An Optimized Method of DG Allocation in Active Distribution Network Considering Risk of Failure
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Abstract. Based on the Particle Swarm Optimization algorithm (PSO) with inertia weight, this paper proposed a distributed generator (DG) optimization method in active distribution considering fault risk with the goal of minimizing economic loss. According to the number of users and the loss of user load caused by power failure of the active distribution network, the fault risk impact factor is proposed and defined and then used to correct the objective function. The effectiveness of the proposed method is verified by a 24-node 6kV network. The results show that, after accessing the DG, the user's loss risk value, load loss risk value and total risk value are greatly improved. And the effectiveness of the DG optimization method considering the risk of failure is confirmed.

Introduction
Distribution network accidents may lead to partial or even integral degradation of regional infrastructure systems, resulting in huge losses in social production. It is very urgent to reveal and evaluate the potential danger and its consequences. Thus, finding the planning and design method for the least loss and the optimal safety investment benefit is important. Domestic and foreign scholars have done a lot of research on the location and capacity of DG [1~3]. The literature [4] applies the voltage stability limit surface normal vector to the location of the DG. Literature [5] proposed a DEMOPSO algorithm based on entropy and distance and FWM technology to determine the DG planning scheme. Literature [6] contains a critical review of the work in this field and described some key challenges ahead which remain to be tackled. In summary, the existing literature has achieved a lot for the planning of DG, but few documents quantify the risk factors of failure when designing the planning scheme. This paper proposes an evaluation method for the risk factors of fault in active distribution network. It is included in the objective function of the planning scheme in the form of a penalty factor, and the DG planning model considering the safety constraints is established to obtain a more realistic planning scheme.

Failure Risk Assessment
First, we need to do the following treatments on the distribution network.
(1) For the same pole and parallel line to be combined. The branch of the shunt capacitor, the high-voltage transmission line, the main wiring of the power plant, and the main wiring of the substation are ignored. (2) Nodes in the network are divided into two types: equivalent power nodes and equivalent load nodes. (3) Distribution lines and transformer branches as edges. The impedance modulus is set to the edge weigh. (4) The distance between the equivalent power node and the equivalent load node is the length corresponding to the shortest path of two points.

Then, the distribution network can be abstracted into a complex network model G. We can define the importance indicator of its node $i$ as follows:

$$
\mu(i) = \frac{s_i}{l_i}
$$

(1)
In the formula, \( s_i \) is the edge weight of node \( i \). That is, the reciprocal of the weights of all edges directly connected to node \( i \). \( l_i \) is the average of the shortest path weights from node \( i \) to each other node. The loss caused by the failure is mainly including the loss of the number of users and the load of users. Its model is as follows,

\[
R_i = \frac{\sum_{i=1}^{N} \mu_i P_i L_i}{\sum_{i=1}^{N} \mu_i P_i} 
\]

(2)

\[
R_2 = \frac{\sum_{i=1}^{N} \mu_i n_i L_i}{\sum_{i=1}^{N} \mu_i n_i} 
\]

(3)

where, \( R_i \) and \( R_2 \) are the consequences of user loss and load loss, respectively. \( N \) is the total number of users. \( P_i \) is the load. \( n_i \) is the number of users of node \( i \). \( \mu_i \) is the importance factor of node \( i \). \( L_i \) represents the power supply state of node \( i \). 1 if not powered, otherwise 0. The integrated model is as follows:

\[
R = \lambda \left( \rho_1 \left( \frac{\sum_{i=1}^{N} \mu_i P_i L_i}{\sum_{i=1}^{N} \mu_i P_i} \right) + \rho_2 \left( \frac{\sum_{i=1}^{N} \mu_i n_i L_i}{\sum_{i=1}^{N} \mu_i n_i} \right) \right) 
\]

(4)

where, \( \lambda \) is the probability of failure for a root node. \( \rho_1 \) and \( \rho_2 \) are respectively the weight for load risk and number risk of user that is affected by power failure. And, \( \rho_1 + \rho_2 = 1 \).

Therefore, we can adopt the penalty function to define the fault risk impact factor:

\[
K(R) = \begin{cases} 
K_R (R - R_{\text{min}})^2, & R > R_{\text{min}} \\
0, & R \leq R_{\text{min}} 
\end{cases} 
\]

(5)

where, \( K_R \) is the consequence penalty factor of power fault.

**DG Allocation Model**

In order to achieve the most preferred location of the DG, the objective function is performed from the aspects of security and economy. Security mainly considers related constraints, including node voltage constraints, line current constraints, and DG operation constraints. The economic aspect mainly considers the network loss caused by DG after accessing to the network.

**Constraints by DG Network Access**

(1) Node voltage constraints

\[
K_v(U) = \begin{cases} 
K_R (U - U_{\text{min}})^2, & U < U_{\text{min}} \\
K_R (U - U_{\text{max}})^2, & U > U_{\text{max}} \\
0, & U_{\text{min}} < U < U_{\text{max}} 
\end{cases} 
\]

(6)

In the formula, \( U_i \), \( U_{\text{max}} \) and \( U_{\text{min}} \) are respectively the voltage of node \( i \), and its upper and lower limits. \( K_v \) is the node voltage penalty factor, which is a penalty for deviation from the operating limit, and generally takes a larger value.

(2) Line current constraint
\[ K_i = \begin{cases} 
K_i(I_j - I_{j_{\text{max}}})^2, & I_j \geq I_{j_{\text{max}}} \\
0, & I_j < I_{j_{\text{max}}}
\end{cases} \tag{7} \]

In the formula, \( I_i, I_{j_{\text{max}}} \) and \( I_{j_{\text{min}}} \) are the current of node \( i \), its upper and lower limits respectively. \( K_i \) is the node current penalty factor.

(3) DG operation constraint
\[ K_{\Sigma_{DG}}(S_{\Sigma_{DG}}) = \begin{cases} 
K_{\Sigma_{DG}}(S_{\Sigma} - S_L)^2, & S_{\Sigma_{DG}} > S_L \\
0, & S_{\Sigma_{DG}} \leq S_L
\end{cases} \tag{8} \]

In the formula, \( S_{\Sigma_{DG}} \) is the total capacity for DG to the grid. \( S_L \) is 10% of the total grid load. \( K_{\Sigma_{DG}} \) is the penalty factor for the amount of DG injection, and the value method is the same as \( K_U \).

**The Objective Function of DG to the Grid**

The objective function is as follows:
\[
\min Z_{\text{cost}} = C_{DG} + C_L + C_{en}
\tag{9}
\]
Where, \( C_{DG} = \sum_{i=1}^{n_{DG}} (\hat{\epsilon}_i C_{DG_i} + C_{pu} \Delta E_{DG_i} + W_{DG_i}) \) is the investment and operating expenses of DG converted to each year. \( n_{DG} \) is the number of DGs to grid. \( \hat{\epsilon}_i \) is the fixed annual investment cost factor for the \( i \)-th DG. \( C_{DG_i} \) is the fixed investment cost for the \( i \)-th DG. \( C_{pu} \) is the electricity price. \( \Delta E_{DG_i} \) is the total annual power loss for the \( i \)-th DG. \( W_{DG_i} \) is the maintenance cost of the \( i \)-th DG.

The formula \( C_{en} = T_{max} \times (P_{\Sigma_{new}} - P_{\Sigma_{DG}}) \times C_{pu} \) is the cost of electricity purchase. Where, \( P_{\Sigma_{DG}} = \sum_{i=1}^{n_{DG}} \lambda_i \times S_{DG_i} ; T_{max} \) is the maximum hours of annual load. \( P_{\Sigma_{new}} \) is the newly increased load. \( P_{\Sigma_{DG}} \) is the total active power. \( \lambda_i \) is the power factor of the \( i \)-th DG. \( S_{DG_i} \) is the capacity of the \( i \)-th DG.

After the DG, the power distribution company can choose to purchase additional power from the regular power supply, or choose to supply the load DG. But their cost are different. Based on this, it is necessary to add the cost of purchasing electricity from the conventional power source as a variable to the objective function. The constraint is normalized to the objective function in the form of a penalty factor, and the new objective function is obtained as follows:
\[
\min Z_{\text{cost}} = C_{DG} + C_L + C_{en} + \sum_{i=1}^{n} K_U(U_i) + \sum_{i=1}^{l} K_i(I_j) + K_{\Sigma_{DG}}(S_{\Sigma_{DG}}) + K(R)
\tag{10}
\]

The above related calculations is based on the calculation of the power flow of the distribution network after the DG is connected to the network. We adopt layered forward and backward substitution method for power flow calculation. The algorithm classifies the network branches according to the characteristics of the branch power forward and the voltage return between the same level of the radiated network. It can calculate the power loss and voltage loss in branch of each level in parallel, thus greatly improving the calculation speed of the distribution network power flow.

**The Optimization Algorithm for Location of DG**

The particle swarm optimization algorithm with inertia weight has a good ability to balance global
and local search. Its optimization result does not depend on the selection of the initial point, and it provides a solution possibility for solving nonlinear combination optimization problems of location and capacity of DG. The program flow of DG location selection based on PSO algorithm with inertia weight is shown in Fig1.

![Optimization flow chart.](image)

**Analysis of Examples**

Taking a 24-node 6kV distribution network as an example. The network topology diagram is as shown in Fig2. Nodes 7~24 in the network can accept DG, and assume that DG is directly installed on the load node. Assume that the power factor of a single DG is 0.9, with 5 DGs, and their capacity respectively 0.1MVA, 0.1MVA, 0.1MVA, 0.2MVA and 0.3MVA, no more than the load of nodes installed. It is stipulated that the maximum access capacity of DG in the power grid is 10% of the total load.
In the model, the penalty factor $K_{UI} = K_J = K_{DG} = 100$, and $K_R = 10000$. The average annual cost factor $\partial_i$ for fixed investment of DG is 0.35. In the case where the number of DGs, location and single power supply capacity are all uncertain, the PSO algorithm with inertia weight is adopted to select and size the DG supply. Finally, the optimal solution is shown in Fig 3.

As can be seen from the figure, due to the influence of DG on load capacity of line and power flow in distribution network, distributed power supply is mainly located at the end of line in radial distribution network. Table 1 shows the comparison results of the risk values before and after DG accessing to grid. The result is the value after applying the penalty function.

Table 1. Comparison of risk values before and after DG accessing to grid.

<table>
<thead>
<tr>
<th>Risk</th>
<th>With DG [ten thousand yuan]</th>
<th>Without DG [ten thousand yuan]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss risk of users</td>
<td>20.453</td>
<td>28.491</td>
</tr>
<tr>
<td>Loss risk of load</td>
<td>13.475</td>
<td>24.551</td>
</tr>
<tr>
<td>Total risk</td>
<td>33.928</td>
<td>53.042</td>
</tr>
</tbody>
</table>

From the perspective of risk, the loss risk value of users can measure the number of users lost in the distribution network before and after accessing the DGs. The loss risk value of load can measure the load loss of the distribution network before and after the DG access. So the total risk value obtained by the combination of the two can measure the reliability of the entire distribution network. The total risk before and after accessing the DGs is 53.042, 33.928 respectively. The risk of user loss and load loss is also greatly improved compared with that before access. This is mainly because the island power supply can be realized after the DGs are connected, and the reliability of the power supply can be significantly improved. In addition, the location scheme of DGs considers the user's loss risk value and the load loss risk value, and also considers various economic factors and various constraints of DG access. In summary, the method proposed in this paper finds a better location scheme for distributed power supply.

**Summary**

This paper proposed the fault risk impact factor of the active distribution network, including the loss risk of user quantity and the loss risk of load, which is used to measure the power supply reliability of the distribution network. In the optimization method of network with DG, the comprehensive fault risk impact factor is included in the objective function. And a DG optimization method with the goal of minimizing economic loss at failure is established. The simulation analysis of the example proves the rationality of the proposed fault risk impact factor and the optimization of the objective function, which has a guiding role for fault risk assessment and DG network optimization in active distribution network in the future.
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References


