Fault Reconfiguration of Distribution Networks with Soft Open Points Considering Uncertainties of Photovoltaic Outputs and Loads

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Abstract. Conventional fault reconfiguration methods assume determinant values for loads and distributed generators outputs, which may lead to a reconfiguration solution that cannot satisfy operational constraints. This paper proposes a fault reconfiguration method for distribution networks with soft open points (SOPs) considering the uncertainties of photovoltaic (PV) output power and loads. Firstly, a fast probabilistic power flow method based on voltage sensitivity for distribution networks with SOPs is proposed to evaluate each reconfiguration scheme. Then a fault reconfiguration model considering uncertainties of PV output powers and loads is formulated and solved to minimize load shedding and line losses. The effectiveness of the proposed reconfiguration method is verified using the modified 33 and 69-bus distribution systems. The proposed method is shown to be very fast and can provide reliable reconfiguration schemes satisfying all system operation constraints.

Keywords: Distribution Networks, Fault Reconfiguration, Probabilistic Power Flow, Soft Open Points

1. Introduction

Fault reconfiguration is an important tool of distribution systems to realize self-healing and reliable power supply. Distribution networks are equipped with section switches and tie switches. When a fault occurs, a distribution network will change its topology by opening/closing the switches to restore power supply to customers who are suffering power interruption. With increasing penetration of distributed generations (DGs) in distribution networks, customers losing power supply can also be reenergized by micro-grids. Fault reconfiguration of traditional AC distribution networks has been studied for decades [1], by formulating and solving mixed integer programming models [2] and considering the uncertainties of DG outputs [3].

With the development of power electronics technology, soft open points (SOPs) are expected to be installed into traditional AC distribution networks, forming new AC-DC mixed distribution networks [4]-[7]. SOPs are capable of controlling power flow in distribution networks by implementing appropriate control strategies, thus can greatly improve the reliability and flexibility of distribution networks. The above studies on fault reconfiguration of distribution networks with SOPs usually assume certain load and DG output values from forecasting without considering their uncertainties.
However, due to random changes in DG outputs and loads, the reconfiguration scheme obtained using certain DG outputs and load values cannot always guarantee the system to satisfy its operating constraints, leading to risk of bus voltages or line power flow exceeding their limits.

This paper proposes a fast fault reconfiguration method for distribution networks with SOPs considering the uncertainties of PV outputs and loads. A fast probabilistic power flow method based on voltage sensitivity for distribution networks with SOPs is first proposed to evaluate each reconfiguration scheme. Then, considering the impact of uncertain PV outputs and loads, a fault reconfiguration model is formulated and solved to minimize load shedding and line losses. The proposed method is shown to be very fast and can provide reliable reconfiguration schemes satisfying all system operation constraints.

The remainder of this paper is organized as follows. Section II presents the proposed probabilistic power flow method. Section III presents the proposed fault reconfiguration method. Case studies are given in Section IV and conclusion is given in Section V.

2. Probabilistic Power Flow for Distribution Networks with Sops
Probabilistic power flow can effectively analyze the influence of uncertain DG outputs and loads on system operating state. Therefore, probabilistic power flow is adopted to evaluate the effectiveness of each reconfiguration scheme considering the PV output and load uncertainties, so that the final results can satisfy all operation constraints.

2.1. Control Strategies of SOPs
The back-to-back VSC-based SOP is adopted in this paper, whose internal structure is shown in Figure 1. When a fault occurs at line L8 in the AC distribution system, the VSC near the fault point, i.e. VSC2, is capable of providing voltage and frequency support for loads in the non-fault area, i.e. N7 and N8. According to the control mode of SOPs, when a fault occurs at line L8, the non-fault side SOP, i.e. SOP1, will be controlled in the $V_{d}Q$ mode, while the fault side SOP will be switched into $Vf$ mode. Therefore, the AC buses near VSC1 and VSC2 can be viewed as a PQ bus and a Vf bus in the power flow model, respectively.

![Figure 1. Power flow model of SOP](image)

2.2. PV Output Model
PV output power can be forecasted according to meteorological conditions. Normal distribution is used in this paper to model the random prediction error of PV output power\(^{[11]}\). The probability density function of PV power output $P_{pv}$ is:

$$ f(P_{pv}) = \frac{1}{\sqrt{2\pi}\sigma_{pv}}\exp\left(-\frac{(P_{pv} - \mu_{pv})^2}{2\sigma_{pv}^2}\right), \quad (1) $$

where $\mu_{pv}$ is the predicted value of the PV power output; $\sigma_{pv}$ is the variance of the prediction error of the PV power output.

2.3. Load Model
The daily load data of distribution networks can be obtained by load forecasting. Normal distribution is used to model the random prediction error of the loads, and the reactive load of a bus is assumed to follow the real load according to a constant power factor. The probability density function of real load power $P_{ld}$ is:

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\[ f(P_{LD}) = \frac{1}{\sqrt{2\pi}\sigma_{LD}} \exp\left(\frac{(P_{LD} - \mu_{LD})^2}{2\sigma_{LD}^2}\right), \]

where \( \mu_{LD} \) is the predicted value of the real load power; \( \sigma_{LD} \) is the variance of the random prediction error of the real power load.

2.4. Fast Probabilistic Power Flow Algorithm

In order to avoid the large computation burden of probabilistic power flow, this paper proposes a fast probabilistic power flow method based on voltage sensitivity for distribution networks with SOPs, which is used to quickly evaluate the effectiveness of a given reconfiguration scheme. Random changes in PV outputs and loads will cause changes of bus voltages and line powers. With the help of voltage sensitivities, one can obtain the relationship between PV outputs and bus voltages, and then decide whether the bus voltages and line power flow exceed their limits, so as to quickly evaluate the effectiveness of the reconfiguration scheme.

Taking the PV output change of bus N8 in Figure.1 as an example, suppose the real and reactive power of PV change \( \Delta P \) and \( \Delta Q \), respectively, the voltage changes of buses N7 and N8 can be approximated as:

\[ \Delta U_{N7} = \Delta P \frac{R_{16}}{U_{N7}} + \Delta Q \frac{X_{16}}{U_{N7}} \]  \hspace{1cm} (3)

\[ \Delta U_{N8} = \Delta U_{N7} + \Delta P \frac{R_{17}}{U_{N8}} + \Delta Q \frac{X_{17}}{U_{N8}} = \Delta P \left( \frac{R_{16}}{U_{N7}} + \frac{R_{17}}{U_{N8}} \right) + \Delta Q \left( \frac{X_{16}}{U_{N7}} \frac{X_{17}}{U_{N8}} \right) \] \hspace{1cm} (4)

where \( U_j \) is the terminal bus voltage of branch \( j \); \( R_j \) and \( X_j \) are resistance and reactance of branch \( j \), respectively.

Ignoring the effect of PV uncertainties on the change in SOP power losses, the change of PV output at bus N8 is equivalent to the load change at bus N4, and the voltage changes at buses N1 and N2 can be approximated as:

\[ \Delta U_{N1} = \Delta P \frac{R_{14}}{U_{N1}} + \Delta Q \frac{X_{14}}{U_{N1}} \] \hspace{1cm} (5)

\[ \Delta U_{N2} = \Delta U_{N1} + \Delta P \frac{R_{12}}{U_{N2}} + \Delta Q \frac{X_{12}}{U_{N2}} = \Delta P \left( \frac{R_{14}}{U_{N1}} + \frac{R_{12}}{U_{N2}} \right) + \Delta Q \left( \frac{X_{14}}{U_{N1}} + \frac{X_{12}}{U_{N2}} \right) \] \hspace{1cm} (6)

Combing (3)-(6), the linear sensitivity relationship of PV or load random variation to the voltage of each bus can be constructed.

The proposed probabilistic power flow method based on voltage sensitivity has the following steps:

Sample load and PV outputs according to their probability density functions using the Latin hypercube sampling method;

Determine the network topology of the system according to the given reconfiguration scheme, and perform conventional power flow using forecasted values of load and PV outputs. The buses at both ends of SOPs are viewed as PQ buses in the power flow calculation;

For each sample, compute the difference between the sampled PV outputs and loads with their forecasted values. Then compute the bus voltage deviations at the current operating point using the voltage sensitivity model. Thus all bus voltages and branch power flows can be obtained;

Compute the probability distribution of all bus voltages and branch power flows, and then calculate the confidence intervals of all bus voltages and branch power flows under this reconfiguration scheme with a certain degree of confidence.

3. Fault Reconfiguration Considering Uncertainties of PV Power Outputs and Loads
3.1. Formulation
The fault reconfiguration problem is formulated as a multi-objective model, i.e. minimizing the line losses and recovering the lost load as much as possible. Bus voltages, branch power flows and SOP power flows will change due to the uncertainties of PV output and loads after reconfiguration. The variation range should not exceed the voltage limits or line thermal limits. The reconfiguration restoration objectives and constraints are expressed as follows.

3.1.1. Objective Function 1: Minimize Load Shedding
\[ f_i = \sum_{n \in N_i} \frac{P_n}{\sum_{n \in N} P_n}, \]  
(7)
where \( P_n \) represents the load at bus \( n \); \( N, N_0 \) are the set of all buses and the set of all reenergized buses, respectively.

3.1.2. Objective Function 2: Minimize Line Losses
\[ P_{\text{loss}} = \sum_{j \in T} \frac{P_j^2 + Q_j^2}{U_j^2}, \]  
(8)
where \( P_{\text{loss}} \) represents line losses; \( P_j, Q_j \) represent the real and reactive power flowing through branch \( j \), respectively; \( T \) is the set of all edges.

3.1.3. Radial Operation Constraint. Voltage Upper And Lower Limit Constraints:
\[ U_{i,\text{min}} \geq U_{i,\text{min}}, \quad U_{i,\text{max}} \leq U_{i,\text{max}}, \]  
(9)
where \( U_{i,\text{min}}, U_{i,\text{max}} \) represent the lower and upper limit of bus voltage, respectively; \( U_{i,\text{min}}, U_{i,\text{max}} \) are the lower and upper bounds of the voltage confidence interval at bus \( i \) with a given confidence degree.

3.1.4. Line Thermal Limit Constraint:
\[ S_{j,\text{max}} \leq S_{j,\text{max}0}, \]  
(10)
where \( S_{j,\text{max}0} \) is the capacity limit of branch \( j \); \( S_{j,\text{max}} \) is the upper bound of the confidence interval of apparent power at branch \( j \) with a given confidence degree.

3.1.5. SOP Operation Constraint:
\[ S_{m,\text{max}}^{\text{SOP}} \leq S_{m,\text{max}0}^{\text{SOP}}, \]  
(11)
where \( S_{m,\text{max}}^{\text{SOP}} \) is the maximum capacity of the \( m \)th SOP; \( S_{m,\text{max}}^{\text{SOP}} \) is the upper bound of the confidence interval of the apparent power for the \( m \)th SOP with a given confidence degree.

It can be seen that (9)-(11) ensure the system to satisfy the operation constraints considering all possible changing scenario of PV outputs and loads with a certain confidence degree.

3.2. The Proposed Fault Reconfiguration Algorithm
Genetic algorithm is used to solve the proposed model. The algorithm uses binary encoding, where 1 means a switch is closed and 0 means it is open. The process is shown as follows:

Step 1: Initialize network parameters, including network structure, line parameters, PV output powers and load distribution, probability power flow sampling number.

Step 2: Sample PV output powers and loads using Latin hypercube sampling method. The samples will be used for probabilistic power flow calculation of all individuals in the population.

Step 3: Generate initial population.
Step 4: For each individual in the current population, perform probabilistic power flow calculation to compute the confidence interval of all bus voltages and branch power flows and evaluate its fitness. The calculation principle of the proportion of deenergized loads is: a) if a voltage cannot satisfy the constraints, this bus is viewed as deenergized; b) if a power flow cannot satisfy the constraints, this line is viewed as disconnected.

Step 5: Run selection, crossover and mutation. Select those individuals with the lowest proportion of deenergized loads through championship selection method. If two individuals have the same proportion of deenergized loads (for example, 0%), the one with less network losses will be selected for the next generation. The order-based crossover operator and the reverse operation-based mutation operator are adopted.

Step 6: After the new population is obtained, eliminate all the loops in the network by modifying chromosomes using the avoiding circle method to ensure the network is radially operated.

Step 7: If the number of iterations reaches the threshold, the algorithm stops and output the optimal reconfiguration scheme; otherwise, go to Step 4.

It can be seen that the two objectives are processed in the algorithm but not explicit combined into one directly in the model.

4. Case Study

4.1. 33-bus Distribution System Test
In this section, the 33-bus distribution system is used to test the proposed method. A PV is configured at bus 30 and the tie line 37 between bus 25 and 28 is replaced with a SOP, as shown in Figure. 2. The maximum transmission capacity of the adopted SOP is 2MW. The PV output is 500kW and the power factor is 0.95. The variance of PV output and load is 10% of the rated power values, the number of samples is set to 500, and the confidence degree is set to 99.73% in the probabilistic power flow calculation.

Figure 2. 33-bus distribution system with a SOP
Suppose a fault occurs at line 3, and different fault conditions are used for simulations, as shown in Table 1.

Case 1: Only the switches are used to restore the power supply, and the PV outputs and loads are assumed to be the rated values without considering their uncertainties.

Case 2: Only the switches are used to restore the power supply in the power loss area, and the uncertainties of PV outputs and loads are considered.

Case 3: Both switches and the SOP are used to restore the power supply, and The PV outputs and loads are assumed to be their rated values without considering their uncertainties.

Case 4: Both switches and the SOP are used to restore the power supply, and the uncertainties of PV outputs and loads are considered.

Table I shows the reconfiguration schemes of Case 1~4. Figure.3 shows the nodal voltages under the reconfiguration schemes of Case 1 and Case 2. It can be seen that the theoretical recovery load ratio of Case 1 is 96.77%. However, due to the random fluctuation of PV outputs and loads, the voltages of buses 5, 6, 7 and 26 cannot satisfy the requirements, leading to the fact that only 88.16% of the load are recovered without voltage violation. In Case 2, by considering the uncertainties of PV
outputs and loads, the theoretical and actual values of the load recovery rate are both 95.15%. Compared with Case 1, the recovery rate is significantly improved, but it still cannot achieve full load recovery. For Case 3 and Case 4, it can be seen from Table 1 that the fault recovery effect are the same. Figure 4 shows the nodal voltages of the reconfiguration scheme with and without considering the influence of uncertainties. It can be seen from Figure 4 that the SOP not only realizes the power supply recovery of all loads, but also ensures the voltage level of each bus.

Table 1. Reconfiguration results of Case 1~4 for the 33-bus system

| Case   | Opened lines | Rate of recovered loads without considering uncertainties | Rate of recovered loads considering uncertainties | Buses without power supply | Buses whose voltages exceed their limits considering uncertainties | Line losses (kW) |
|--------|-------------|----------------------------------------------------------|--------------------------------------------------|-----------------------------|-----------------------------------------------------------------|-----------------|
| 1      | 7, 14, 9, 32, 4 | 96.77%                                                   | 88.16%                                           | 4                           | 5, 6, 7, 26                                                       | 139.91          |
| 2      | 7, 14, 9, 32, 5 | 95.15%                                                   | 95.15%                                           | 4                           | -                                                               | 115.73          |
| 3      | 7, 14, 9, 32   | 100%                                                    | 100%                                             | -                           | -                                                               | 174.98          |
| 4      | 7, 14, 9, 32   | -                                                       | -                                                | -                           | -                                                               | 174.98          |

Figure 3. Verification results of the reconfiguration scheme in Case 1~2

Figure 4. Verification results of the reconfiguration results in Case 3~4

We can conclude that compared with the common switches, the use of SOPs in the distribution networks can effectively improve the proportion of power supply recovery when fault occurs without violating the system operation constraints.

In terms of computing time, the proposed probabilistic power flow method can effectively reduce the total computing time of reconfiguration. The evaluation time of each reconfiguration scheme is 6.55s and 0.09s, respectively, by using the conventional probabilistic power flow method and the proposed probabilistic power flow method when the number of random samples is set to 500.

4.2. 69-Bus Distribution System Test
In this section, the 69-bus distribution system is used for case study. A PV is connected at bus 59, and the tie switch 71 between bus 50 and 59 is replaced by a SOP. The maximum transmission capacity of the SOP is 1MW. The PV output is 300kW and the power factor is 0.95. The variance of PV output and load are set to 10% of their rated power value. The number of samples in each probabilistic power flow calculation is set to 500.
Suppose a fault occurs at line 49. Table III shows the restoration results in Case 1, Case 2 and Case 4. It can be seen that the introduction of SOP can effectively help realize power supply recovery of all loads and improve the nodal voltages.

Table 2. Reconfiguration results of Case 1, 2 and 4 for the 69-bus system

|                      | Case 1       | Case 2       | Case 4       |
|----------------------|--------------|--------------|--------------|
| Opened lines         | 14,70,9,61   | 14,70,9,61,71| 14,70,9,61   |
| Rate of recovered loads without considering uncertainties | 100%         | -            | -            |
| Rate of recovered loads considering uncertainties | 89.88%       | 89.88%       | 100%         |
| Buses without power supply | -            | 50           | -            |
| Buses whose voltages exceed their limits considering uncertainties | 50           | -            | -            |
| Line losses (kW)     | 171.19       | 114.76       | 167.53       |

5. Conclusion
Considering the uncertainties of load and PVs outputs, this paper proposes a fault reconfiguration method for distribution networks with SOPs. A fast probabilistic power flow method for distribution network with SOPs is proposed. The fault reconfiguration model is formulated to simultaneously minimize load shedding and line losses. The effectiveness of the proposed method is verified by simulation analysis, which has certain engineering application value.

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