Company, Jingdezhen Jiangxi, People’s Republic of China

Abstract: Soft open points (SOPs) have the ability to regulate the power flow among their terminals in a continuous manner, which can solve the problems brought by the synergy of distribution networks and distributed generation, and improve the system reliability and power supply capability. To address the current lack of quantitative measurement on the effects of SOPs, the power supply capability evaluation method for active distribution networks (ADNs) with four-terminal SOPs considering reliability is proposed. Firstly, the topology and configuration modes of four-terminal SOPs are studied, and their control modes are investigated in normal operation and supply restoration conditions. Then, using the feeder partition method, the effects of four-terminal SOPs on the power outage duration of different load areas after a fault are studied, and the reliability evaluation process for ADNs with four-terminal SOPs is developed based on the quasi-Monte Carlo method. Later, with reliability as the main constraint, the power supply capability evaluation model for ADNs with four-terminal SOPs is established, and the solution algorithm is proposed. Finally, the effectiveness and applicability of the method proposed are verified through a case study.

1 Introduction

In recent years, the increasing access to distributed generations (DGs) has reduced the operation loss and improved the environmental benefits of distribution networks [1, 2]. Meanwhile, the stochastic property of DGs increases the risk of voltage violation and reverses power flow, which poses adverse impacts on the reliability of distribution networks [3, 4]. As a new distribution device, soft open points (SOPs) can accurately control the power flow in a real-time fashion, thus affecting the overall power flow distribution in the networks [5, 6]. Compared with the traditional tie switches, which only have on and off states, SOPs can continuously regulate the power flow, which effectively overcomes the on-and-off limits of tie switches and solves the power supply fault problem [7, 8]. In [9], the basic operation principles and the mathematical model of SOPs were investigated. In [10, 11], the steady-state and transient operation properties of SOPs were obtained through numerical simulations. In addition, SOPs transform the closed-loop design and open-loop operation pattern of distribution networks and realise the flexible closed-loop operation, which is promising in addressing the severe short-term power supply fault problem and improving the reliability and power supply capability (PSC) of distribution networks [12, 13].

According to the number of terminals, SOPs are divided into two-terminal and multi-terminal SOPs. The two-terminal SOPs are suitable for the simple single-connection mode [14]. In the urban distribution networks, more complex connection modes, such as double-ring connection and multi-operation-one-backup connection, are widely adopted. Therefore, it is of greater research significance to study the planning and operation of flexible distribution networks based on multi-terminal SOPs. Currently, multi-terminal SOPs mainly include three-terminal and four-terminal SOPs. From the perspective of structural transformation, three-terminal SOPs are only applicable to two-operation-one-backup connection mode, which limits the extensibility of three-terminal SOPs. In comparison, four-terminal SOPs are applicable to multiple complex connection modes, including double-ring connection and three-operation-one-backup connection. Featured by higher extensibility, four-terminal SOPs can satisfy the power supply requirements under more complex connection modes, provide more flexible and smoother network structures by connecting more feeders in a flexible manner and regulating the feeder loading status, thereby significantly improving the reliability and PSC of distribution networks. Therefore, this study mainly targets four-terminal SOPs. However, there is a lack of specific quantitative measure on the effects of four-terminal SOPs on reliability and PSC. Regarding reliability evaluation, the Monte Carlo simulation and analytical method are the most common methods. In [15], quasi-Monte Carlo simulation was used to evaluate the reliability of distribution networks with DG access. In [16], based on the analytical method, the estimation model for different reliability indices was built, and the load changes and capacity constraints were adopted to revise the indices. As quasi-Monte Carlo simulation is more applicable to the distribution networks with more components and devices, it is widely applied in the reliability evaluation [17]. Regarding PSC evaluation, in [18], the PSC model for flexible distribution networks was established based on N−1 criterion, and requires the network assets will often not be fully utilised. In contrast, if reliability constraint is introduced in the PSC evaluation process, it can reflect the balance between the stochastic loads and the constant network capacity, thereby greatly increasing the asset utilisation efficiency. Therefore, it is necessary to integrate the reliability constraint into the PSC evaluation process to further develop the power supply potential of distribution networks [21]. To sum up, under the widespread access of DGs and energy storage, it is of both practical and research significance to explore the solution and description method to the PSC of active distribution networks (ADNs) with four-terminal SOPs, and comprehensively evaluate the reliability and PSC. To address the above problems, the main contributions of this study are organised as follows:
(i) Based on feeder partition, the influences of four-terminal SOPs on the power outage duration of different load areas are investigated, the reliability evaluation method for ADNs with four-terminal SOPs is developed based on quasi-Monte Carlo method, and the load shedding and transfer model is established. This method quantifies the reliability improvement effects of four-terminal SOPs by increasing the number of connection feeders.

(ii) Based on the continuous power flow regulation ability of four-terminal SOPs, the influences of four-terminal SOPs on PSC are explored, and the PSC evaluation model for ADNs with four-terminal SOPs is established with reliability as the main constraint. This model reflects the improvement effects of four-terminal SOPs on PSC under different reliability requirements and develops the power supply potential of ADNs.

(iii) The traditional ADN and the ADN with four-terminal SOPs are constructed, and the correlation between reliability and PSC is established through case comparison, which reveals the improvement mechanism of four-terminal SOPs on reliability and PSC.

2 Topology and control modes of four-terminal SOPS

2.1 Topology of four-terminal SOPs

Used to replace the tie switches, four-terminal SOPs can flexibly control the active power flow among multiple feeders, and provide certain reactive power support. Currently, four-terminal SOPs are mainly realised back-to-back voltage source converters (B2B VSCs) [22]. The specific topology of four-terminal SOPs is shown in Fig. 1.

Four-terminal SOPs are mainly applicable to double-ring and four-operation-one-backup connection modes. Fig. 2 shows the transformation diagram of double-ring connection mode. Fig. 3 shows the transformation diagram of four-operation-one-backup connection mode, in which the four feeders operate in a closed-loop after four-terminal SOPs replace the tie switches.

2.2 Control modes of four-terminal SOPs

Four-terminal SOPs adopt different control modes in normal operation and fault restoration states of distribution networks [20]. During normal operation state, four-terminal SOPs work in the power flow control mode, which means to regulate the active and reactive power flow at the four terminals. In this mode, one VSC works in $U_{dc}Q$ mode and regulates the dc-side voltage. The other three VSCs work in $PQ$ mode and control the output active and reactive power, thus regulating the network power flow. After a fault occurs, four-terminal SOPs work in fault recovery mode, which means to restore the power supply of affected loads in cooperation with DGs. In this mode, the VSC at the fault side works in $U_f$ mode and provides stable voltage for the affected loads as a voltage source. The other normal VSCs work in $U_{dc}Q$ mode and ensure the uninterrupted power supply of non-affected loads as a current source.
3 Reliability evaluation of ADNs with four-terminal SOPs

Four-terminal SOPs will improve the fault restoration process and thus enhance the power supply reliability, which is mainly reflected in that four-terminal SOPs change the power fault/supply states of affected load areas after a fault occurs, reducing the power outage time of affected load areas, and increasing the number of feeders which can provide load transfer capacity. Based on DG access and feeder partition, the influencing mechanism of four-terminal SOPs on reliability is analysed, the load shedding and transfer model is established, and the reliability evaluation method is developed based on quasi-Monte Carlo method.

3.1 State sampling based on quasi-Monte Carlo

The reliability evaluation subject of this study is the ADNs with four-terminal SOPs, with the focus on the impact of the reliability of the four-terminal SOPs. The quasi-sequential Monte Carlo simulation method [23] was used to evaluate the reliability of the ADNs with four-terminal SOPs.

Owing to the uncertainty of DG output, the DG circuit breaker needs to be cut-off after the distribution network is faulted, and DGs should be re-connected to the system after the fault has been removed. However, if the network is equipped with appropriate protection devices, it can support the island operation of DGs and partial load, thereby enhancing the reliability index. This study considers whether DGs support the island operation for fault analysis, thus improving the practicality of the evaluation method.

The non-source components, including transformers, feeders, and switches, are represented in a two-state Markov model [24], where the fault rate is \( \lambda \) and the repair transfer rate is \( \mu \). The fault-free operating time (time-to-fault (TTF)) and fault repair time (time-to-repair (TTR)) of the components obey the exponential distribution. The state duration sampling method was adopted to sequentially sample the states of the non-source components, while the exponential distribution was used to calculate the moment of the fault and the duration of the fault.

Photovoltaic (PV) and battery are presented by a three-state model, including normal, outage, and derating operation states, and their outage and derating operation probabilities are defined, respectively. When the non-source components fail, the operation states of PV and battery are sampled based on the non-sequential sampling and remain unchanged during the fault of the non-source components.

3.2 Fault analysis of transformers and feeders based on feeder partition

According to the concept of feeder partition [25], the distribution network is divided into several minimum isolation zones, as shown in Fig. 4. This study focuses on the scenario in which there is only one isolation zone at each branch. After the fault occurs, different locations and DG states will have different effects. The specific types of the minimum isolation zones and their states at different time points during the fault period are shown in Table 1. In Table 1, \( t_1 \) indicates the time when the fault occurs, \( t_2 \) means the time when the fault is isolated, \( t_3 \) indicates the time when the interconnection switch is closed and the downstream transfer is completed, and \( t_4 \) means the time when the fault is removed. State A1 indicates that the corresponding zone suffers from loss of power, state A2 means that the corresponding zone is normally supplied, state A3 means that the corresponding zone is in an island operation state, and state A4 means that the corresponding zone is supplied by the downstream interconnection lines. The table presents examples of different zones shown in Fig. 4.

3.3 Influencing mechanism of four-terminal SOPs on reliability

After a fault occurs, the states of different load areas are determined at each stage. In Fig. 4, this study considers the real-time load transfer support of four-terminal SOPs in fault restoration process based on the failure mode and effect analysis (FMEA) in [26, 27], which took DGs and traditional load transfer into account. There are a total of 12 types of load areas. Specifically, the new three types considered in this study include downstream seamless connected area 2 (S12–S14 when F2 fails), downstream isolated connected area 2 (S12 and S14 when F2 fails), and downstream islanded connected areas (S13 when F3 fails).

Regarding the downstream seamless connected areas, four-terminal SOPs transfer the loads within these areas to the connected feeders in a real-time manner until the failed component is restored. Thus, the supply to the loads within these areas is normal during the entire process. For the downstream isolated connected areas, the loads within these areas are out of power from the fault occurrence moment to the fault isolation moment and are then transferred to the connected feeders according to the load transfer capacity until the failed component is restored. Regarding the downstream islanded connected areas, the loads within these areas operate in an islanded state from the fault occurrence moment to the fault isolation moment and are then transferred to the connected feeders according to the load transfer capacity until the failed component is restored.

In addition, as shown in Fig. 3, in the traditional distribution network, if feeders 1, 3, or 4 fails, only feeder 2 can provide load transfer support. After four-terminal SOP replaces tie switches, it can regulate the power flow among the four feeders, and any feeder that fails can be supported by other feeders. Owing to the access of four-terminal SOPs, the number of connected feeders to the single-connected feeders is increased, which raises the load transfer capacity and reduces the load shedding and power outage time, thus improving the system reliability. Furthermore, the increase in connected feeders raises the problem of how to allocate the

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Table 1 Zoning principle of ADN

| Region type                                      | \( t_1-t_2-t_3-t_4 \) | Example |
|-------------------------------------------------|------------------------|---------|
| faulted zone                                    | A1 A1 A1 S5            |         |
| normal zone                                     | A2 A2 A2 S1            |         |
| upstream isolated zone                          | A1 A2 A2 S2 S3         |         |
| upstream seamless islanding zone                | A3 A2 A2 S4            |         |
| downstream seamless islanding zone              | A3 A3 A3 S7            |         |
| downstream isolated islanding zone              | A1 A3 A3 S8            |         |
| downstream seamless islanding connected zone    | A3 A3 A4 S9            |         |
| downstream isolated islanding connected zone    | A1 A3 A4 S10           |         |
| connection transfer zone                        | A1 A1 A4 ——            |         |

Note: if there is no DG in S6, S9 or S10, they are the connection transfer zones.

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affected loads to different feeders in a rational way. Hereunder, a load shedding and transfer model is established.

### 3.4 Load shedding and transfer model

After a fault occurs, the affected loads which require to be transferred are transferred to the connected feeders through four-terminal SOPs according to their load transfer capacity. Considering that the connected feeders cannot provide sufficient load transfer capacity in some extreme fault conditions, part of the affected loads may lose their power supply. Besides, it is necessary to formulate a rational method to allocate the affected loads to multiple connected feeders. Therefore, the following model is established to address the load shedding and transfer problem when the load transfer capacity is insufficient.

Under the network constraint, this model aims to minimise the load shedding amount and optimise the network operation conditions. To reduce the network loss, ensure supply safety and economy, the loading status of the connected feeders should be balanced after the affected loads are transferred. The objective of this model is as follows:

\[
\min \sum_{i,j=1}^{n} (R_i - R_j) \quad i, j = (1...n)
\]

where \( R_j \) is the loading rate of feeder \( j \) after the affected loads are transferred.

In addition, this model also considers maximising the load successfully transferred, which is expressed as

\[
\max \sum_{j=1}^{n} L_j X_j
\]

where \( L_j \) is the amount of the affected loads in load area \( j \) to be transferred; \( X_j \) is the transfer status of load area \( j \). 0 indicates that the loads cannot be transferred while 1 indicates that the loads can be transferred.

### 3.5 Reliability evaluation process

Based on the above FMEA analysis, load shedding, and transfer model, when a component fails, the specific types of affected load areas can be determined according to the network topology and feeder partition considering the influence of four-terminal SOPs. Then, the states of these load areas in different fault restoration stages can be determined, which provides the basis for the calculation of reliability indicators. The evaluation process is shown in Fig. 5. Based on the above evaluation model, the reliability evaluation process for considering the main transformers based on pseudo sequential Monte Carlo simulation method is presented as follows:

- **Step 1:** Set the number of simulation years. At the initial moment of the simulation, all the \( m \) components are in normal condition. Generate \( m \) random quantities between 0 and 1 while combining with the fault transfer rate \( \lambda \) and the exponential distribution to determine the normal operation time \( TTF \) of \( m \) components between two failures.

- **Step 2:** Find the smallest \( TTF_{\min} \), whose corresponding component is the faulted component. Generate a random quantity for it. Also, the fault repair time \( TTR \) is determined according to the repair transfer rate \( \mu \) and exponential distribution. The fault isolation and load transfer times are also generated. The simulated clock is pushed to \( TTF_{\min} + TTR \).

- **Step 3:** The type of each minimum isolation zone in the network is determined according to the type of faulted component and the fault analysis method described in Section 3.2. Also, the outage time of the faulted zone, normal zone, and upstream isolated zone can be directly determined.

- **Step 4:** For the rest zones, which run in islanding mode, the operation state of distributed PV and battery is non-sequentially sampled by generating random quantities according to the two-state Markov chain model in Section 3.1. Combined with the real-time load, the SoC sequence, charge–discharge power sequence, and PV output sequence, calculate the outage time of each load during the islanding stage.

- **Step 5:** Analyse the zones requiring interconnection transfer similar to Step 4. The operation state, real-time output, and real-time load of the distributed PV and battery in the transfer and interconnection zone are sampled, combined with the load rate constraints, to judge whether the load can be transferred while the minimum isolation zone is taken as the basic zone.

- **Step 6:** The outage time of each load point during the component fault period is calculated. Sample a new operation time \( TTF_{\text{new}} \) for the faulted component and update its normal operation time to \( TTF_{\min} + TTR + TTF_{\text{new}} \).

- **Step 7:** Determine whether the simulation clock crosses the year. If not, then the load point outage time is added to the current annual load point outage time \( U_i \). Otherwise, calculate the reliability index of feeder and system meanwhile \( U_i \) is cleared.

- **Step 8:** Determine whether the simulation clock reaches the set number of simulation years. If not, then go back to Step 2. If yes, the simulation process ends. The average value of the reliability index of each simulation year is calculated and the average system availability index (ASAI) of the system can be obtained.

In this study, ASAI is adopted as the reliability indicator, which requires to calculate the number of power consumers in optimising the feeder loading status. Considering that the number of power consumers is discrete while the feeder loading status is continuous, the number of power consumers in load area \( i \) is set as follows:

\[
N_j = \left[ \frac{L_j}{L_{\text{op}}} \right]
\]

where \( L_j \) is the amount of initial load in load area \( j \); \( L_{\text{op}} \) is the optimised load in load area \( j \); \( N_j \) is the number of power consumers in load area \( j \); the number of initial power consumers is set as 1; and \( \left[ \right] \) indicates rounding down.

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Fig. 5 Reliability evaluation process of ADNs with four-terminal SOPs
4 PSC evaluation of ADNs with four-terminal SOPs

The traditional 𝑁−1 criterion-based PSC calculation method considers the substation interconnection and inter-substation load transfer, which combines reliability and economic indicators. However, this method is flawed in simplifying the reliability requirement as the 𝑁−1 criterion and requires the networks to comply with the 𝑁−1 criterion at all times, even at non-peak load times, which fails to analyse the changes of PSC under different reliability requirements, and quantify the influences of SOPs on PSC. As a result, a PSC evaluation model for ADNs with four-terminal SOPs considering reliability is established and its solution algorithm is proposed.

4.1 Influencing mechanism of four-terminal SOPs on PSC

In traditional ADNs, the transfer of the affected loads after a fault occurs can only be realised through the coordination of section switches and tie switches. In comparison, four-terminal SOPs can regulate the power flow on multiple feeders at peak load times, improve the feeder loading status and balance the loading rates of all the feeders, thus increasing loads of ADNs and fully utilising the capacity of ADNs. As the PSC of ADNs is reflected in loads of all the feeders on the feeder level, four-terminal SOPs can develop the power supply potential of ADNs.

4.2 PSC evaluation

The objective of this model is to maximise the PSC of ADNs. Assuming that there are 𝑛 transformers in the ADNs, numbered from 1 to 𝑛. Specifically, 𝑚𝑖 feeders are connected to the 𝑖th transformer, numbered from 1 to 𝑚. The objective function of this model is as follows:

\[
\text{max } \text{psc} = \sum_{i=1}^{n} \sum_{q=1}^{m_i} L_{iq,\text{max}} \tag{4}
\]

where psc is the PSC of ADNs; \(L_{iq,\text{max}}\) is the amount of load of the 𝑞th feeder connected to the 𝑖th transformer at peak load times, namely the optimisation subject in this model. The specific constraints are described as follows:

(i) Constraint of reliability indicator: ADNs should satisfy the network reliability indicator constraint in normal operation. The excepted ASAI is adopted as the reliability indicator as follows:

\[
\text{ASAI} = \frac{T \times \sum_{i=1}^{n} \sum_{q=1}^{m_i} U_{iq} N_{iq} \cdot H_{ij} / \sum_{j=1}^{N} N_{ij}}{\sum_{i=1}^{n} \sum_{j=1}^{N} N_{ij}} \geq E_{i} \tag{5}
\]

where 𝑇 is the number of hours in which reliable power supply is required; \(U_{ij}\) is the outage time of load area 𝑗 in a year; \(N_{ij}\) is the number of power consumers in load area 𝑗; \(p\) is the number of load areas in ADNs; \(E_{i}\) is the expected ASAI.

(ii) Constraint of match between transformers and feeders: This constraint implies that the sum of loads and DG outputs of all the feeders should be equal to those of the transformer which these feeders are connected to

\[
L_{i} = \sum_{q=1}^{m_i} L_{iq} \tag{6}
\]

\[
G_{i} = \sum_{q=1}^{m_i} G_{iq} \tag{7}
\]

where \(L_{i}\) is the real-time load of the 𝑖th transformer; \(L_{iq}\) is the real-time load of the 𝑞th feeder connected to the 𝑖th transformer; \(G_{i}\) and \(G_{iq}\) are the real-time total DG outputs of the 𝑖th transformer and its 𝑞th feeder.

(iii) Constraint of loading rate: This constraint implies that transformers and feeders cannot be overloaded, which is expressed as follows:

\[
0 \leq (L_{iq} - C_{iq}) / C_{iq} \leq 1 \tag{8}
\]

\[
0 \leq (L_{i} - G_{i}) / C_{i} \leq 1 \tag{9}
\]

where \(C_{i}\) and \(C_{iq}\) are the rated capacity of the 𝑖th transformer and its 𝑞th feeder connected.

4.3 Genetic algorithm solution

Genetic algorithm is adopted to solve the PSC evaluation model and the real-time loads of all the feeders at peak load times are optimised. The initial loads of transformers and feeders are set to satisfy the 𝑁−1 criterion while the maximum loads of transformers and feeders are set as reaching a 100% loading rate. The objective of the model is to maximise PSC, which is the fitness in the algorithm. Individuals with higher PSC have higher fitness. Besides, the ratio between the actual loads of feeders and their initial loads is coding subject, which is referred to as the load multiple in binary coding and ranges between \([1, H]\), where \(H\) is the ratio between the maximum loads of feeders and their initial loads. Moreover, the genes and chromosomes in the algorithm represent the load multiple of one individual feeder and the load multiple of all the feeders, respectively. The individuals refer to the annual peak loads of all the feeders, which is the PSC, while the populations indicate the group of individuals. The specific algorithm process is shown in Fig. 6.

5 Case study

5.1 Case profile

A typical ADN with DGs and energy storage systems in a demonstration project of China is selected as shown in Fig. 7. Specifically, feeders 1, 6, 11, 16, 20, and 24 are backup feeders.
The specific feeder structure of the traditional ADN is shown in Figs. 8–14. After four-terminal SOPs replace tie switches, the ADN with four-terminal SOPs is shown in Fig. 15. Specifically, loads can be accessed to the original backup feeders. The specific feeder structure of the ADN with four-terminal SOPs is shown in Figs. 16–21. The types, quantities, reliability parameters of network components, initial residential, industrial, and commercial loads as well as the DG and energy storage system parameters are included in Tables 2–5 and Fig. 22 (energy storage systems are provided where there is DG). The fault isolation stage and load transfer stage both last for 1 h. The initial loads of feeders satisfying the $N-1$ criterion are listed in Tables 6 and 7.

5.2 Result analysis

5.2.1 Analysis of reliability evaluation results: As shown in Fig. 2, after feeders 1, 3, or 4 fail, only feeder 2 can provide load transfer support. If the feeder loading rates satisfy the $N-1$ criterion, feeder 2 can provide sufficient load transfer capacity even in the most severe fault conditions. However, if the feeders are...
heavily loaded, not satisfying the $N-1$ criterion, feeder 2 cannot always provide sufficient load transfer capacity, which reduces the reliability. After four-terminal SOPs replace tie switches, they can increase the number of connected feeders which can provide load transfer support, thus offering sufficient load transfer capacity even in the most severe fault conditions. Therefore, based on different feeder loading status, case 1 (feeder loading rates satisfy $N-1$
criterion) and case 2 (feeder loading rates do not satisfy \( N-1 \) criterion) are selected in this study to compare the reliability of the traditional ADN and the ADN with four-terminal SOPs. The initial feeder loading rates in cases 1 and 2 are listed in Tables 6 and 7.

(i) Reliability comparison in case 1: In case 1, the ASAI of the traditional ADN and the ADN with four-terminal SOPs is shown in Fig. 23, which are 99.9793% and 99.9817%, respectively. The difference between the two is 00.0024%. The ASAI values of the ADN with four-terminal SOPs are higher because, after a fault, the real-time load transfer function of four-terminal SOPs reduces the power outage time of loads in the downstream seamless connected areas, downstream isolated connected areas, and downstream islanded connected areas. In addition, in the quasi-Monte Carlo
based reliability evaluation method, multiple simultaneous may occur simultaneously. In the traditional ADN, the feeders connected to the failed feeders cannot provide sufficient load transfer capacity, which aggravates the load shedding amount and reduces the reliability. In the ADN with four-terminal SOPs, the increased number of connected feeders ensures sufficient load transfer capacity even in the most severe conditions. However, the possibility of multiple simultaneous faults is extremely low, limiting their influences on reliability. In one single fault condition, the connected feeders in both the traditional ADN and the ADN with four-terminal SOPs can provide sufficient load transfer capacity, and thus four-terminal SOPs cannot improve the network reliability by increasing the number of connected feeders which can provide load transfer support.

(ii) Reliability comparison in case 2: In case 2, the ASAI of the traditional ADN and the ADN with four-terminal SOPs is shown in Fig. 24, which are 99.9699 and 99.9771%, respectively. The difference between the two is 0.0072%. It can be seen from Figs. 23 and 24 that the ASAI values of case 2 are lower than those in case 1. Specifically, the decline in the ASAI values of the ADN with four-terminal SOPs is lower than that of the traditional ADN. Apart from the reason discussed in case 1, the ASAI values of the ADN with four-terminal SOPs is higher because, after a fault, the connected feeders in the traditional ADN cannot provide sufficient load transfer capacity in some severe conditions, which increases the load shedding amount and reduces the network reliability. However, in the ADN with four-terminal SOPs, four-terminal SOPs can prevent the network reliability from decreasing by increasing the number of connected feeders which can provide load transfer support, which enhances the network reliability in a relative term. Compared with case 1, it can be seen that the reliability improvement effect of four-terminal SOPs when the network is in light loading is lower than that when the network is in heavy loading. Therefore, when the network loading becomes heavier, the reliability improvement effect of four-terminal SOPs becomes more obvious.

5.2.2 Analysis of PSC evaluation results: The PSC evaluation results of the traditional ADN and the ADN with four-terminal SOPs are shown in Fig. 25. From the y-axis direction, under the same reliability constraint, four-terminal SOPs significantly improve the power supply reliability of ADN. From the x-axis direction, as the feeders are more heavily loaded, the improvement effects of four-terminal SOPs on reliability are more prominent. In addition, to increase the reliability indicator, the load transfer capacity reserved in ADN should be increased, which in turn reduces loads of ADN, namely the PSC. Furthermore, the decline in PSC gradually increases as the reliability requirement becomes higher.

In addition, in the traditional ADN, when the ASAI is 99.9793%, the PSC is 115.17 MVA; in the ADN with four-terminal SOPs, when the ASAI is 99.9817%, the PSC is 115.17 MVA, which is the PSC based on \( N-1 \) criterion and considering inter-substation load transfer. In this case, ADN can satisfy the \( N-1 \) constraint at peak load times. Therefore, four-terminal SOPs can effectively improve network reliability while satisfying \( N-1 \) constraint and considering inter-substation load transfer.

In the traditional ADN, when all the feeders are 100% loaded, the ASAI is 99.9688% and the PSC is 230.34 MVA; in the ADN with four-terminal SOPs, when all the feeders are 100% loaded, the ASAI is 99.9754% and the PSC is 230.34 MVA, which is the...
limiting PSC of ADN. Further increase of feeder loading rates will lead to overloaded operation of transformers at peak load times.

6 Conclusions
In this study, the influences of four-terminal SOPs on reliability and PSC are studied. Then, based on feeder partition, the reliability evaluation method for the ADNs with four-terminal SOPs is developed to quantify the reliability improvement effects and the PSC evaluation model for the ADNs with four-terminal SOPs considering reliability constraint is established. Finally, the effectiveness and applicability of the method are verified through a case study, and the following conclusions are drawn:

(i) Four-terminal SOPs can improve the network reliability by reducing the power outage time of load areas through their real-time load transfer function and increasing the number of connected feeders which can provide load transfer support. When the network loading becomes heavier, the reliability improvement effect of four-terminal SOPs becomes more obvious.

(ii) Under the same reliability requirement, four-terminal SOPs can improve the network PSC and the asset utilisation efficiency of distribution networks.

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**Fig. 24** Comparison of ASAI values in case 2

**Fig. 25** Comparison of PSC

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**Figures and tables are not included in this text.**