Grounding Grid Corrosion Diagnosis and Uncertainly Analysis of Branches

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***Abstract*—A hierarchical model of grounding grid is presented, based on which, a testability evaluation method is put forward. The branches are classified into clear branches and uncertain branches according to the testability of them. The concept of uncertain branch group is defined, which consists of related uncertain branches. The prototype of an uncertain branch group is also defined, the branches in which are all clear. The nonlinear incremental diagnosis equations are established and solved by an iteration method, with which, the resistances of clear branches can be directly determined. A dichotomy based method is proposed to evaluate the resistance ranges of uncertain branches for each uncertain branch group, respectively. Experiments are made on a grounding grid with sixty branches, the results of which show the correctness and feasibility of the proposed approach.**

***Index Terms*—Grounding grid, Corrosion diagnosis, hierarchical model, Testability evaluation, Dichotomy, Least square method, Touchable nodes**

I. INTRODUCTION

The grounding grid is an important device to ensure the stable operation of electric power system and safety of operators and power apparatus. The shape, size and structure of the conductors of the grounding grid greatly affect the performance of the grounding grid.

The grounding grids are made of steel or galvanized steel in many countries including China. After years of operation, corrosion will occur on the conductors of the grounding grid, some conductors even break. Accidents due to the damage of grounding grid usually occur, not only causing economic losses but also producing serious social impact. Thus, it is of great significance to detect the faults of the grounding grid in time and take the corresponding measures.

Recently, much work has been done on grounding grid corrosion diagnosis. In [1] and [2], electromagnetic approaches to calculate the performance of grounding grids and to find the breaks in grounding grids are given. However, electromagnetic approaches cannot give a satisfied diagnosis result for the branches corroded but not broken. In [3], an electric circuit method based on Tellegon theory for grounding grid diagnosis is presented, and the diagnosis results are based on the measurements of port resistances. But it is difficult to get the accurate values of port resistances due to the negligible resistances of leading lines. [4]-[6] established a group of corrosion diagnosis equations, in which, the resistance increments of branches are used as diagnosis parameters. Simplex method and linear least square method are used to obtain the solution with the lowest energy losses, but the diagnosis results are with quite large errors due to the non-linear behavior of the problem.

The achievements in analog circuit faults diagnosis are helpful for grounding grid corrosion diagnosis. K-fault allocation method [7][8] are promising but it is sensitive to tolerance effects. Besides, in practice, there are corrosions on most of the branches of a grounding grid. The other typical approaches are Artificial Neural network (ANN) based fault diagnosis [9][10], Ant Colony algorithm[11], Tabu search based diagnosis method[12], Rough set theory based diagnosis method[13] and Genetic based diagnosis method[13]. But the amount of calculation is quite large for the above approaches.

Although many achievements have been made, the following problems still need investigating.

It is quite necessary to evaluate the testability of a grounding grid under the given touchable nodes. Lack of touchable nodes, only some of the branch resistances of a grounding grid can be exactly determined. Thus, we need identify which branches are clear and which branches are uncertain.

Although the resistances of some branches cannot be exactly determined, the possible ranges of the resistances need to be evaluated. To improve the efficiency, a large scaled grid needs to be divided into several small scaled sub grids. In this paper, we will investigate the above problems.

II. HIERARCHICAL MODEL OF GROUNDING GRIDS

A grounding grid can be converted into four levels: the Actual grounding Grid (AG), the Circuit Domain Grid (CDG), the Touchable grounding Grid (TG) and the Intrinsic grounding Grid (IG).

AG is the unconverted topology of a grounding grid.

Taking the touchable nodes as splitting points, a AG can split into many sub-grids. If a sub-grid is not able to be further split, it is called a Quasi-Circuit-Domain (QCD).

As for a QCD, we can merge the series or parallel branches as much as possible but leave all touchable

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nodes. We call the result of above process as a Circuit-Domain (CD).

A CDG is the grid formed by all of the CDs.

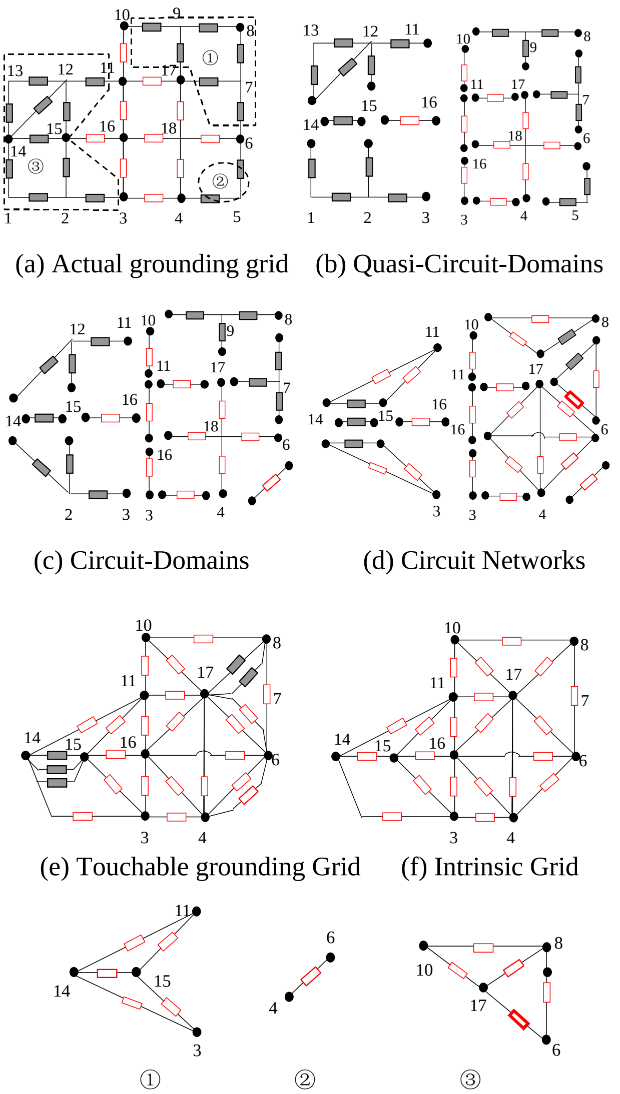
Based on circuit theory, we can eliminate all un-touchable nodes in a CD and model it by equivalent branches between each two touchable nodes. We call the result of the above process a Circuit Network (CN).

A TG is the grid formed by all of the CNs.

We can form an IG by merging the parallel branches in the TG as much as possible but leave all touchable nodes. The branches in the IG are called intrinsic branches.

The QCDs, CDs and CNs are called units of the levels of AG, CDG and TG, respectively.

The hierarchical model of a grounding grid is shown in Fig.1, in which, the touchable nodes are indicated by solid spots.



(a) Actual grounding grid (b) Quasi-Circuit-Domains

(c) Circuit-Domains (d) Circuit Networks

(e) Touchable grounding Grid (f) Intrinsic Grid

(g) Prototypes of the three uncertain branch groups

Fig.1 Hierarchical model of a grounding grid

III.TESTABILITY EVALUATION

If we can establish independent equations the same number as that of intrinsic branches from the testing data of grounding grids, we call the testing scheme as complete measurement.

The reciprocity theorem and superposition theorem can be used to find out the related testing data. It is found that the test scheme of adding the DC current exciter on each intrinsic branch while measuring the voltage on it forms a complete measurement, which is called the basic complete test scheme.

As for the discussions in this paper, we all assume that complete measurement is reached.Lack of touchable nodes, sometimes only a number of branches can be determined in the diagnosis. If the resistance of a branch can be uniquely determined, it is called a clear branch. Otherwise, it is called an uncertain branch.

A. Rules to Determine Clear or Uncertain

1)As for an Intrinsic Grounding Grid, all the nodes are touchable and there is no more than one intrinsic branch between two nodes. Thus, if complete measurement is reached, all intrinsic branches are clear branches.

2)As for a branch in the touchable grounding grid, it is clear if no branches are parallel to it or all of the branches are parallel to it are clear.

3)If all of the branches in a circuit domain are clear, all of the branches in the corresponding circuit network are clear.

4)Besides Rule 2 and 3, a numerical process is necessary to determine the testability of the branches in circuit domains and circuit networks, which will be detailed in C.

5)As for a clear branch in a circuit domain, if it is related to a single branch in the actual grounding grid level, the corresponding branch in the actual grounding grid is clear.

6)The branches, which are not determined as clear by committing Rule 1 to 5 in an iteration approach described in D, are uncertain.

B. Numerical Process to Evaluate Testability

Assuming $\boldsymbol{b}_1$is the set of branches in a circuit domain, and $\boldsymbol{b}_2$ is the set of branches in its corresponding circuit network. The steps of the numerical method are as follows:

Step 1: Establish K groups of $\boldsymbol{b}_1$ randomly.

Step 2: Based on the K groups of $\boldsymbol{b}_1$, calculate the corresponding K groups of $\boldsymbol{b}_2$ according to circuit theory. (refer to Appendix)

Step 3: As for each group of $\boldsymbol{b}_2$, keep the clear branches in $\boldsymbol{b}_2$ not changed and add resistors with resistance of R_D in parallel of each uncertain branches of the circuit network, forming a new topology named Augmented Circuit Network. Add the resistors of R_D in the corresponding positions of the circuit domain, forming a new topology named Augmented Circuit Domain.

Step 4: Commit the basic complete test scheme by adding the DC current exciter on each branch of Augmented Circuit Network and calculate the voltage on the corresponding branch, respectively. The voltages are used as the measuring data of the Augmented Circuit Domain, based on which, the branch resistances of the Augmented Circuit Domain are worked out by using the least square based iteration method which will be described in section V. Thus, K groups of $\hat{\boldsymbol{b}}_1$ are obtained.

Step 5: Calculate the averaged relative error e(%) of each branch according to $\boldsymbol{b}_1$ and $\hat{\boldsymbol{b}}_1$. If the e(%) of a branch is less than the given threshold, it is a clear branch. Otherwise, it is an unknown branch. In this step, augmented branches are not considered.

It is found that to evaluate the testability for just once is not enough. Thus, an iteration approach of testability evaluation is suggested, the steps of which are as follows.

Step 1: Clear the queue $\boldsymbol{Q}_1$ and $\boldsymbol{Q}_2$.

Step 2: Testability evaluation by Rule 1 to 6 and put the clear branches into $\boldsymbol{Q}_2$.

Step 3: If $\boldsymbol{Q}_1$=$\boldsymbol{Q}_2$, the branches in $\boldsymbol{Q}_1$ are clear, and testability evaluation is completed. Otherwise, let $\boldsymbol{Q}_1$=$\boldsymbol{Q}_2$, return to Step 2.

Testability evaluation is committed on the grounding grid in Fig.1, in the results of which, the clear branches are shown by hollow rectangles and the uncertain branches are shown by shadow rectangles.

IV UNCERTAIN BRANCH GROUPS

The definition of uncertain branch is helpful to evaluate the ranges of uncertain branches in rather small scales to improve the efficiency of diagnosis.

If one branch in a circuit network is in parallel with a branch in another circuit network and both of the paralleled branches are uncertain, the corresponding two circuit networks are called related circuit networks.

As for a set of circuit networks, if the circuit networks in it are all related and none of the circuit networks outside the set is related with those inside the set, the set is called a circuit network group. A single circuit network without paralleled branches forms a circuit network group itself.

If there is at least one uncertain AG branch in a circuit network group, the AG branches corresponding to the circuit network group form a Class I uncertain branch group.

If a branch of a circuit domain is clear, but its corresponding branches of the actual grounding grid are uncertain, the corresponding uncertain branches of the actual grounding grid form a Class II uncertain branch group.

The prototype of a Class I uncertain branch group is formed by merging the paralleled branches in the set of related circuit networks corresponding to the uncertain branch group.

The prototype of a Class II uncertain branch group is its corresponding branch of the circuit domain.

It is obvious that all of the branches in the prototypes are clear.

As for the grid in Fig.1, there are three uncertain branch groups, which are encircled by dashed blocks and labeled by numbers in circle.

The first and third uncertain branch groups are of Class I. The second uncertain branch group is of Class II.

The prototypes of the three uncertain branch groups are shown in Fig.1(g), respectively. Note that the branch $b_{17,6}$ in Fig.1(g) is the branch labeled by thick rectangle in Fig.1(d).

V DIAGNOSIS EQUATIONS AND THE OPTIMUM SOLUTIONS

As for a grounding grid with N nodes and B branches, we have

$$\boldsymbol{U} = \boldsymbol{G}^{-1}\boldsymbol{J} \tag{1}$$

Where $\boldsymbol{U}$, $\boldsymbol{G}$ and $\boldsymbol{J}$ are the node voltage matrix, the node admittance matrix and the node injection current vector, respectively.

$$\boldsymbol{G} = \boldsymbol{AYA^T} \tag{2}$$

Where $\boldsymbol{A}$ is the relevancy matrix of nodes to branches, and $\boldsymbol{Y}$ is the diagonal matrix of branch admittances.

In the case of constant DC current excitation, by taking the derivatives of node voltages with respect to branch resistances, we have

$$\mathrm{d}\boldsymbol{U} = \sum_{i=1}^{B} -\boldsymbol{G}^{-1}\boldsymbol{A}\frac{\partial \boldsymbol{Y}}{\partial R_i}\boldsymbol{A^T}\boldsymbol{U}dR_i \tag{3}$$

where R_i is the resistance of the i-th branch.

Rewriting (4) into the increment form, we have

$$\Delta\boldsymbol{U} = \boldsymbol{m}\Delta\boldsymbol{R} = \left[\boldsymbol{m}_1\boldsymbol{m}_2 ... \boldsymbol{m}_B\right]^T \Delta\boldsymbol{R} \tag{4}$$

where $\Delta\boldsymbol{U}$ is the incremental node voltage vector, $\Delta\boldsymbol{R}$ is the incremental branch resistance vector.

$$\boldsymbol{m}_i = -\boldsymbol{G}^{-1}\boldsymbol{A}\frac{\partial \boldsymbol{Y}}{\partial R_i}\boldsymbol{A^T}\boldsymbol{U} \tag{5}$$

Usually, we measure the voltages between a couple of touchable nodes under the h-th excitation condition, thus we have

$$\Delta\boldsymbol{V}(h) = \boldsymbol{M}^{/}(h)\Delta\boldsymbol{R} \tag{6}$$

where, the

$$\Delta V_i(h) = \Delta U_p(h) - \Delta U_q(h) \tag{7}$$

$$M^{/}_{i,j}(h) = m_{p,j}(h) - m_{q,j}(h) \tag{8}$$

We may enlarge the number of equations by changing the positions of DC current excitation. Therefore, we have the diagnosis equations as

$$\Delta\boldsymbol{V} = \begin{bmatrix} \Delta\boldsymbol{V}(1) \\ \Delta\boldsymbol{V}(2) \\ ... \\ \Delta\boldsymbol{V}(L) \end{bmatrix} = \begin{bmatrix} \boldsymbol{M}^{/}(1) \\ \boldsymbol{M}^{/}(2) \\ ... \\ \boldsymbol{M}^{/}(L) \end{bmatrix} \Delta\boldsymbol{R} = \boldsymbol{M}\Delta\boldsymbol{R} \tag{9}$$

where, L is the number of excitation positions.

The diagnosis equations shown in (9) are nonlinear because the elements in $\boldsymbol{M}$ depend on the branch resistances. Thus, we introduce an iteration method to solve the diagnosis equations.

In the k-th iteration, we have

$$\Delta\boldsymbol{V}^{<k>} = \boldsymbol{V}_T - \boldsymbol{V}_e^{<k>} = \boldsymbol{M}^{<k>}\Delta\boldsymbol{R}^{<k>} \tag{10}$$

$$\boldsymbol{R}^{<k>} = \boldsymbol{R}^{<k-1>} + \Delta\boldsymbol{R}^{<k>} \tag{11}$$

Where, $\boldsymbol{R}^{<k>}$ is the branch resistance vector. $\boldsymbol{V}_T$ is the vector of measured voltages. $\boldsymbol{V}_e^{<k>}$ is the vector of voltages calculated according to $\boldsymbol{R}^{<k>}$.

In the iteration, the initial value of resistance of a branch is its designed value, i.e.,

$$\boldsymbol{R}^{<0>}=\boldsymbol{R}_0 \quad (12)$$

Where, $\boldsymbol{R}_0$ is the vector of designed branch resistances.

The iteration continues until (13) is met and we may finally obtain the optimum solutions of branch resistances $\boldsymbol{R}^*$, i.e., $\boldsymbol{R}^*=\boldsymbol{R}^{<k>}$.

$$\left\|\boldsymbol{R}^{<k>}-\boldsymbol{R}^{<k-1>}\right\|_2<\varepsilon \quad (13)$$

The diagnosis equations shown in (9) are nonlinear because the elements in $\boldsymbol{M}$ depend on the branch resistances. Thus, we introduce an iteration method to solve the diagnosis equations.

The steps of corrosion diagnosis approach of a grounding are as follows:

Step1. Establishing the hierarchical model of the grounding grid.

Step2. Evaluating the testability of branches.

Step3. Dividing uncertain branch groups and forming the corresponding prototypes.

Step4. Committing the iteration method described in section V on the actual grounding grid. Taking the optimum solutions of the clear branches of the actual grounding grid as the diagnosis results of them.

Step5. Calculating the resistances of the branches in the prototypes of the uncertain branch groups.

Step6. Evaluating the resistance ranges of the branches in each uncertain branch group, respectively.

Step1 to Step4 are easy to be understood. Step 5 and step 6 will be detailed in the following paragraphs

As for a branch of the actual grounding grid, the resistance is no less than its designed value. Besides, an extremely large value of resistance provides no more information due to the fact that the soil is a conductor. Therefore, we limit the resistance domain of an actual grounding grid branch to the range between its designed value and Ψ times of the designed value.

Based on a dichotomy method, the maximum and minimum resistances of uncertain branches may be evaluated for each uncertain branch group, respectively.

The steps to evaluate the maximum possible resistance $R_{\max,i}$ of the i-th branch in one uncertain branch group are as follows

Step 1. k=1. $R_i^{<0>}=R_i^*$, $R_{dn}=R_i^{<0>}$, $R_{up}=\Psi R_i^{<0>}$, $R_i^{<1>}=0.5(R_{up}+R_{dn})$ .Where, R_{dn} and R_{up} are temporary variables.

Step 2. Commit the basic complete test scheme by adding the DC current exciter on each branch of the prototype of the uncertain branch group and calculating the voltage on the corresponding branch, respectively. The voltages are used as the measuring data of the uncertain branch group forming the vector of $\boldsymbol{V}_{\mathrm{T}}$.

Step 3. Fix the value of $R_i^{<k>}$, evaluate the optimum solutions of the branches in the uncertain branch group except the i-th branch, based on which and adding $R_i^{<k>}$ into it and form a solution vector of $\boldsymbol{R}^{<k>}$.

Step 4. Calculate the evaluated voltage vector of $\boldsymbol{V}_e^{<k>}$.

Step 5. Check whether the voltage restriction of $\left\|\boldsymbol{V}_e^{<k>}-\boldsymbol{V}_T\right\|_2<\varepsilon$ is reached. If it does, and $R_{dn}=R_i^{<k>}$, go to step 6; otherwise, go to step 7.

Step 6. If $\left(R_i^{<k>}-R_i^{<k-1>}\right)^2<\varepsilon$ is reached, and $R_{\max,i}=R_i^{<k>}$, escape the iteration; otherwise, $R_i^{<k+1>}=0.5(R_{dn}+R_{up})$, and k=k+1, return to step 3.

Step 7. If $\left(R_i^{<k>}-R_i^{<k-1>}\right)^2<\varepsilon$ is reached, and $R_{\max,i}=R_i^{<k-1>}$, escape the iteration; otherwise, $R_{up}=R_i^{<k>}$, $R_i^{<k+1>}=0.5(R_{dn}+R_{up})$, and k=k+1, return to step 3.

The steps to evaluate the minimum possible resistance $R_{\min,i}$ of the i-th branch in one uncertain branch group are similar and will not be detailed.

VI Probability Distribution & Entropy Evaluation

A Probability Distribution Evaluation

In the practice, it is not satisfied to obtain the resistance ranges of uncertain branches, especially when the range is rather wide. Evaluation of probability distribution of resistances of uncertain branches is quit necessary.

The evaluation of probability distribution may be carried out for each uncertain branch group, respectively.

As for an uncertain branch group with B branches, the branches are divided into N1~NB segments, respectively. A vector to count the number of feasible solutions is established for each branch, respectively. As for the *i*-th branch, we have

$$\boldsymbol{T}_i=[T_{i,1}, T_{i,2},\ldots,T_{i,NB}]^{\mathrm{T}} \quad (14)$$

Where, $T_{i,m}$ is the counter of the m-th segment of the *i*-th branch.

A probability distribution vector is established for each branch, respectively. As for the *i*-th branch, we have

$$\boldsymbol{p}_i=[p_{i,1}, p_{i,2},\ldots,p_{i,NB}]^{\mathrm{T}} \quad (15)$$

Where, $p_{i,m}$ is the probability of the m-th segment of the *i*-th branch.

The steps of probability distribution evaluation are as follows.

Step 1. k=1 , $\boldsymbol{p}_i^{(0)}=\boldsymbol{0}$ $n^{(1)}=1$ $(i=1\sim B)$. Where, n is the number of sub-segments of each segment.

Step 2. Divide each branch into sub-segments forming the space of discrete solution areas. As for the *i*-th branch, $n^{(k)}N_i$ sub-segments are obtained.

Step 3. Corrosion diagnosis of each discrete solution areas by the approach described in section V. The number of feasible solutions within each segment of branch is counted and filled into $\boldsymbol{T}=[\boldsymbol{T}_1, \boldsymbol{T}_2,\ldots,\boldsymbol{T}_B]^{\mathrm{T}}$.

Step 4. The probability of each segment is calculated. As for the m-th segment of the i-th branch, we have

$$p_{i,m}^{(k)} = T_{i,m}^{(k)} / \sum_{j=1}^{N_i} T_{i,j}^{(k)} \qquad (16)$$

Step 5. If $\sum_{i=1}^{N}\sum_{j=1}^{N_j}\left(p_{i,j}^{(k)} - p_{i,j}^{(k-1)}\right)^2 < \varepsilon$ is reaches, $\boldsymbol{p}^{(k)} = [\boldsymbol{p}_1^{(k)}\boldsymbol{p}_2^{(k)}...\boldsymbol{p}_B^{(k)}]^T$ is the probability distribution. Otherwise, $n^{(k+1)} = n^{(k)} + 1$, k=k+1, return to Step 2.

B Entropy Evaluation

The extent of corrosion is described by Fuzzy information with five degrees as shown in Fig. 2. where, μ is the mumbership degree, r is the relative resistance. As for the *i*-th branch, $r_i = R_i / R_{i,0}$, where Ri,0 is the designed resistance of the *i*-th branch.

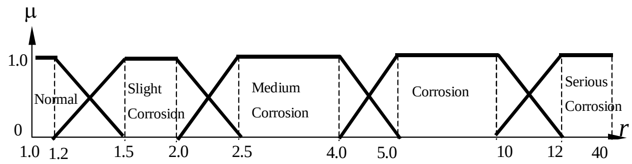


Fig.2 Five types of corrosion of branches

The entropy of the *i*-th uncertain branch is

$$H_c(b_i) = -\sum_{j=1}^{5} P_{i,j} \log P_{i,j} \qquad (17)$$

Where, $P_{i,j}$ is the probability of the i-th branch being with corrosion of the j-th degree.

$$P_{i,j} = \frac{\sum_{m=1}^{N_i} \mu_{i,j}(m) p_{i,m}}{\sum_{h=1}^{5}\sum_{m=1}^{N_i} \mu_{i,h}(m) p_{i,m}} \qquad (18)$$

where,

$$\mu_{i,h}(m) = \frac{N_i S_{i,h}(m)}{R_{\max,i} - R_{\min,i}} \qquad (10)$$

Where, $S_{i,h}(m)$ is the area of the *h*-th corrosion in the m-th segment of the *i*-th branch.

VI EXPERIMENTS

An experimental grounding grid with sixty branches shown in Fig.3 is used as an example. The touchable nodes are Node 0, 3, 5, 8, 10, 12, 13, 15, 17, 18, 20, 21, 22, 23, 24, 25, 27, 29, 30, 32, 33 and 34, which are illustrated by solid circles in the figure.

The resistances of the labeled branches are shown in Table 1. The resistances of other branches are all 0.1 Ω .

TABLE I
RESISTANCE OF ABNORMAL BRANCHES OF THE GROUNDING GRID

Type of Branch	/	//	///	□	O	×
Resistance (Ω)	0.19	0.36	0.47	0.57	0.78	1.35

The hierarchical model described in section II is established with twenty-nine circuit domains and twenty-nine circuit networks.

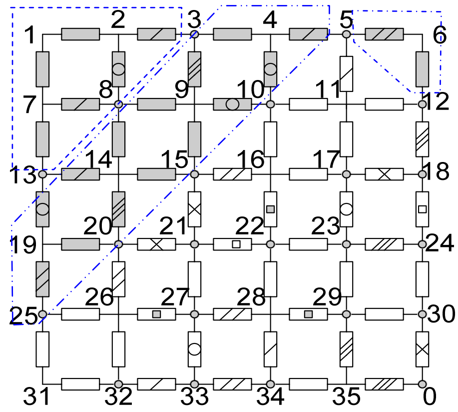


Fig.3 An experiment grounding grid with sixty branches

The testability is evaluated, showing that there are thirty-eight clear branches and twenty-two uncertain branches in the actual grounding grid. In Fig.2, the clear branches are shown by hollow rectangles and the uncertain branches are shown by shadow rectangles. The correctness of testability evaluation is verified by a Monte-Carlo based method.

There are three uncertain branch groups in the grounding grid, which are circled by dashed blocks.

A constant DC current source of 30 A is used as the exciter, with which, the test scheme of complete measurement is committed in the experiment.

Based on the test data, the approach proposed in section VI and the algorithm described in section V are used in the corrosion diagnosis of the grounding grid, the results of which are shown in Table II and Table III.

TABLE II
THE CORROSION DIAGNOSIS RESULTS OF CLEAR-BRANCHES (Ω)

Branches	Exact Resistances	Diagnosis Results	Branches	Exact Resistances	Diagnosis Results
5-11	0.19	0.191	22-28	0.1	0.100
10-11	0.1	0.100	23-29	0.1	0.100
11-12	0.1	0.100	24-30	0.1	0.100
10-16	0.1	0.100	25-26	0.1	0.100
11-17	0.1	0.100	26-27	0.57	0.564
12-18	0.47	0.472	27-28	0.36	0.366
15-16	0.36	0.359	28-29	0.57	0.578
16-17	0.1	0.100	29-30	0.1	0.100
17-18	1.35	1.357	25-31	0.1	0.100
15-21	1.35	1.345	26-32	0.1	0.101
16-22	0.57	0.566	27-33	0.78	0.774
17-23	0.78	0.783	28-34	0.19	0.193
18-24	0.57	0.571	29-35	0.47	0.454
20-21	1.35	1.346	30-0	1.35	1.354
21-22	0.57	0.578	31-32	0.1	0.100
22-23	0.1	0.100	32-33	0.19	0.100
23-24	0.47	0.440	33-34	0.36	0.367
20-26	0.36	0.353	34-35	0.1	0.100
21-27	0.1	0.100	35-0	0.47	0.465

TABLE III
THE CORROSION DIAGNOSIS RESULTS OF UNCERTAIN-BRANCHES (Ω)

Branches	Exact Resistances	Optimum Solutions	R_{min}	R_{max}
1-2	0.1	0.100	0.100	0.250
2-3	0.19	0.187	0.100	0.216
3-4	0.1	0.102	0.100	0.104
4-5	0.19	0.187	0.185	0.189
5-6	0.36	0.178	0.100	0.356
1-7	0.1	0.100	0.100	0.250
2-8	0.78	0.868	0.681	4.00
3-9	0.47	0.467	0.460	0.472
4-10	0.78	0.768	0.761	0.776
6-12	0.1	0.178	0.100	0.356
7-8	0.19	0.180	0.129	0.196
8-9	0.1	0.100	0.100	0.107
9-10	0.78	0.785	0.775	0.794
7-13	0.1	0.100	0.100	0.127
8-14	0.1	0.100	0.100	0.107
9-15	0.1	0.100	0.100	0.108
13-14	0.19	0.190	0.185	0.195
14-15	0.1	0.100	0.100	0.107
13-19	0.78	0.771	0.746	0.802
14-20	0.47	0.472	0.459	0.484
19-20	0.1	0.101	0.100	0.110
19-25	0.36	0.366	0.362	0.370

The probability distribution of each uncertain branch can also be obtained. For instance, the probability distribution of branch 1-2 is shown in Fig.4.

The results of entropy evaluation of uncertain branches are shown in Table IV.

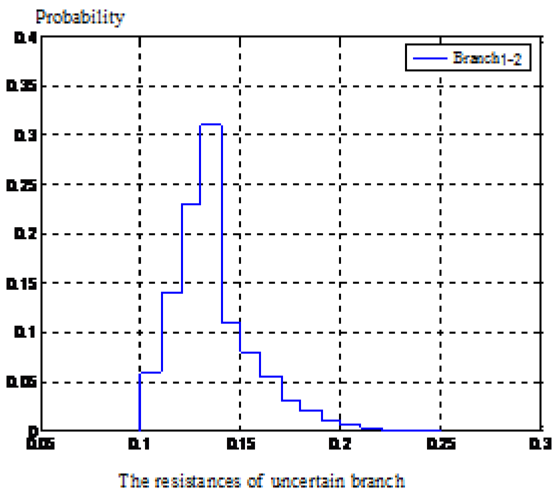


Fig. 4 Probability distribution of the resistance of branch

VII CONCLUSIONS

The hierarchical model presented in this paper is a great help to the corrosion diagnosis of grounding grids.

Branches are classified into clear branches and uncertain branches, which can be determined by the proposed testability evaluation approach based on the hierarchical model.

Related uncertain branches form an uncertain branch group. The branches of the prototype of an uncertain branch group are all clear.

The incremental diagnosis equations are established and can be solved by an iteration method, with which, the resistances of clear branches can be directly determined.

By the proposed dichotomy based method, the maximum and minimum resistances of uncertain branches may be evaluated for each uncertain branch group, respectively.

The correctness and feasibility are proved by the experiment results. Based on the proposed theory, a software of corrosion diagnosis for universal grounding grid is developed and applied in the practice.

TABLE IV
PROBABILITIES OF FAULTS AND ENTROPY OF UNCERTAIN BRANCHES

Branches	Probability(%)					Entropy
	Normal	Slight Corrosion	Medium Corrosion	Corrosion	Serious Corrosion	
1-2	35.01	64.28	0.71			0.9908
2-3	39.05	60.95				0.9651
1-7	35.01	64.28	0.71			0.9908
2-8				24.46	75.54	0.8025
7-8	1.18	98.82				0.0924
7-13	99.94	0.06				0.0069
5-6	4.39	21.72	73.89			0.9991
6-12	4.39	21.72	73.89			0.9991

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