THREE-STAGE MODEL BASED OPERATIONAL RISK ANALYSIS OF ACTIVE DISTRIBUTION NETWORK

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Abstract: Contraposing to all kinds of distributed energy and load characteristic in active distribution network, this paper establishes a three-stage model of the operational risk analysis in accordance with the time. In this paper, a quick uncertain power flow calculation is completed with joint possibilistic-probabilistic uncertain model based on evidence theory. According to the out-of-limit problems in results, an operation risk analysis system is established considering the power loss. The buses and branches in risk can be located by improved IEEE 33 distribution system model simulation and verifying the necessity of the joint uncertain power flow calculation model and the efficiency of the algorithm. And based on the establishment of the active distribution network security region, excogitate possible guidance of the risk control.

INTRODUCTION

Active distribution network (ADN) has a large scale and a complex structure; in addition, the access points of distributed generations (DG) spread, so controllability and uncertainty problems are increasing, as well as the requirements of operational risk analysis.

Operational risk assessment is focused on the short-term risk assessment and calculation, which should be able to represent system’s real-time status and predict short-term risk indexes. Literatures [1] proves that, applying the fast probabilistic power flow calculation can obtain system’s operation states based on power flow results. The solving methods of uncertain power flow (UPF) in power system are divided into two kinds: probabilistic power flow (PPF) and fuzzy power flow (FPF). PPF is used when input variables’ probability distribution is known [2], while in FPF, uncertain input variables are turned into a range subject to certain membership functions by possibility theory, as the output, which can be quantified from a range [3].

In this paper, a three-stage model of the operational risk analysis is established, including the process of solving UPF by joint possibilistic-probabilistic uncertain model with unscented transformation (UT) method to possibilistic variables and α-cut method to probabilistic variables based on evidence theory, and the foundation of operational risk indexes system and the analysis of the UPF outputs by security region of ADN. And by simulation, the necessity and efficiency of method is proved, and guidance for risk control can be obtained.

THREE-STAGE RISK MODEL IN ADN

There are many uncertain input variables in ADN, thus a probability or possibility distribution model of input variables needs to be established at first stage, as well as to obtain the probability distribution of bus voltage and branch power by UPF; Then analyse the out-of-limit probability of bus voltage magnitude and the branch active power based on the cumulative density function (CDF), as well obtain risk effect indexes combining with the outage loss and load important level coefficient, and establish current security region model of ADN; Finally, sort buses and branches according to operational risk value and discuss the output adjustment direction of controllable variables with large impact factor in security domain model. The whole process above constitutes the three-stage model ADN, and its flow chart is shown in figure 1 below.

UPF calculation

The processing of uncertain input variables

According to whether can be expressed by probability or not, the uncertain input variables are divided into probability uncertainty input and possibilistic uncertainty input. In ADN, wind turbine generations (WTG) and solar cell generations (SCG) are considered as the probability uncertainty input variables; while other controllable DGs, such as the micro turbine (MT), and energy storage system (ESS) are considered as possibilistic uncertainty input, expressed with membership functions.

The solution model of UPF

In order to solve UPF in ADN, considering uncertain input variables of both probability and possibility, this paper adopts joint possibilistic–probabilistic uncertain model based on evidence theory.

Figure 2 shows the flowchart of the algorithm. The algorithm is composed of two loops, internal loop and external loop. The former one considers the possibilistic...
uncertainty of variables. This paper uses UT algorithm, and shows its advantages through the comparison with the Monte Carlo Simulation (MCS) algorithm. The latter one calculates possibilistic uncertainty of variables, applying α-cut set method.  

Fig. 2 Flowchart of joint possibilistic-probabilistic uncertainty method

Operational risk assessment model of ADN

Risk analysis of distribution network is designed to measure the potential impact degree of disturbance events on the distribution network. This paper ignores power failure situations, and simply decides the risk of the current buses or branches by predicting out-of-limit through UPF in short-term and its effect.

Risk probability index
(1) Risk probability index \( P_r(U_i) \) of out-of-limit of bus voltage
\[
P_r(U_i) = 1 - F(U_{\text{max}}) + F(U_{\text{min}})
\]
Where, \( U_{\text{max}} \) and \( U_{\text{min}} \) are the upper and lower limits of the node voltage magnitude respectively; \( F(U_i) \) is the CDF of voltage magnitude of bus \( i \) according to UPF calculation results. Usually, the upper and lower limits of the bus voltage magnitude are 105% and 95% of rated value respectively.

(2) Risk probability index \( P_r(P_{ij}) \) of out-of-limit of branch active power
\[
P_r(P_{ij}) = 1 - F(P_{\text{max}})
\]
Where, \( P_{\text{max}} \) is the upper limit of branch active power; \( F(P_{ij}) \) is the CDF of branch \( ij \) active power. Usually the allowed active power upper limit of branch \( ij \) is set to 1.1 times that of the normal value.

Risk effect index
Risk effect index takes two aspects into account: one, to characterize the out-of-limit severity of voltage or active power; two, to characterize economic consequences which is considered to be illustrated by outage loss. And the two parts is linked by load loss function.

(1) Severity index \( I \)
The expression of voltage severity is
\[
I(U_i) = \begin{cases} 
0 & \text{if } U_i < U_{\text{min}} \\
1 - F(U_{\text{max}}) & \text{if } U_i > U_{\text{max}} \\
1 - F(U_{\text{max}}) + F(U_{\text{min}}) & \text{if } U_i < U_{\text{max}} \text{ and } F(U_{\text{min}}) > \delta \\
1 & \text{if } U_i > U_{\text{max}} \text{ and } F(U_{\text{min}}) > \delta 
\end{cases}
\]
The expression of active power severity is
\[
I(P_{ij}) = \begin{cases} 
0 & \text{if } P_i < P_{\text{min}} \\
1 & \text{if } P_i > P_{\text{max}} \\
1 - F(P_{\text{max}}) & \text{if } P_i > P_{\text{max}} \text{ and } 1 - F(P_{\text{max}}) > \delta 
\end{cases}
\]
Where, \( \delta \) is the occurrence probability of small probability events, taken 0.001%.

(2) Outage loss \( L \)
This paper uses indirect method, choose the ratio of output value to unit electric energy consumption \( C \) as assessment factors, and to distinguish loads by load importance factor. Load importance factor \( k \) is simply set to 1, 3 and 5 according to the first class load, secondary class load and third class load in this paper, which can be given by engineer of experience of operation and maintenance of actual distribution network. Outage loss expression is as follows:
\[
Loss(U_i) = k(U_i) \cdot EENS(U_i) \cdot C
\]
\[
Loss(P_{ij}) = k(P_{ij}) \cdot EENS(P_{ij}) \cdot C
\]
Where, \( EENS \) represents the current total load of the bus \( i \) or the branch \( ij \).

(3) Load loss percentage \( P_{\text{load}} \)
To eliminate the out-of-limit of voltage or active power, a load shedding should be proceeded. Load loss percentage \( P_{\text{load}} \) shares function relationships of severity indexes of out-of-limit of voltage and active power as shown in Figure 3.

Fig. 3 I-Pload function

Then the risk effect indexes are as below:
\[
S_{ev}(U_i) = Loss(U_i) \cdot P_{\text{load}}
\]
\[
S_{ev}(P_{ij}) = Loss(P_{ij}) \cdot P_{\text{ij}}\text{load}
\]
Furthermore, the operational risk value is the product of the risk probability index and the risk effect index of the bus or the branch.

Security region model of ADN

There is no stability problems in conventional
distribution network, in which power flow security domain is the only consideration. Because of the fluctuations of DGs and the uncertainties of loads in ADN, the introduction of static voltage security region (SVSR) under small perturbations can effectively narrow the scope of the security domain, and to ensure the stable and secure operation of the system at the time of the prediction.

According to the definitions of SVSR in cut-set space in literature [9], similarly a SVSR of ADN in cut-set space can be obtained as follows after choosing numbers of cut-set by ranking the risk values:

\[ \varepsilon \Omega_{ADN} (i) = \{ x, \text{st. the real parts of eigenvalues} \} \]

And the space can be approximated by the following hyperplane formula:

\[ \sum_{i \in C} (\alpha_i P_i + \beta_i Q_i) = 1 \]

Where, C represents the critical cut-set, \( P_i \) is the active power in the branch of critical cut-set, \( Q_i \) is the reactive power in the branch of critical cut-set.

When the voltage stability boundary is represented by hyperplane, the original nonlinear problem of static voltage security can be obtained as follows after choosing numbers of cut-set by ranking the risk values:

\[ \frac{\partial \Omega_{ADN}}{\partial x} = \begin{bmatrix} \lambda_1 \\
\vdots \\
\lambda_n \end{bmatrix} \]

The parameters of additional DERs are shown below.

### Table 1 Parameters of DERs

<table>
<thead>
<tr>
<th>Node No.</th>
<th>DER</th>
<th>Node type</th>
<th>Capacity (kW)</th>
<th>Model type</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>WTG</td>
<td>PQ</td>
<td>100*5</td>
<td>Probability model</td>
</tr>
<tr>
<td>22/24</td>
<td>SCG1/SCG2</td>
<td>PV</td>
<td>200/300</td>
<td>Probability model</td>
</tr>
<tr>
<td>7/14</td>
<td>MT1/MT2</td>
<td>PQ</td>
<td>100/100</td>
<td>Possibility model</td>
</tr>
<tr>
<td>18</td>
<td>ESS</td>
<td>PQ</td>
<td>30</td>
<td>Possibility model</td>
</tr>
</tbody>
</table>

### Stage 1

To obtain the UPF of improved IEEE 33-bus distribution systems at a certain prediction time \( t \), assume that the probability of possibility distribution parameters of loads and DERs are as follows.

### Table 2 Parameters of uncertain input variables

<table>
<thead>
<tr>
<th>Uncertain inputs</th>
<th>Distribution model</th>
<th>Relevant model parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loads</td>
<td>Normal distribution</td>
<td>( \mu (\text{MW}) )</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Weibull distribution</td>
<td>( \alpha_w, \beta_w ) (m/s)</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>Beta distribution</td>
<td>( \alpha, \beta ) (W/m²)</td>
</tr>
<tr>
<td>Output of MT</td>
<td>a-cut distribution</td>
<td>( [P_{\text{min}}, P_{\text{p}}, P_{\text{max}}] ) (p.u.)</td>
</tr>
<tr>
<td>Output of ESS</td>
<td>a-cut distribution</td>
<td>( [P_{\text{min}}, P_{\text{p}}, P_{\text{max}}] ) (p.u.)</td>
</tr>
</tbody>
</table>

Assume IEEE standard load values represent the present predicted load values.

Proceed a simulation by joint possibilistic-probabilistic uncertainty model in MATLAB R2014a, in which probabilistic model is solved by MCS and UT method respectively. Figure 5 shows the UPF results of the voltage magnitude of bus 6.

### Fig. 5 CDF of voltage magnitude at bus 6

For more accurate output data, some nodes or branches are selected as in Table 3 below.

### Table 3 Output and relative errors of improved IEEE 33-bus distribution systems

<table>
<thead>
<tr>
<th>Output (p.u.)</th>
<th>Mean value</th>
<th>( \varepsilon )</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>UT</td>
<td>0.00102</td>
<td>0.000107</td>
<td>0.000102</td>
</tr>
<tr>
<td>MCS</td>
<td>0.008580</td>
<td>0.008692</td>
<td>0.0005779</td>
</tr>
<tr>
<td>UT</td>
<td>1.2824</td>
<td>0.006500</td>
<td>0.0005779</td>
</tr>
</tbody>
</table>

Where, \( \varepsilon \) represents the relative error percentage between the outputs of MCS and UT method.

The result shows that UT and MCS method share a small error with less than 0.0028% in mean value and less than 4.5723% in standard deviation among the given nodes or branches. However, the running time consumed by MCS method is 16539.029, with only 88.354s by UT method. Then a great advantage of UT method shows in accelerating computation, which meets real-time engineering requirements.

### Stage 2

Assume loads connected at bus 4,5 are first class loads and at bus 9,11,29 are second class loads, otherwise are third class loads. Compute risk values of buses and branches by electricity than 8 yuan/kWh and outage time 2h and pick the largest 5 presenting in the
following Table 4.

Table 4 Risk values of improved IEEE 33-bus distribution systems

<table>
<thead>
<tr>
<th>Bus voltage magnitude</th>
<th>Out-of-limit buses/branches</th>
<th>Risk probability index</th>
<th>Risk index</th>
<th>Risk effect index (yuan)</th>
<th>Risk value (yuan)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14</td>
<td>1</td>
<td>553.597</td>
<td>553.597</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1</td>
<td>480.828</td>
<td>480.828</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>1</td>
<td>457.968</td>
<td>457.968</td>
<td></td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>1</td>
<td>253.512</td>
<td>253.512</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>1</td>
<td>249.065</td>
<td>249.065</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6-7</td>
<td>1</td>
<td>1658.762175</td>
<td>1658.762175</td>
<td></td>
</tr>
<tr>
<td></td>
<td>31-32</td>
<td>0.9845</td>
<td>1254.454389</td>
<td>1235.010346</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7-8</td>
<td>1</td>
<td>1142.640288</td>
<td>1142.640288</td>
<td></td>
</tr>
<tr>
<td></td>
<td>29-30</td>
<td>0.9845</td>
<td>1116.847949</td>
<td>1099.536806</td>
<td></td>
</tr>
<tr>
<td></td>
<td>28-29</td>
<td>0.9845</td>
<td>1080.888916</td>
<td>1064.135138</td>
<td></td>
</tr>
</tbody>
</table>

By analysing the risk probability and risk effect index, the risk order is not complied with risk probability, while risk effect index contributes a lot to operational risk values. The results calculated by UPF satisfy time-sensitive risk trend and could reflect real risks of buses and branches, which provides a basis for follow-up risk treatments and regulations.

Stage 3

By analysing the growth of load points and changes of allocations of DGs, as well as selecting the 5 branches as cut-set, a relevant coefficient table can be obtained as bellow. Easily a hyperplane can be drawn by cut into sections and an security region is shown.

Table 5 Parameters of uncertain input variables

<table>
<thead>
<tr>
<th>Branch active power</th>
<th>Branch reactive power</th>
<th>Branch coefficient $\alpha$</th>
<th>Branch reactive power coefficient $\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{1,6}$</td>
<td>$Q_{1,6}$</td>
<td>0.0093</td>
<td>0.0083</td>
</tr>
<tr>
<td>$P_{2,26}$</td>
<td>$Q_{2,26}$</td>
<td>-0.0261</td>
<td>-0.0298</td>
</tr>
<tr>
<td>$P_{3,7}$</td>
<td>$Q_{3,7}$</td>
<td>0.0023</td>
<td>0.0453</td>
</tr>
</tbody>
</table>

CONCLUSIONS

In this paper, a three-stage model of the operational risk analysis of active distribution network is established in accordance with the time, including a quick uncertain power flow calculation completed with joint possibilistic- probabilistic uncertain model based on evidence theory, the operation risk analysis system and the simple introduction of security region of ADN to guide the risk aversion. Simulations is proceed in an improved IEEE 33-bus distribution systems which verifies the feasibility of the three stage model and the practicability of the relevant methods or algorithms.

ACKNOWLEDGEMENT

This work is financially supported by 2016 Beijing Natural Science Foundation (No.3161002) and Science and Technology Project of State Grid Corporation of China, “Energy Internet Oriented Application Researches of Multi-source Coordination Optimization Operation”.

REFERENCES


