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RELIABILITY AND POWER SUPPLY CAPABILITY EVALUATION OF ACTIVE DISTRIBUTION NETWORKS WITH FOUR-TERMINAL SOFT OPEN POINTS

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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 PV, 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 with four-terminal SOPs considering reliability is proposed. Firstly, the topology and configuration modes of four-terminal SOPs are studied, and the control modes of them are investigated in normal operation and supply restoration conditions. Then, using the feeder partition method, the effects of four-terminal SOPs on the states of different load areas after a fault are studied, and the reliability evaluation process for active distribution networks 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 active distribution networks with four-terminal SOPs is established, and the solution algorithm is proposed. Finally, the effectiveness and applicability of the method proposed are verified through case study.

Keywords: four-terminal soft open points, reliability, power supply capability, active distribution networks

NONMENCLATURE

Abbreviations

SOP	Soft Open Points
ADN	Active Distribution Networks
PSC	Power Supply Capability
PV	Photovoltaic Generation
ESS	Energy Storage System

Symbols

i/j, l, k	Feeder, load area, transformer
n, m, c, T, n_l	Number of feeders, load areas transformers, hours in which reliable power supply is required and feeders connected to transformer l
R_i, R_j	Loading rates of feeders i and j after the affected loads are transferred
L_k, L_{k0}, L_{limax}, L_l, L_{li}	Affected loads to be transferred and initial loads in load area k; loads of feeder i connected to transformer l at peak load times, namely the optimization subject in PSC evaluation model; load of transformer l; load of feeder i connected to transformer l
X_k	Transfer status of load area k. 0 indicates that the loads cannot be transferred while 1 indicates that the loads can be transferred
N_k	Number of power consumers in load area k. The number of initial power consumers is set as 1
[]	Rounding down to integer
U_k	Outage time of load area k in a year
E_s	Expected ASAI indicator
G_l, G_{li}	Total PV outputs of transformer l and its feeder i
C_l, C_{li}	Rated capacity of transformer l and its feeder i

1. INTRODUCTION

In recent years, the increasing access of PV has reduced the operation loss of distribution networks but also increases the risk of voltage violation and poses adverse impacts to the reliability of distribution networks [1-2]. As a new distribution device, SOPs can accurately control the power flow in a real-time fashion, thus affecting the overall power flow distribution [3]. Compared with tie switches with only on-off states, SOPs can continuously regulate the power flow, effectively overcoming the on-and-off limits and solves the outage problem [4]. In [5], the basic operation principles and mathematical model of SOPs were investigated. In [6-7], the steady-state and transient operation properties of SOPs were obtained through numerical simulations. In addition, SOPs realize the flexible closed-loop operation of distribution networks, which is promising in addressing the severe short-term outage problem and improving the reliability and PSC.

According to the number of terminals, SOPs are divided into two-terminal, three-terminal and four-terminal SOPs. The former two model are suitable for the simple connection modes. As four-terminal SOPs are applicable to more complex and widespread connection modes, such as double-ring and multi-operation-one-backup, they are featured by higher extensibility and provide more flexible network structures, thereby significantly improving the reliability and PSC of distribution networks. Thus, it is of greater significance to study the influences of four-terminal SOPs on reliability and PSC, which is lacking in specific quantitative measurement methods. In [8], the PSC model for distribution networks was established based on N-1 security criterion, which, however, simplifies the reliability demand into the rigid N-1 security criterion, and requires the networks to satisfy the rigid N-1 security criterion at peak load times. However, as the peak load only lasts for a very short period, there will a huge margin to the PSC based on N-1 security criterion. In this paper, reliability constraint is introduced in the PSC evaluation process to reflect the balance between the stochastic loads and the constant network capacity, thus increasing the asset utilization efficiency and developing the power supply potential. To sum up, this paper mainly quantitatively evaluates and describes the PSC of ADNs with four-terminal SOPs considering reliability. The main contributions of this paper are as follows:

(1) Based on feeder partition, the influences of four-terminal SOPs on the states of load areas after a fault occurs are investigated, and the reliability evaluation method for ADNs with four-terminal SOPs is developed based on quasi Monte Carlo method. This method quantifies the reliability improvement of four-terminal SOPs by increasing the number of connected feeders providing load transfer support.

(2) The influences of four-terminal SOPs on PSC are explored, and the PSC evaluation model for the ADNs with four-terminal SOPs is established with reliability as the main constraint. This model reflects the improvement of four-terminal SOPs on PSC under different reliability requirements.

(3) The traditional ADNs and the ADNs with four-terminal SOPs are constructed, and the correlation between reliability and PSC is established through case study, 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 realized by back-to-back voltage source converters (B2B VSC) [9]. The specific topology of four-terminal SOPs is shown in Fig. 1.

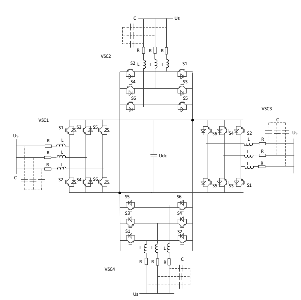

Fig 1 Topology of B2B VSC based four-terminal SOPs

Four-terminal SOPs are mainly applicable to double-ring and four-operation-one-backup connection modes. Due to space limit, the transformation diagram of three-operation-one-backup connection mode is given as an example as shown in Fig. 2, in which the four feeders operate in a closed loop.

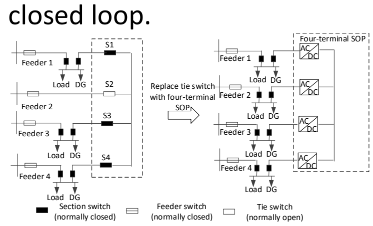

Fig 2 Transformation of three-operation-one-backup connection mode

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 [10]. During normal operation, four-terminal SOPs work in power flow control mode, which means to regulate the active and reactive power flow at the four terminals. One VSC works in $U_{dc}Q$ mode and regulates the dc-side voltage. The other three VSCs work in PQ mode and controls the active and reactive power output, thus regulating the power flow. After a fault occurs, four-terminal SOPs work in fault restoration mode, which means to restore the power supply of affected loads with PV and ESS. The VSC at the fault side works in Uf mode, and provides stable voltage for the affected loads as a voltage source. The other 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

3.1 *Influences of four-terminal SOPs on reliability*

Four-terminal SOPs improve the fault restoration process and enhance network reliability, which is mainly reflected in that they change the outage/supply states of affected load areas after a fault, reducing the outage time of affected load areas, and increasing the number of feeders providing load transfer capacity. After a fault occurs, the states of different load areas are determined at each stage. In Fig. 3, this paper considers the real-time load transfer support of four-terminal SOPs in failure restoration process based on the FMEA analysis in [11] which took DG and traditional load transfer into account. There are a total of 12 types of load areas. Specifically, the new three types in this paper include downstream seamless connected areas (S12-S14 when F1 fails), downstream isolated connected areas (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 in these areas to the connected feeders in real time until the failed component is restored. Thus, these loads are not affected during the entire process. For the downstream isolated connected areas, the loads in these areas are cut off from when the fault occurs to when the fault is isolated, 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 in these areas operate in islanded state from when the fault occurs to when the fault is isolated, and are then transferred to the connected feeders according to the load transfer capacity until the failed component is restored.

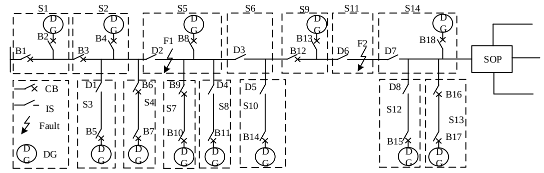

Fig 3 Typical feeder partition

In addition, as shown in Fig. 2, in the traditional ADN, 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. Due to four-terminal SOPs, the number of connected feeders providing load transfer support is increased, which raises the load transfer capacity and reduces the load shedding amount and outage time, thus improving the network reliability.

3.2 Load shedding and transfer model

After a fault occurs, the connected feeders cannot provide sufficient load transfer capacity in some extreme fault conditions, part of the affected loads may lose power. Therefore, it is necessary to formulate a rational method to allocate the affected loads to connected feeders when the load transfer capacity is insufficient.

Under the network constraint, this model aims to minimize the load shedding amount and optimize the network operation conditions. To reduce the power loss, the feeder loading status should be balanced after the loads are transferred. The objective of this model is:

$$\min \sum_{i \neq j}^{n} \left| R_i - R_j \right|, \quad i, j = (1, \ldots, n) \tag{1}$$

In addition, this model also considers minimizing the load shedding amount, which is expressed as:

$$\max \sum_{k=1}^{n} L_k X_k, \quad k = (1, \ldots, m) \tag{2}$$

3.3 Reliability evaluation process

Based on FMEA analysis, load shedding and transfer model, when a component fails, the specific types of the affected load areas can be determined according to the network topology and the feeder partition considering the influences of four-terminal SOPs. Then, the states of these load areas in different fault restoration stages can be determined, which provides basis for the calculation of reliability indicators. Quasi Monte Carlo method is adopted to calculate the reliability indicator [11-12]. In the evaluation process, the non-source components, such as transformers, feeders and switches, are represented by the two-state model in [12]. The states and duration of non-source components are sampled in a sequential manner. The source components, such as PV and ESS, are represented by the three-state model, including normal operating, shutdown and derated operating states. When the fault of non-source components is detected in the sequential sampling process, the operating states of PV and ESS are sampled in a non-sequential manner and are assumed as constant in the fault restoration process of non-source components. Due to space limit, the PV output, load and ESS output models are not described in details.

The evaluation process is shown in Fig. 4. In this paper, ASAI is adopted as the reliability indicator, which requires to calculate the number of power consumers in optimizing 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 k is set as follows:

$$N_k = \left[L_k / L_{k0} \right] \tag{3}$$

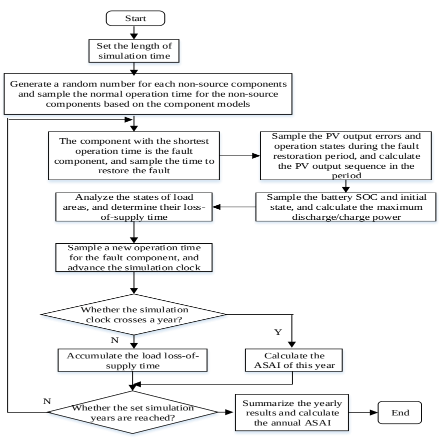

Fig 4 Reliability evaluation process of ADNs with four-terminal SOPs

4. PSC EVALUATION OF ADNS WITH FOUR-TERMINAL SOPS

4.1 *Influences of four-terminal SOPs on PSC*

In traditional ADNs, the transfer of the affected loads after a fault occurs can only be realized through 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 the loads of ADNs and fully utilizing the capacity of ADNs. As the PSC is reflected in the feeder loads on the feeder level, four-terminal SOPs can develop the power supply potential.

4.2 PSC evaluation model

The objective of this model is to maximize the PSC, which is as follows:

$$\max psc = \sum_{l=1}^{c} \sum_{i=1}^{n_l} L_{li\max} \tag{4}$$

The specific constraints are described as follows:

(1) 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:

$$ASAI = \frac{T \times \sum_{k=1}^{m} N_k - \sum_{k=1}^{m} U_k N_k}{T \times \sum_{k=1}^{m} N_k} \geq E_s \tag{5}$$

(2) Constraint of match between transformers and feeders. This constraint implies the sum of loads and PV outputs of all the feeders should be equal to those of the transformer which these feeders are connected to.

$$L_l = \sum_{i=1}^{n_l} L_{li} \tag{6}$$

$$G_l = \sum_{i=1}^{n_l} G_{li} \tag{7}$$

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

$$0 \leq (L_{li} - G_{li}) / C_{li} \leq 1 \tag{8}$$

$$0 \leq (L_l - G_l) / C_l \leq 1 \tag{9}$$

4.3 Genetic algorithm solution

Genetic algorithm is adopted to solve the PSC evaluation model, and the feeder loading status at peak load times is optimized. The initial loads of transformers and feeders are set to satisfy the N-1 security criterion while the maximum loads of transformers and feeders are set as reaching 100% loading rate. The objective of the model is to maximize PSC, namely the fitness. Individuals with higher PSC have higher fitness. Besides, the ratio between the actual and initial feeder loads is coded, which is referred to as the load multiple and ranges between [1, H], where H is the ratio between the maximum and initial feeder loads. Moreover, the genes and chromosomes represent the load multiple of individual feeder and all the feeders respectively. Individuals refer to the annual peak feeder loads, namely the PSC, while populations indicate the group of individuals. The algorithm process is shown in Fig. 5.

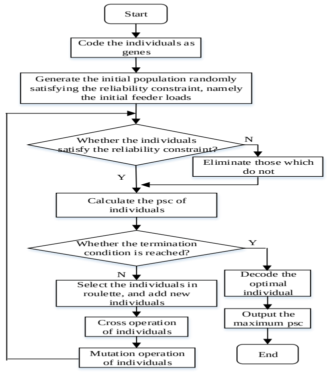

Fig 5 Solution process based on genetic algorithm

5. CASE STUDY

5.1 Case profile

A typical ADN with PVs and ESSs in a demonstration project is selected as shown in Fig. 6 (left). Specifically, Feeders 1, 6, 11, 16, 20 and 24 are backup feeders. After four-terminal SOPs replace tie switches, the ADN with four-terminal SOPs is shown in Fig. 6 (right). Specifically, loads can be accessed to the originally backup feeders. ESS is provided where there is PV. The fault isolation stage and the load transfer stage both last for 1h. The initial loads of feeders satisfy N-1 security criterion.

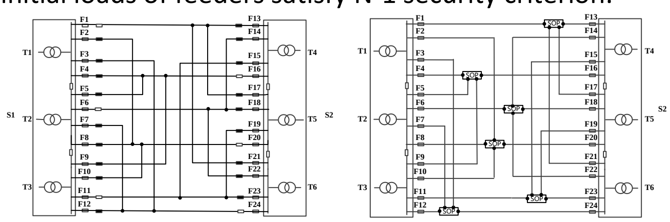

Fig 6 Traditional ADN (left) and ADN with four-terminal SOPs (right)

5.2 Results analysis and discussion

5.2.1 Analysis of reliability evaluation results

Considering that four-terminal SOPs are more effective in improving network reliability in severe feeder loading status, based on different feeder loading status, Case 1 (feeder loading rates satisfy N-1 security criterion) and Case 2 (feeder loading rates do not satisfy N-1 security criterion) are selected in this paper to compare the reliability of the traditional ADN and the ADN with four-terminal SOPs.

(1) Reliability comparison in Case 1

In Case 1, the ASAI values are shown in Fig. 8, which are 99.9793% and 99.9817% respectively. The ASAI values of the ADN with four-terminal SOPs is higher because after a fault, four-terminal SOPs reduce the outage time in the downstream seamless connected areas, downstream isolated connected areas and downstream islanded connected areas. In 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 providing load transfer support.

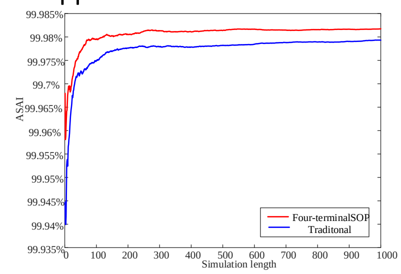

Fig 8 Comparison of ASAI values in Case 1

(2) Reliability comparison in Case 2

In Case 2, the ASAI values are shown in Fig. 9, which are 99.9699% and 99.9771% respectively. 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 providing load transfer support, enhancing the network reliability relatively.

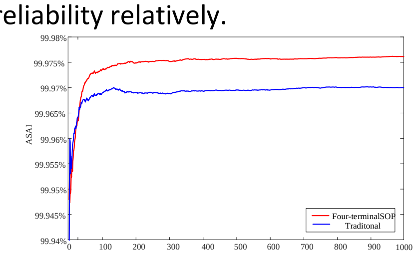

Fig 9 Comparison of ASAI values in Case 2

5.2.2 Analysis of PSC evaluation results

The PSC evaluation results are shown in Fig. 10. From the y-axis direction, under the same reliability constraint, four-terminal SOPs significantly improve the PSC. From the x-axis direction, as the feeders are more heavily loaded, the improvement of four-terminal SOPs on reliability is more prominent. In addition, to increase the reliability indicator, the load transfer capacity reserved should be increased, which in turn reduces the 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 value is 99.9793%, the PSC is 115.17MVA; in the ADN with four-terminal SOPs, when the ASAI value is 99.9817%, the PSC is 115.17MVA, which is the PSC based on N-1 security criterion. Therefore, four-terminal SOPs can effectively improve the network reliability while satisfying N-1 constraint. In the traditional ADN, when all the feeders are 100% loaded, the ASAI value is 99.9688% and the PSC is 230.34MVA; in the ADN with four-terminal SOPs, when all the feeders are 100% loaded, the ASAI value is 99.9754% and the PSC is 230.34MVA, which is the limiting PSC.

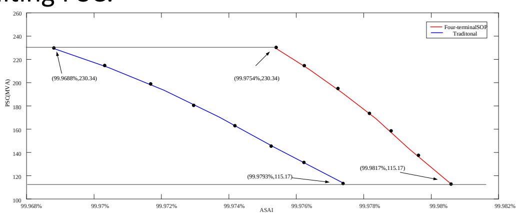

Fig 10 Comparison of PSC

6. CONCLUSIONS

In this paper, the influences of four-terminal SOPs on reliability and PSC are quantified, and following conclusions are drawn:

(1) Four-terminal SOPs can improve the network reliability by reducing the outage time of loads in the downstream seamless connected areas, downstream isolated connected areas and downstream islanded connected areas through their real-time load transfer function, and increase the number of connected feeders providing load transfer support.

(2) Relaxing the network reliability requirement can significantly optimize the PSC. In addition, under the same reliability requirement, four-terminal SOPs can improve the PSC and the asset utilization efficiency of distribution networks.

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