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INFLUENCE OF SUPPLY RELIABILITY WITH THE INTEGRATION OF SOFT OPEN POINT IN ACTIVE DISTRIBUTION NETWORKS

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ABSTRACT

Soft open point (SOP) refers to a novel power electronic device installed in active distribution networks (ADNs) to replace traditional tie switch. When a fault occurs, power outage areas are formed after fault location and isolation, SOP can provide voltage and power support for the outage areas, which improves the power supply reliability of ADNs. In this paper, a reliability index calculation method based on fault incidence matrix is used to calculate the reliability indexes of nodes and system. The principle of reliability improvement based on SOP is described, and the influence factors of SOP affecting the reliability of ADNs are analyzed. Compared with traditional tie switch, the integration of SOP can effectively improve the power supply reliability of ADNs. As the impact of position and capacity of SOP on supply restoration, it also significantly influences reliability improvement. The analysis of reliability improvement based on SOP is demonstrated on modified IEEE 33-node system.

Keywords: active distribution network (ADN), soft open point (SOP), reliability, supply restoration

NONMENCLATURE

Abbreviations	
SOP	Soft Open Point
ADN	Active Distribution Network
DG	Distributed Generator
FIM	Fault Incidence Matrix
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
ENS	Energy Not Supplied
Symbols	
$i,\ j$	Indices of nodes
ij	Indices of branches
Ω_{b}	Set of all branches
Ω_{n}	Set of all nodes except source node
$P_i^{\mathrm{SOP,L}}$	Active power losses of SOP at node i
P_i^{LOAD}	Active power consumption at node i
μ_i	Coefficient associated with the recovery level of load at node i
$\omega_R,\ \omega_L$	Weight coefficients in the objective
$\boldsymbol{A}$	Fault incidence matrix A
$\boldsymbol{B}$	Fault incidence matrix B
$\boldsymbol{C}$	Fault incidence matrix C
$\boldsymbol{\lambda}_{\mathrm{l}}$	Failure rate of branches
$\boldsymbol{\lambda}_{\mathrm{b}}$	Outage frequency of nodes
$\boldsymbol{T}_{\mathrm{b}}$	Outage duration of nodes
$\boldsymbol{L}_{\mathrm{b}}$	Energy not supplied of nodes
$\boldsymbol{t}_{\mathrm{l}}$	Repair time of branches
$\boldsymbol{t}_{\mathrm{sw}}$	Action time of switches
$\boldsymbol{t}_{\mathrm{op}}$	Action time of SOPs
$\lambda_{\mathrm{b},i}$	Outage frequency of node i
$T_{\mathrm{b},i}$	Outage duration of node i
$\boldsymbol{P}^{\mathrm{LOAD}}$	Active power consumption of nodes
r_{ij}	Resistance of branch ij
N_i	Number of customers at node i
M	Total number of customers

1. INTRODUCTION

According to the statistics, more than 80% of power outages are caused by the faults in distribution level, which requires high-level self-healing ability of ADNs to cope with complex and variable operating scenarios [1].

With the high penetration of distributed generators (DGs) and flexible loads, the characteristics of faults have fundamentally changed. Due to the limitation of device capability, response speed and control accuracy, traditional methods can hardly meet the requirements of high-reliability power supply for ADNs. The main factors affecting the power supply reliability include the failure rate of each power component, the power outage range and duration of the system. SOP can accurately adjust the power flow between feeders, provide fast voltage support to expand the load restoration range and shorten the power outage duration, and further improve the power supply reliability of ADNs.

Previous studies have investigated the reliability improvement of ADNs and the control strategy of SOP. Ref. [2] analyzed the influence of increased decentralised generation on the reliability of ADNs. A fast reliability calculation method based on the fault incidence matrix for complex distribution system is proposed in [3]. Ref [4] proposed a supply restoration method of distribution system based on SOP, which significantly expand the scope of supply restoration. Thus, it is of great significance to make full use of the potential benefits of SOP for reliability improvement in ADNs.

In this paper, a reliability index calculation method based on fault incidence matrix is used to calculate the node reliability indexes and the system reliability indexes. Then the principle and influence factors of reliability improvement based on SOP are analyzed. Finally, the analysis of SOP integration on the reliability of ADNs is conducted on the modified IEEE 33-node system. The results show that the integration of SOP has a positive impact on the reliability improvement of ADNs.

2. ANALYSIS OF THE RELIABILITY INFLUENCE OF SOP

2.1 Reliability index calculation method

2.1.1 Reliability indexes of nodes

The reliability indexes of nodes are used to describe the reliability level of each node, which can be calculated as follows:

1) Node average interruption frequency index

$$\boldsymbol{\lambda}_{\mathrm{b}} = \boldsymbol{\lambda}_{\mathrm{l}} \times (\boldsymbol{A} + \boldsymbol{B} + \boldsymbol{C}) \tag{1}$$

2) Node average interruption duration index

$$\begin{aligned} \boldsymbol{T}_{\mathrm{b}} = \boldsymbol{\lambda}_{\mathrm{l}} \circ \boldsymbol{t}_{\mathrm{l}} \times \boldsymbol{A} + \boldsymbol{\lambda}_{\mathrm{l}} \circ \boldsymbol{t}_{\mathrm{sw}} \times \boldsymbol{B} \\ + \boldsymbol{\lambda}_{\mathrm{l}} \circ \left(\boldsymbol{t}_{\mathrm{sw}} + \boldsymbol{t}_{\mathrm{op}}\right) \times \boldsymbol{C} \end{aligned} \tag{2}$$

Where the symbol $\circ$ represents the Hadamard product operation.

3) Node average energy not supplied

$$\boldsymbol{L}_{\mathrm{b}} = \boldsymbol{T}_{\mathrm{b}} \circ \boldsymbol{P}^{\mathrm{LOAD}} \tag{3}$$

Matrix A, B and C are the fault incidence matrixes, which are incidence matrixes concluding the effect of each branch fault event on each node [3].

2.1.2 Reliability indexes of distribution system

According to the calculation of node reliability indexes, the system indexes can be obtained.

1) System average interruption frequency index

The system average interruption frequency index (SAIFI) is the average number of the interruptions that a customer would experience.

$$SAIFI = \frac{\sum_i \lambda_{\mathrm{b},i} N_i}{M} \tag{4}$$

2) System average interruption duration index

The system average interruption duration index (SAIDI) is equal to the average outage duration of each customer.

$$SAIDI = \frac{\sum_i \lambda_{b,i} T_{b,i} N_i}{M} \tag{5}$$

3) Energy not supplied

Energy not supplied (ENS) represents the energy not supplied of the whole system.

$$ENS = \sum_i T_{b,i} P_i^{\mathrm{LOAD}} \tag{6}$$

2.2 Impact of SOP on the reliability of ADNs

The impact of SOP on the power supply reliability depends on its fast operating action and voltage support ability of SOP, which will shorten the power outage duration and expand the load restoration range, corresponding to SAIDI and ENS, respectively. Thus, SOP has the potential benefits for the reliability improvement of ADNs.

According to the principle of SOP based supply restoration described in [4], the range of power supply restoration is limited by the position and capacity of the SOP. The recovery states of each node under every branch fault can be summarized as the following cases:

1) The load cannot be restored by the SOP. The load can only be restored when the fault branch is repaired, and the outage duration depends on the repair time.

2) The load can be restored by the main power supply immediately after fault isolation, the outage duration depends on the action time of segment switch.

3) The load can be restored by SOP after fault isolation, the outage duration depends on the time of fault clearance and SOP switching to Vf mode.

Limited by the position and capacity, SOP usually cannot restore all the loads from outages. Thus, the effect of SOP on reliability improvement is also restricted.

2.3 Reliability index calculation process

The analysis process of the impact of SOP on the power supply reliability of ADNs is as follows:

Step 1: The SOP based supply restoration model of ADNs is used to obtain the load restoration states under each branch fault. The combination of the maximum of restored loads and minimum power losses is taken as the objective function:

$$min\ f = -\omega_R \sum_{i\in\Omega_n} \mu_i P_i^{\mathrm{LOAD}} + \omega_L\left(\sum_{ij\in\Omega_b} r_{ij} I_{ij}^2 + \sum_{i\in\Omega_n} P_i^{\mathrm{SOP,L}}\right) \tag{7}$$

The constraints include the operation constraints of ADNs and SOP which are described in [4].

Step 2: The fault incidence matrix is generated to calculate the reliability indexes of each node.

Step 3: The reliability indexes of the system can be calculated to analyze the reliability level of the system.

3. CASE STUDY

3.1 Modified IEEE 33-node system

The proposed method was implemented in the YALMIP optimization toolbox using MATLAB R2014a and solved by IBM ILOG CPLEX 12.6.

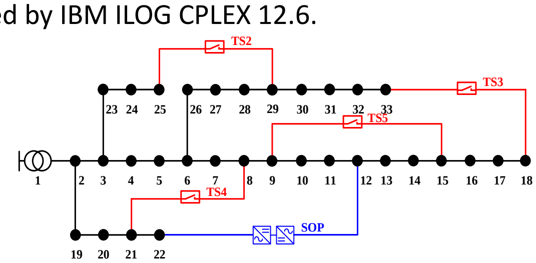


Fig. 1 IEEE 33-node test feeder

The modified IEEE 33-node system is shown in Fig. 1. There is one breaker at the branch between 1 and 2. The tie switch between 12 and 22 is replaced by SOP with a capacity of 1000 kVA, and the loss coefficient is 0.199. The failure rate of each branch refers to [2]. The fault repair time and the switching time of switches are supposed to be 5 hours and 1 hour, and the action time of SOP is set as 5 minutes.

3.2 Reliability analysis of ADNs base on SOP

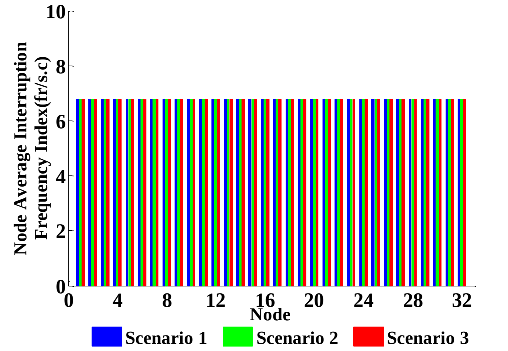
The following three scenarios are selected to analyze the impact of SOP on the reliability of ADNs.

Scenario 1: No tie switch is considered to restore the loads in outage area.

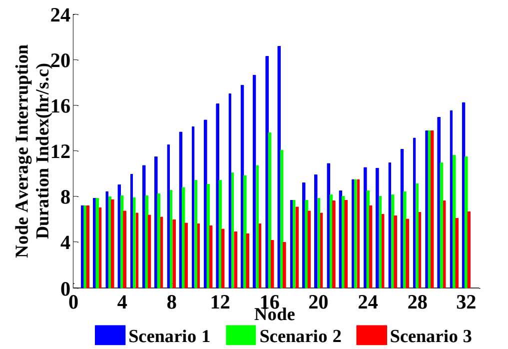
Scenario 2: Five tie switches are installed to restore the loads in outage area.

Scenario 3: Tie switch between nodes 12 and 22 is replaced by SOP to restore the loads in outage area.

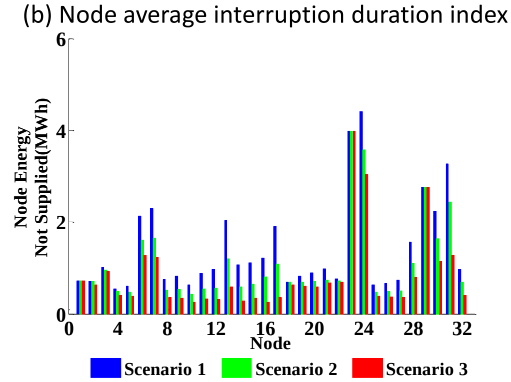
The node reliability indexes and system reliability indexes are shown in Fig 2 and Table 1, respectively.



(a) Node average interruption frequency index



(b) Node average interruption duration index



(c) Node average energy not supplied

Fig. 2 Comparison of the node reliability indexes

It can be seen that the average interruption frequency of each node under different scenarios is completely the same, because only one breaker is installed at the branch between nodes 1 and 2, which will cause the entire network out of service after a permanently fault happened. The average interruption duration of the nodes is shown in Fig 2(b). Comparing the three scenarios, the application of the tie switch and SOP can effectively shorten the outage duration. For the nodes close to the end of the feeder, there will be more branch faults affecting its power supply, which leads to a longer average outage duration. Compared with tie switch, SOP achieves rapid supply restoration, which reducing outage duration of nodes considerably. With the enhanced load recovery capability from SOP, the average energy not supplied index of the node is significantly reduced.

Table 1 Comparison of the system reliability indexes

Index	Scenario 1	Scenario 2	Scenario 3
SAIFI/(fr/syst.cust)	6.76565	6.76565	6.76565
SAIDI/(hr/syst.cust)	12.28101	9.31452	7.00004
ENS/(MWh)	44.76082	34.67415	26.68464

For the system reliability indexes, the integration of SOP also has a better effect on reliability improvement than tie switch. In Scenario 2, the average interruption duration of each customer decreased by 2.97 hours (24%), and that in Scenario 3 decreased by 5.28 hours (43%). In Scenario 2, the energy not supplied of the system decreased with 10.09 MWh (23%), and Scenario 3 decreased by 18.08 MWh (40%). The reliability indexes are significantly adjusted, and the power supply reliability of the system is effectively improved by SOP.

3.3 Reliability influence of the position and capacity of SOP

The following two cases are chosen to analyze the impact of SOP position and capacity on the reliability improvement, and the tie switches are not considered.

3.3.1 Reliability influence of the SOP position

SOPs with a capacity of 1000 kVA between nodes 12 and 22, 25 and 29, 9 and 15 are chosen to analyze the impact of position of SOP on reliability of ADNs.

Table 2 Comparison of system reliability indexes

Index	SOP 12-22	SOP 25-29	SOP 9-15
SAIFI/(fr/syst.cust)	6.76565	6.76565	6.76565
SAIDI/(hr/syst.cust)	10.23241	10.85232	11.56646
ENS/(MWh)	38.30492	39.38819	42.39495

For the system reliability indexes shown in Table 2, the capacities of installed SOPs are same, but the installation sites are different, SOP between nodes 12 and 22 have a better performance on the improvement of reliability index. It can be seen that the position of SOP extremely impact the reliability improvement of ADNs.

3.3.2 Reliability influence of the SOP capacity

To analyze the impact of capacity of SOP on reliability improvement, the capacities of SOP between nodes 12 and 22 are set as 500kVA, 1000kVA and 2000kVA.

Table 3 Comparison of system reliability indexes

Index	500kVA	1000kVA	2000kVA
SAIFI/(fr/syst.cust)	6.76565	6.76565	6.76565
SAIDI/(hr/syst.cust)	10.96739	10.23241	9.52580
ENS/(MWh)	40.83611	38.30492	35.81773

For the system reliability indexes shown in Table 3, as the increasing capacity of SOP, the reliability indexes are gradually improved, because SOP with a larger capacity can reduce the power supply range affected by faults.

Based on the above analysis, it can be seen that the integration of SOP has a positive impact on the reliability improvement of ADNs, and the position and capacity of SOP significantly impact the effect on reliability improvement. Due to the high investment cost of power electronic devices, the optimal siting and sizing of SOPs can achieve a more economical reliability improvement of ADNs.

4. CONCLUSION

Depending on the capability to shorten power outage duration and reduce power outage range of the system, the integration of SOP has a positive impact on the reliability of the power supply. In this paper, the potential benefits of SOP integration on reliability improvement are explored, and the impacts of the position and capacity of SOP on the reliability improvement are also analyzed. SOP based supply restoration is conducted to obtain the states of load nodes under each branch fault, and reliability index calculation method based on fault incidence matrix is used to calculate the reliability indexes of nodes and the system. SOP can effectively enhance the power supply recovery capability, optimize the reliability indexes, and improve the power supply reliability of ADNs. Considering the impact of the position and capacity of SOP on power supply reliability, the optimal siting and sizing of SOPs can be further investigated to realize the reliability and economic improvement of ADNs.

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