Analysis of Fault Recovery Process in Distribution Networks with the Integration of Soft Open Point

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*Abstract*—After a fault occurs in the distribution network, the real-time balance between power supply and load demand must be met. Load can be restored through upper sources and the nearby power supply of distributed generators. Therefore, it is necessary to construct the power transmission path between each node, namely transmission matrix. Furthermore, the access of new controllable devices such as soft open point (SOP) makes it possible for power supply quickly by providing a path for power loss loads. In this paper, a fault recovery model of distribution network considering SOP is established. The dynamic balance of node power is firstly considered, then the the impact mechanism of SOP on fault recovery is elaborated. The cone relaxation process and the objective function of fault recovery is further introduced. Through the simulation analysis of the modified IEEE 33-node test system, scenarios of single fault and multi-point fault are built. The effectiveness of the proposed method and the improvement of load recovery after fault by SOP are verified.

*Index Terms*--Distribution network, fault recovery process, transmission matrix, soft open point.

# Introduction

After a fault occurs in distribution network, to ensure the safe operation status of the whole system, it is necessary to isolate the faulty line by protection devices, then restore load power supply through feasible power supply routes, which is named as the fault recovery process[1]. During fault recovery process, the main consideration is to restore the power supply, which is reflected in indicators such as the total amount of lost power and network operation losses[2]. So that the distribution network needs to meet the constraints of connectivity, radiation, and safe operation [3]. Considering the integration of renewable energy, the active power of distributed generators (DGs) can compensate for power loss loads and improve the reliability index of distribution network. However, DG outputs are highly uncertain because of the intermittency and randomness. Traditional distribution network fault recovery methods cannot be fully applicable [4]-[5].

Considering the increasing regulation ability of controllable devices in distribution networks and operational losses caused by traditional tie switches, it has become an inevitable trend to gradually replace traditional tie switches with soft open points (SOP)[6]. Compared to traditional tie switches, SOP has the characteristics of faster response speed and lower loss, which improves the reliability of power supply. After a fault occurs, the operation strategy of inverters can also be adjusted to effectively meet the demand for load recovery. However, it also brings new challenges for modeling the steady-state analysis of distribution networks during fault recovery process[7]-[8]. It is necessary to analyze the improvement mechanism of SOP on fault recovery.

From the view of fault recovery, the possibility of self-healing in the process of fault recovery after the integration of DG and various controllable devices is conceived in reference [9]. A fault recovery method that considers priority restoration of power supply for important loads is proposed in reference [10]. A chance constrained load recovery model is proposed in reference [11] further considering the randomness of DG output. However, the methods proposed in references [10] and [11] both have the problem of high computational complexity and high dimensionality. From the view of SOP, reference [12] proposed a three-layer coordination model between SOP and DG. An optimization model is proposed in [13] that takes into account the multi-ternimal SOP and the self-healing strategy oriented to the risk of load shortage.

In order to improve the reliability of distribution network, a fault recovery model of considering the integration of SOP is established. The key contributions of this paper are as follows:

* A power transmission matrix is constructed to represent the power exchange relationship between nodes, the mechanism of SOP during the fault recovery process is elaborated.
* The unified model of node power exchange during fault recovery process is established.
* A fault recovery model of distribution network considering SOP and various objective functions is established considering cone relaxation.

The rest of the paper is organized as follows: the methodology of fault recovery is introduced in Section II. Section III denotes the simulations of the proposed method and detailed results. The conclusion is described in Section IV.

# Methodology

## Power transmission during fault recovery processs

During fault recovery process, the principle of radial operation should be met and the power flow after the fault should be further analyzed. The traditional fault recovery path is from the source node to the load node. If this path is disconnected, load node will lose its power. However, loads can alse be restored through the nearby power supply of DGs. Therefore, it is necessary to construct the power transmission path between each node. At the same time, distribution network still needs to meet the steady-state power flow equation during the recovery process.

### Connectivity between nodes

In the process of fault recovery, the principle of radial operation should be met [14], which can be expressed as follows:

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|  | (1) |
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is defined as the set of all lines in the distribution network, represents the set of all nodes, represents the set of source nodes, with only one source node in the case of a single power source. represents the operating status of line , where indicates disconnection while indicates connection. After the fault occurs, when the protection device acts, the indicator of all lines has been determined. represents the subordinate relationship between node and node , indicates that node is the parent node of node , meaning that power flows transfer from node to node , indicates that node is not the parent node of node .

Further considering power supply of DG, it is necessary to further construct the power transmission path between each node, namely the power transmission matrix. When node and node have a subordinate relationship, which is ; node and node also have a subordinate relationship, which is , it is easy to determine the power exchange path between node and node . So that during the fault recovery process, the load of node can be recovered through the excess power of node , vice versa.

Meanwhile, is defined as the set of lines with a unique path from node to the source node in a radial network. It can also be confirmed that there is a power transmission path between the two nodes by the intersection between and . By combining the above two methods, the power transmission matrix is constructed to represent the power exchange relationship between nodes, where the element is set to express the corresponding to the path between nodes.

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| --- | --- |
|  | (2) |
|  |

represents the set of lines connecting the paths between node and node . A path connecting any two nodes in a radial distribution network is firstly determined, then the on-off state of the lines on the path is further considered. shows the power interaction between two nodes, when , it indicates that node and node can interact with each other. Conversely, indicates the presence of a disconnected line on the path.

Compared to traditional methods, the proposed method has following advantages: Firstly, the matrix can be calculated and save in advance. When a fault occurs, only the corresponding element in the matrix need to be replaced. A new matrix required for calculation is obtained. Compared to search algorithms, the calculation of elements 0 and 1 in the matrix is efficient. The second is to clearly represent the power transmission relationship between nodes. When a node has regulation ability of net power, it can effectively represent its impact on other nodes. At the same time, it can effectively represent the impact of controllable device on fault recovery.

### Power flow constraints

After a fault occurs, distribution network still needs to meet the steady-state power flow equation during the recovery process [15]. The power transmission constraints are as follows:

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| --- | --- |
|  | (3) |
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Constraint (3) denotes the steady-state of power flow in the network at time period . and represent the active and reactive power flow of line during time period . When line is cut, it is obvious that and . represents the power exchange between grid and node . is the branch set. and represent the resistance and reactance while is defined as the current through line . represents the voltage of node .

|  |  |
| --- | --- |
|  | (4) |
|  |

With the constraints of line power and node voltage, the power exchange cannot be freely realized. In which reason the constraint (4) is adopted to show that there is no line overloads and node voltage violations. represents the upper limit of line transmission power. When line is cut, it is set that . and are the lower and upper bounds of node voltage.

## Dynamic balancing of node power

The power balance of a single node is necessary to meet the dynamic balance of source and load. Based on power node model, the power exchange at node can be analyzed. Considering the access of renewable resources, most of DGs are uncontrollable, so they cannot participate in the optimization operation of the distribution network. The active power outputs of DGs can realize the fault recovery of nearby loads. The active and reactive power of DGs can be assumed to be the predicted values. After being connected to the distribution network, they can be considered as PQ nodes with given power, and their active and reactive power can be calculated using the predicted values. Further considering the integration of controllable devices such as SOP, a unified model of power change at node during fault recovery process is established [16]. The active power exchange between grid and device is analyzed, as can be seen in constraint (5) and Fig.1.

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|  | (5) |
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Constraint (5) represents the active power balance at node during time period . If an energy storage system is connected, the equivalent storage capacity , otherwise . represents the equivalent value of state of charge, which fluctuates from 0 to 1. represents the total power output. represents the total amount of load recovery. represents the total active power injection of controllable devices. represents a power supply and denotes an energy absorption. Furthermore, there is an interval of regulating ability of controllable devices connected to node, and are defined as the lower and upper boundaries of output.

At the same time, the reactive power cannot be stored. So that the reactive power exchange is analyzed as equation (6).

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|  | (6) |
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represents the total load recovery at node during time period , which is generally calculated at a constant power factor. and are defined as the lower and upper boundaries of reactive power regulating ability.



1. Unified model of power exchange.

## The impact of soft open point

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SOP is based on fully-controlled power electronic devices, which can quickly and accurately control its own power outputs, thereby regulating the power flow of entire network [6]. The flexible interconnection between different feeders are realized by the integration of SOP. The operational constraints of SOP during fault recovery process are shown in constraint (7), with loss factors are considered.

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|  | (7) |
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SOP is installed between nodes and . During time period , and represent the active and reactive power injection by SOP at node . denotes the active power loss of SOP. is defined as the loss coefficient of SOP. and represent the upper and lower limit of reactive power provided by SOP. denotes the capacity limit of SOP at node .

When a fault occurs in distribution network, the connection of SOP does not change the original short-circuit capacity of the network, which is capable of coordinating with protection equipment. As is shown in Fig.1, considering the different installation positions, SOP cannot have an impact on any power loss area when used for power restoration. It can only adjust the net load of the connected nodes. After a failure, the power loss area formed by fault localization and isolation can be divided into the following three situations, based on the position of SOP:

1) The two terminals of SOP are outside the power loss area;

2) One terminal of SOP is within the power loss area, the other is set outside the power loss area;

3) The two terminals of SOP are within the power loss area.

Based on the control mode and mechanism of SOP, it can be seen that when SOP is used for fault recovery, SOP cannot generate active power, and one terminal must be connected to a non-power-loss area to obtain the power support for active power [12]. The other terminal need to be connected to the power loss area to provide voltage support. Taking Figure 1 as an example, the line protection cuts line 4-5 when a grounding fault occurs. Without SOP, the loads on node 6 and 7 lose power. With the integration of SOP, the two feeders are connected. In which reason loads can obtain power supply through node 8.



1. Fault recovery considering soft open point

According to the analysis in section A, the power transmission matrix can effectively represent the paths of each node in the fault recovery process. Taking node 6 and node 7 of power loss area in Figure 1 as an example, the original power transmission matrix is as follows:

When SOP is integrated, the matrix is changed as:

It can be seen that the access of SOP provides more power transmission paths for node 6 and node 7. SOP can effectively connect two feeders and provide a new path of power. Therefore, the load recovery ratio will effectively increase. Furthermore, traditional SOP are mostly two-terminal structure. Considering the strong portability of power electronic devices, the integration of three-terminal structure (or more terminals) provides more effectiveness for fault recovery in distribution networks.

In distribution network, SOP is generally installed in the position of tie switch to improve the intelligence level of the entire network. Compared to traditional tie switch, SOP has the following advantages: firstly, SOP can provide reactive power in specific scenarios through inverters. Secondly, it has the advantage of adjustable and controllable transmission power, which can prioritize the restoration of power supply for important loads. The above two advantages enable the integration of SOP to effectively improve the load recovery after a fault occurs. The mechanism of SOP during the fault recovery process can be devided into three categories:

1) On node side, the range of controllable resources is effectively inproved. So that the power recovery of node is increased.

2) For network, SOP directly communicates power loss area and operating area, affecting the elements in the transmission matrix. The power loss area can only be restored through the active power of nearby DGs. When the power factor of the user is determined, SOP can provide reactive power support, which effectively compensates the reactive power shortage in traditional networks.

3) The strategy of SOP is based on the actual operational needs, so that the power regulation ability of SOP can optimize the operation status of the distribution network and meet the priority needs of important users to restore power supply.

## Cone relaxation and objective function

### Cone relaxation

Since the model contains the optimal control of controllable devices, the model cannot be solved by a solver. Cone programming problem has always been a hot issue in the field of international mathematical optimization. In which reason the second-order cone program (SOCP) oriented to the distribution network is adopted [17].

By employing the variable substitution method, the square of the voltage amplitude and line current are defined, which can be seen in equation (8).

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|  | (8) |
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Then bring it into the system power flow constraints (3). Focusing on the multiplication of state variables, the cone relaxation method is used to transform the constraints into an easy-to-solve form, which can be expressed as:

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|  | (9) |
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### Objective function

In the process of fault recovery, it is necessary to restore the power supply of load under the existing network structure. The main goal in the fault recovery process is to restore load power supply, while the secondary goal covers goals such as reducing losses and improving voltage deviation. Therefore, large M method can be used to construct an objective function for distribution network fault recovery:

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|  | (10) |
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is the objective function, M is a large constant, usually taken as 100. is set as the objective function of restoring load, which is the main objective for fault recovery. is the objective function for reducing system losses, is the objective function for reducing voltage deviation. is the total number of time periods for analysis, is the total number of all load nodes in the distribution network. is the total active load on node. is the analysis step.

# Case study

To verify the effectiveness of the proposed method, a modified IEEE 33-node test system [18] is adopted. Figure 2 shows the structure of the distribution network. To ensure the security of distribution network, the limit of the transmission capacity of lines is set to 8 MVA and the upper and lower limits of node voltage are set as 1.1 - 0.9 (p.u.). There are two types of DG installed in the distribution network. The photovoltaic (PV) access points are nodes 12 and 18, with the capacity of 400.0 kVA and inverter power factor set to 0.9. Wind turbine (WT) access points are nodes 22 and 25, with the capacity of 300.0 kVA and inverter power factor set to 0.9. To simplify the analysis of load recovery during the fault recovery phase, the importance of load is not considered in the calculation process. Considering the time sequence analysis of a day, the simulation step is set as 1 hour. In this paper, the typical operational curves are adopted to describe the uncertainties of DG and load, which is shown in Fig.4. The curve of load demand is obtained by the load forecasting method and the value of each simulation step is the average value within 60 minutes. The processing methods of DG outputs are the same.



1. Modified IEEE 33-node system



1. Operating curve of active distribution network

The proposed method is implemented in the YALMIP [19] optimization toolbox using MATLAB R2014a and solved by CPLEX 12.6. The numerical experiments were performed on a PC with Intel(R) Core(TM) i5-5300M 3.20-GHz processor and 8 GB of RAM.

To verify the effectiveness of the integration of SOP and the impact of different access locations on fault recovery process, three scenarios are adopted. The capacities of SOPs are set as 1 MVA and loss coefficient is set to 0.02. The fault point is set at line 2-3 and the time of fault occurrence at 10:00. At 16:00 the power supply is restored, with a total power loss time of 6 hours.

Scenario I: The initial operation status of distribution network is obtained.

Scenario II: SOP is set at node 18 and 33 (Location 1), the fault recovery method is applied.

Scenario III: SOP is set at node 12 and 22 (Location 2), the fault recovery method is applied.

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| --- | --- | --- | --- | --- |
| **Scenario** | **Load recovery capacity /kWh** | **Operation loss of network /kWh** | **Operation loss of SOP /kWh** | **Max voltage deviadtion /p.u.** |
| I | 6543.19 | 743.74 | / | 0.071 |
| II | 6561.84 | 687.45 | 34.44 | 0.046 |
| III | 12522.53 | 1037.91 | 169.70 | 0.057 |

1. Operation Status under Different SOP Position

The simulation results are shown in Table I. It can be seen that compared with Scenario I and II, the load recovery of the distribution network does not significantly increases. At the same time, the operation loss and maxium value of voltage deviadtion is decreased. When SOP is located between node 12 and 22, the load recovery capacity is effectively increased. The operation loss of the network is increased, however, the increment is relatively small compared to the load recovery amount. The power transmission of SOP is shown from figure 5 to figure 10. Results show that SOP can only applied in the fault recovery with the scenario of one terminal is within the power loss area and the other is set outside the power loss area, which is scenario III. SOP can realize the dynamic power balance by real-time adjustment of power flow between feeders, which effectively improves the operating status of line, and reduces the voltage deviation of node at the same time. The results are consistent with the analysis in Chapter II.



1. Active power of SOP in Scenario II



1. Reactive power of SOP in Scenario II



1. Capacity utilization of SOP in Scenario II



1. Active power of SOP in Scenario III



1. Reactive power of SOP in Scenario III



1. Capacity utilization of SOP in Scenario III

Furthermore, a typical scenarios of multi-point fault is built to verify the effectiveness of the proposed method. Two fault occurrence points are set as lines 6-7 and 12-13 respectively. Time of fault occurrence is set from 10:00 to 16:00. Three schemes are adopted to show the influence of SOP location.

Scheme I: The initial operation status of distribution network is obtained.

Scheme II: SOP is set at node 18 and 33 (Location 1).

Scheme III: SOP is set at node 12 and 22 (Location 2).

Scheme IV: Both SOPs are enabled.

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| --- | --- | --- | --- | --- |
| **Scheme** | **Load recovery capacity /kWh** | **Operation loss of network /kWh** | **Operation loss of SOP /kWh** | **Max voltage deviadtion /p.u.** |
| I | 5562.46 | 490.44 | / | 0.091 |
| II | 16762.16 | 572.10 | 136.60 | 0.072 |
| III | 16757.62 | 736.51 | 133.02 | 0.064 |
| IV | 17460.50 | 460.41 | 168.11 | 0.057 |

1. Operation Status under Different SOP Position

The simulation results are shown in Table II. By dispatching SOP, the load recovery capacity is effectively enhanced. Meanwhile the power loss of distribution network is slightly increased after faults. However, considering that the subordinate nodes 7-11 and 13-18 can only recover power through nearby DGs, SOP can provides more power transmission paths to these nodes from feeder 2-22 and 6-33. In Scheme 4, through the collaboration of two SOPs, the overall load recovery of fault recovery has been improved compared to only on SOP integrated. The factors of power loss and the voltage deviation are also reduced. Comparing the four schemes, the effectiveness of the proposed method and the efficiency of SOP are verified.

# Conclusion

After a fault occurs in the distribution network, the real-time balance between power supply and load demand must be met. Load can be restored through upper sources and the nearby power supply of distributed generators. The access of SOP makes it possible for power supply quickly by providing a path for power loss loads. In this paper, a fault recovery model of distribution network considering SOP is established. Power transmission matrix is constructed to represent the power transmission path between each node. The dynamic balance of node power is firstly considered, then the the impact mechanism of SOP on fault recovery is elaborated. The cone relaxation process and the objective function of fault recovery is further introduced. Through the simulation analysis of the modified IEEE 33-node test system, scenarios of single fault and multi-point fault are built. Results show that SOP can only applied in the fault recovery with the scenario of one terminal is within the power loss area and the other is set outside the power loss area. The effectiveness of the proposed method and the improvement of load recovery after fault by SOP are verified.

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