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An Explicit Formula Based Estimation Method for Distribution Network Reliability

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***Abstract*—An improved explicit estimation algorithm is proposed for reliability estimation of the distribution network. Firstly, hierarchical clustering is used to identify and cluster typical feeders based on the topology structure. Secondly, the explicit formula of reliability index under each typical feeder topology is derived by regression analysis, to establish the model for network reliability estimation. Numerical simulations show the suitability of the proposed method in obtaining accurate reliability index for diversified network topology.**

***Index Terms*—reliability evaluation, explicit estimation, hierarchical clustering, distribution network planning**

I. Introduction

THE system average interruption frequency index (SAIFI) and system average duration index (SAIDI) [1] are widely applied as reliability indicators for power outages in distribution networks.

$$S_F = \sum_{k=1}^{N_E} N_{Ek}\lambda_k(\beta_{Ak}u_A + \beta_{Bk}u_B + \beta_{Ck}u_{Ck}) \tag{1}$$

$$S_D = \sum_{k=1}^{N_E} N_{Ek}\lambda_k(\beta_{Ak}T_A + \beta_{Bk}T_B + \beta_{Ck}T_{Ck}) \tag{2}$$

where S_F is SAIFI, S_D is SAIDI, λ_k is the failure rate of the k_{th} type of equipment, N_E is the equipment amounts, β is the affected customers after a failure caused by k_{th} type equipment. T_A, T_B, and T_C represent the corresponding outage time from Table A in [2]. u_A, u_B, and u_C are 0-1 variables which reflect the status of power failures respectively. In (1-2), β is hard to calculate due to the complexity of network topology and load distribution.

The SAIFI and SAIDI are often embedded into the optimization model for distribution network planning. However, the quantitative evaluation of such index is often dominated by analytical or simulation method [3]. Either method requires to search and analyze the network topology for β calculation. Consequently, the optimization of following network planning schemes is greatly restricted. In addition, the estimation algorithm in [4] proposed a simplified method to estimate β. However, there were significant assumptions and empirical judgment in the estimation algorithm which still needs to be improved.

An improved estimation algorithm by using explicit formula is proposed to obtain the reliability index for distribution network planning. The typical feeder structures are classified and clustered by hierarchical clustering algorithm based on the tree edit distance (TED). Reliability index function is derived from regression analysis by considering the fault isolation and load transfer. The proposed algorithm considers the various impacts of network topology and system faults, and offers an embedded optimization model for distribution network planning.

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II. Hierarchical Clustering of Network Topology

A. Topological characterization of feeder structure

The analysis of feeder topology is based on fault isolation and load transfer. Therefore, the nodal location with branch structure is extracted from the distribution network, while the detailed assets are usually ignored. One specific topology diagram can be seen from Fig. 1.

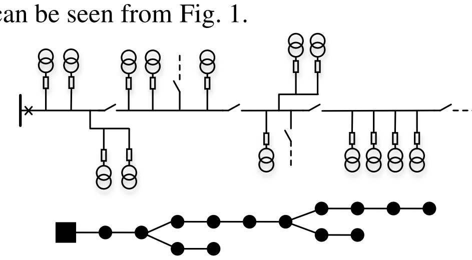

Fig. 1. Topology characterization of feeders

B. Similarity analysis based on TED

For network topology clustering, it is necessary to measure the distance between two different topologies. Therefore, TED [5] is used to measure the similarity between different networks. TED indicates the minimum cost from one tree to another.

$$D(M_1, M_2) = \min \sum_{i=1}^{|S|} C(s_i) \tag{3}$$

where S={$s_1, s_2, \ldots, s_k$} denotes a set of tree edit operations converted from M_1 to M_2, $|S|$ is the number of tree edit operations in S set, and C(s_i) is the cost of the s_i-step operation.

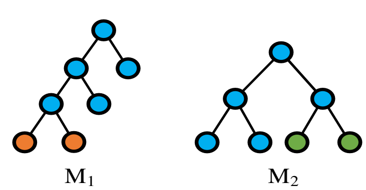

Fig. 2. Identification of TED in different tree structures

The strategy of TED for computing trees is to decompose the tree into multiple subtrees, and calculate the TED between subtrees from bottom to the top until the TED between the two original trees is completed.

Fig. 2 shows two tree structures M_1 and M_2, assuming the nodes in M_1, M_2 are numbered according to the inorder traversal. In addition, the isomorphic set $G(M_1, M_2)$ is defined. The G is composed of (i, j), which represent the node number in M_1, and M_2 respectively. From Fig.2, the blue nodes represent the isomorphic set of two trees. When the nodes that do not belong to G in the two trees are deleted, the two trees will get the same substructure. Therefore, the following formula can be used to calculate the cost from M_1 to M_2.

$$D(\mathrm{M}_1,\mathrm{M}_2)=\min\Big(\sum_{(i,j)\in \mathrm{M}} C_c(i,j)+\sum_{i\notin \mathrm{M}} C_d(i)+\sum_{j\notin \mathrm{M}} C_i(j)\Big) \quad (4)$$

where C_c, C_d, and C_i are the costs of node change, node deletion and node insertion respectively. To avoid size impact on similarity analysis, the tree topology is adjusted to have the same number of nodes for TED calculation.

C. Hierarchical clustering for feeder structure

Although the purpose of TED algorithm is to calculate the degree of difference between feeder topology, there is no absolute attribute value for each feeder topology. In this paper, the agglomerative hierarchical clustering algorithm based on distance is adopted to cluster the typical topologies K. Firstly, the distance between N feeders in the region is calculated, then the two nearest feeders are merged to form $N-1$ classes. The distance between $N-1$ feeders is further calculated, and the above process is repeated until all feeders are merged into one class or the termination condition is met. In the clustering process, TED is used as the distance between feeder, and the distance between the feeder is calculated by average distance

$$L(K_i,K_j)=\frac{1}{n_{ki}n_{kj}}\sum\sum\left|N_i-N_j\right| \quad (5)$$

where K are the typical topologies, N are the number of the feeders, n_{ki} and n_{kj} are respectively the number of samples in K_i and K_j.

III. ESTIMATION METHOD FOR NETWORK RELIABILITY

In equation (1)-(2), how to calculate β quickly is the core problem of the improved estimation algorithm. Therefore, this paper calculates the β of the typical topology under different sections, and then obtain the expression of β through regression analysis.

$$\beta_{mk}=\sum_{j=1}^{N_{Ek}} N_{mj}\Big/\sum_{i=1}^{N_D} N_i N_{Ek} \qquad m=A,B,C \quad (6)$$

where N_D is the total number of feeder nodes, N_{Ek} is the total number of class k devices, N_{mj} is the number of class m, users after the failure of equipment j.

A. Analysis of failure isolation capability

The fault isolation capability is mainly reflected by β_{Ak} and it gets stronger as β_{Ak} increases. In practice, $0\leq\beta\leq1$ and the increased segments in feeder would lead to the more robust fault isolation capability. Therefore, the β_{Ak} will increase as the number of feeder segments (P_F) increases until β_{Ak} reaches a certain limit in the region.

From Fig. A(a) in [2], the functional relationship between β_{Ak} and P_F could be established by regression analysis.

$$f(x)=ae^{-bx}+c \quad (7)$$

$$f(x)=a(1+b/x)^x \quad (8)$$

$$f(x)=(ax+b)/(x+c) \quad (9)$$

In the situation of switch failure, circuit breaker fails to isolate fault or transfer load. In this case, the change trend of β_{Ak} with P_F is similar to the Sigmoid function from Fig. A(b) in [2], the function is introduced into the regression analysis.

$$f(x)=1/(a+e^{-bx+c}) \quad (10)$$

The constraint $0\leq\lim f(x)\leq1$ is applied to the regression function, the function with the highest correlation coefficient is taken as the formula of β_{Ak} and denote as $\beta_{Ak}=f_1(P_F)$.

B. Analysis of load transfer capability

The tie line is added at end of the feeders, the users downstream of the fault section can be supplied by the backup power. After the failure of any devices in the feeder, only A, B users exist, and $\beta_{Ak}+\beta_{Ck}=1$. Therefore, a similar regression method can be used to solve the $\beta_{Ck}=f_2(P_F, P_Z)$. Meanwhile, a simplified method is adopted to reduce the complexity of β_{Ck}. For each P_F, the regression effect of β_{Ck} on P_F is solved under the condition of the supply capacity of the feeder (P_Z=0% and P_Z=100%). Ultimately, a regression linear relationship is used to represent the effect of P_Z on β_{Ck}.

C. Analysis of other impact factors

Distribution automation terminals can effectively identify the fault location and reduce fault clearance time. If the feeder contains such terminals, the T_{dw} and β will be rectified.

In case of the closed single-loop network with double power supply, the fault segments will be isolated by protection, which leaves the rest of the network structure still energized by power supply. Therefore, the T_{dw}, T_{dn}, T_g, and T_z should be set to 0 in the calculation, which could improve the reliability of distribution network.

D. Method Implementation

Based on the above analysis, the pseudo-code for implement the proposed method is illustrated as follows.

Algorithm for Method Implementation	
1	Initialization: P_F, P_Z, N_E, u_x, P_{DE}, P_{DS}, T, etc.
2	Input the feeder topology structure
3	Get the typical topology based on (5)
4	for $i\leftarrow1,\ldots, N$
5	for $j\leftarrow1,\ldots, N_E$
6	Deduce the f_1, f_2 based on (7)-(10)
7	Combine steps 3, 6 to obtain the β in typical topology
8	Set the λ_k, T_x according to the types of blackout
9	Modified β, T_{dw} according to the number of terminals
10	Modified T_{dw}, T_g, T_z according to the mode of operation
11	Calculate the (1) and (2) to obtain the reliability index

IV. Case Study

The real urban distribution network with specific topology [6] is selected to verify the feasibility and effectiveness of the proposed algorithm. The network includes 6 × 110 kV substations with a total capacity of 636MVA and 4 × 35 kV substations with a total capacity of 71MVA. Set the C_d and C_i as 1 while C_c as 0. After applying the TED based hierarchical clustering algorithm, the 96 × 10 kV feeders can be clustered into 4 types. The clustering results are shown in Fig 3.

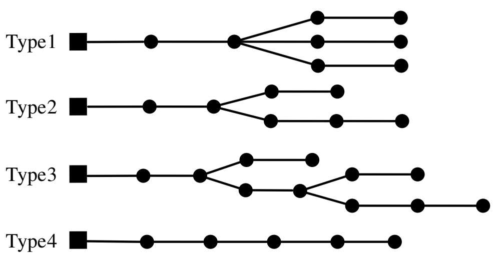

Fig. 3. Typical topology of each clustered feeder structure

It can be concluded that the proportions of each typical structure are 14%, 24%, 20%, and 42% respectively. The 4 types are distinct in terms of network topology: Type 1 has multiple sub-branches, Type 2 has double sub-branches, Type 3 has multiple layers of sub-branches, while Type 4 has the single branch structure.

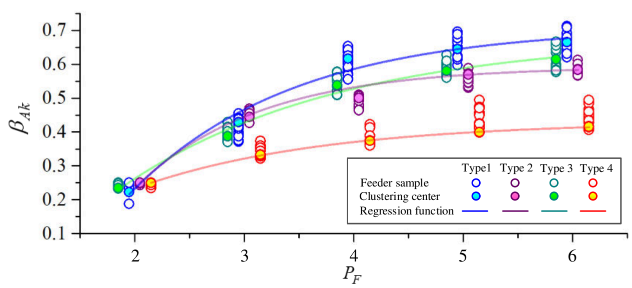

Fig. 4. Distribution of β_{Ak} in 4 types of clustered topology

As shown in Fig. 4, under the same P_F (P_F>2), the β_{Ak} of type 1 is the largest, while the β_{Ak} of type 4 is the smallest. The β_{Ak} curves of types 2 and 3 are similar and located between types 1 and 4. In addition, the β_{Ak} of the four topologies increase with the growth of the number of line segments (P_F), and finally tends to flatten.

Under different types of faults, the fault isolation capability and load transfer capability of each typical topology are analyzed, and the corresponding regression function is calculated in Table I.

TABLE I
Function of β Paraments

Type	**Regression Function**	
	β_{Ak} (P_Z=0)	**β_{Ck} (P_Z=100%)**
1	$0.7e^{-0.25P_F}+0.77$	$0.57e^{-0.14P_F}+0.045$
2	$(0.73P_F-2.03)/(P_F-1.8)$	$(0.19P_F-0.25)/(P_F-3.36)$
3	$(0.68P_F-2.9)/(P_F-3.88)$	$(0.22P_F-0.54)/(P_F-3.9)$
4	$(0.5P_F-1.0)/(P_F-1.01)$	$(0.5P_F-0.013)/(P_F-1.0)$

The reliability index can be calculated through regression function obtained from Table I. The calculation error of the proposed algorithm is solved by network equivalent method and compare with approximate estimation algorithm.

TABLE II
Comparison of Calculation Errors under Reliability Index

Type	**Average Errors of SAIDI**	
	Reference [4]	**Proposed Algorithm**
1	21.32%	6.13%
2	15.74%	4.06%
3	16.89%	5.75%
4	3.12%	3.06%
total	11.26%	4.16%

As shown in Table II, the computational error of the proposed algorithm is reduced by 7.74% compared with that by the algorithm in [4]. For type 4, the two algorithms have similar errors due to the simplicity of the network topology. The reliability of other feeders can be estimated by using the parameters of the typical topology.

The proposed reliability estimation method can help improve the solving efficiency, particularly applied in the optimal distribution network planning, and an extended case is given at Section B in [2].

V. Conclusion

This paper presents an improved method for estimating distribution network reliability. TED based hierarchical clustering method is used to identify the typical topology structure of feeders in the area to be evaluated, and cluster the similarity feeders for network reliability assessment. In addition, the proposed method could deduce the formula of reliability index and the corresponding β through regression analysis. Case study shows its effectiveness and advantages in network reliability evaluation and planning.

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