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MODELLING OF EQUIPMENT FAILURE RATE ACCOUNTING FOR THE UNCERTAINTY

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Abstract: A fuzzy model for failure rate with the consideration of the effects of uncertain factors in distribution reliability evaluation is presented. The possibility and credibility distribution analyzed on the basis of sample datum are used for quantifying effects of the uncertainty done to failure rate. Mathematically, the failure rate can be obtained in the interval integration. Moreover, aiming to make the calculating quantity of system reliability evaluation simple and easy, the fuzzy clustering analysis of equipment is adopted. The technique proposed has been implemented in an example distribution system for illustration and the results obtained have been compared with those obtained with average model.

Keywords: fuzzy model, failure rate, uncertainty, fuzzy clustering analysis.

I. INTRODUCTION

Prediction of reliability is extremely important for the distribution network and it is considered as a property of performance evaluation in distribution network [1]-[2]. It is very important to make a proper invest for power enterprise, which aims to gain a better profit. The equipment failure rate is the basis for the reliability prediction. Meanwhile the accuracy of equipment failure rate is closely bound up with the result of reliability prediction [3].

There are many different fields like water supply system and computer system focus that the importance of failure rate of equipment should be modeled more accurate. That means we need to consider the uncertainty of it whatever methods we have used such as artificial neural networks [4], application of Poisson distribution in generalized linear failure rate [5] or SER in computer system [6]. The distribution network like the water-pipe system [7], however, the parameters of equipment operating in distribution network have uncertainty which make specific influence on equipment failure rate because of the changing of operation situation and/or environment [8].Unfortunately, most of these studies adopt the average failure rate model to evaluate the reliability of distribution system [9]-[13]. Manifestly, this kind of method neglects the effect of uncertainty to failure rate which may cause large error in the evaluation. More recently, some research scholars proposed some new methods to take the effect of uncertainty into account, such as interval mathematics, Dempster-Shafer(D-S) theory[14]-[18]. However there are still some aspects which need to be improved and completed.

1) The failure rate with the uncertainty is treated as interval value without considering the difference between the equipment’s in different operation situation and environment;

2) The effects of uncertain factors, operation situation and environment, are not quantified in appropriate either.

As for the uncertainty substantially affect equipment failure rate, which means it also affects the result of reliability prediction, it is important to determine how uncertain the failure rate are if the parameters of equipment, such as operating voltage, frequency and load rate, can be assessed roughly [19].the fuzzy algebra is applied to process the uncertainty factors in distribution network operation and quantify their influence to failure rate. A simple fuzzy-algebra method to model the equipment failure rate is presented, which is that the failure rate is treated as a fuzzy variable with the parameters of equipment, sufficiently, representing the historical data of equipment in distribution network[20]. The uncertainty of failure rate is measured in an interval, weighting by the possibility and credibility distribution. Then expectation values of credibility distribution are applied to judge the credibility of equipment failure rate in fuzzy algebra[21]-[22]. Subsequently, the number of equipment is quite enormous, so the fuzzy clustering analysis is put forward to equipment reduce the calculation quantity.

II. Equipment Failure Rate Model

A. description of Fuzzy algebra

As the core concept of fuzzy algebra, the function of membership grade can be used to weigh the uncertainty relation, which, more objectively, shows the effect between the fuzzy variables. It stands to reason that the failure rate λ is treated as a fuzzy variable based on the concept mentioned above.

It is assumed that Γ is a non-null space of λ and (Γ, A) is the set which consist of the subset of Γ, $\lambda(\gamma)$ is function between Γ and $\Re$ ($\lambda_t \in \Re$).The fuzzy description of failure rate λ is given as:

$$\{\gamma \mid \lambda(\gamma) \le \lambda_t\} \in \mathrm{A} \tag{1}$$

The possibility $\mu_\lambda(\lambda_t)$ and credibility $G_{Cr,\lambda}(x)$ distribution of λ, are shown as below respectively

$$\mu_\lambda(\lambda_t) = pos\{\gamma \in \Gamma \,|\, \lambda(\gamma) = \lambda_t\} \tag{2}$$

$$G_{Cr,\lambda}(x) = Cr\{\gamma \in \Gamma \,|\, \lambda(\gamma) \ge x\}, \quad x \in \Re \tag{3}$$

Generally, to each equipment, an interval value of λ is attached with lower bound $\lambda_{\min}$ and upper bound $\lambda_{\max}$ as depicted in Fig.1. The uncertainty of $\lambda = r_0$ is the highest value of all as the assumption that λ has an exactly specified value. If λ is modeled by the classic model, like triangular or trapezoid model, this λ could be completely defined by the triple $\lambda = (r_0, \alpha, \beta)$ or the quaternion $\lambda = (r_1, r_2, \alpha, \beta)$, which are expressed as equation (4) and (5).

$$\mu_\lambda(r) = \begin{cases} \dfrac{r - r_0 + \alpha}{\alpha} & r_0 - \alpha \le r < r_0 \\ \dfrac{r_0 + \beta - r}{\beta} & r_0 \le r \le r_0 + \beta \\ 0 & \text{else} \end{cases} \tag{4}$$

$$\mu_\lambda(r)=\begin{cases}\dfrac{r-r_1+\alpha}{\alpha} & r_1-\alpha\le r<r_1\\ 1 & r_1\le r<r_2\\ \dfrac{r_2+\beta-r}{\beta} & r_2\le r\le r_2+\beta\\ 0 & \text{else}\end{cases} \tag{5}$$

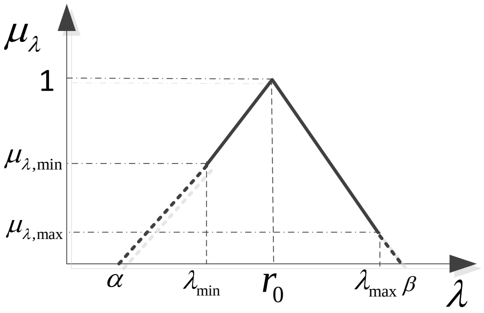

Fig.1 Typical distribution of λ

B. Distribution model of possibility

Apparently, equipment relevant sample datum must be gathered in order to model the failure rate of equipment with uncertainty, which should be made of their historical datum. The datum of sample i needed to be collected are shown as

$$\Omega_i=\{\lambda_i \quad u_i \quad \eta_i \quad f_i \quad T_i \quad \theta_i \quad \chi_i\} \tag{4}$$

Where Ω_i is the data unit of sample i . λ_i 、 u_i 、 η_i 、 f_i 、 T_i 、 θ_i are respectively failure rate, operating voltage, load rate, frequency, service time and air temperature of sample i .Particularly some distinctive datum must be collected besides the basal ones, such as oil temperature of distribution transformer, which is more coincident with the equipment factual situation in distribution network.

On the basis of the sample datum, the interval value $[\lambda_{\min} \quad \lambda_{\max}]$ is averagely divided in m parts. As presumed that the interval value of part k is $[\lambda_k \quad \lambda_{k+1})$, then the possibility of uncertainty can be shown as

$$\mu_\lambda(\lambda_k)=pos\{\gamma\in\Gamma|\lambda(\gamma)=\lambda_k\}=\frac{f_k}{n} \quad k=1,2,\cdots,m \tag{5}$$

Where n is the amount of sample equipment. f_k is the frequency number which must be met with the constrain, $[\lambda_k \quad \lambda_{k+1})\subset[\lambda_{i,\min} \quad \lambda_{i,\max}]$,in which $\lambda_{i,\min}$ and $\lambda_{i,\max}$ are the lower bound and upper bound of sample i .

Subsequently the possibility distribution of λ could be obtained through the fuzzy statistical analysis. According to the procedure mentioned above, the possibility distribution models of different equipments are analyzed, which include distribution transformer, breaker, disconnector and overhead line. As for the sample curves, the possibility distribution of these equipments are modeled with the classic model and precise model based on equation (6), as depicted in figure.2 to figure.5.The parameters of these model for the possibility distribution are shown in Table.1 and Table.2

$$\mu_{\lambda}\left(r\right)=\sum_{i=1}^{n}a_{i}e^{-\left(\frac{r-b_{i}}{c_{i}}\right)^{2}} \qquad (6)$$

Table 1: Parameters of the probability distribution using classic model

equipment	r0/(r1, r2)	α	β
distribution transformer	0.0114	0.0106	0.0986
breaker	0.0102	0.006	0.0796
disconnector	(0.0301,0.0778)	0.0247	0.0415
overhead line	(0.0681,0.1461)	0.0646	0.0781

Table 2: Parameters of the probability distribution using precise model

equipment	n	$\left(a_i,b_i,c_i\right)$
distribution transformer	2	(0.5547,0.0146,0.0107)、 (0.6478,0.0383,0.0386)
breaker	2	(0.5601,0.0137,0.0101)、 (0.6631,0.0377,0.0367)
disconnector	3	(0.9542,0.0754,0.0277)、 (0.8168,0.0374,0.0221)、 (0.4896,0.0183,0.0088)

overhead line	4	(0.826,0.155,0.0309)、 (0， -1270,223.5)、 (0.97554,0.0752,0.0462)、 (0.3912,0.1194,0.0265)

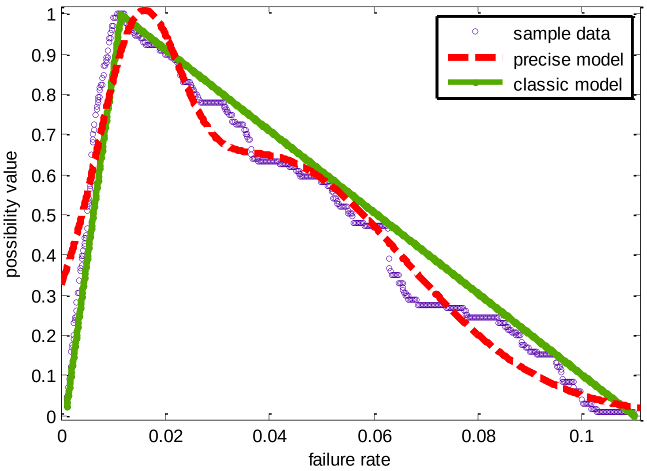

Fig. 2 Typical distribution model of distribution transformer

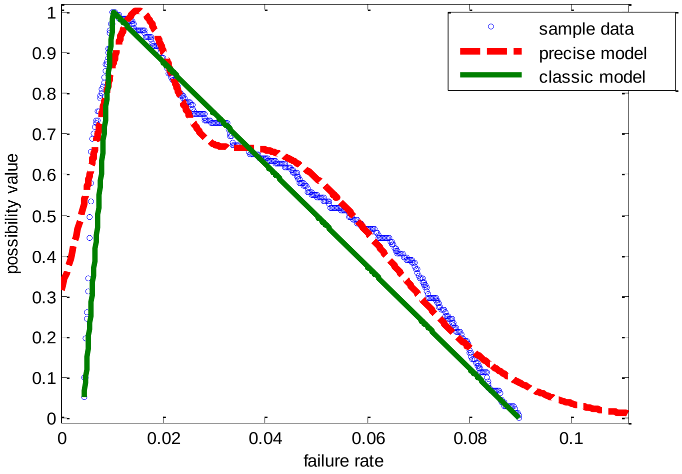

Fig. 3 Typical distribution model of breaker

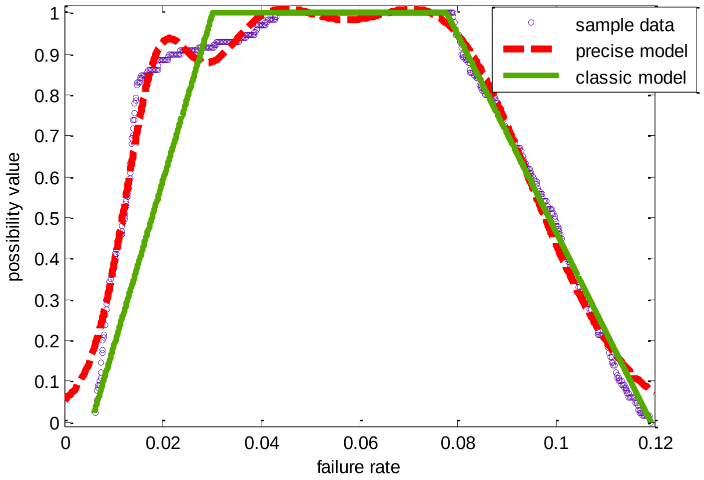

Fig. 4 Typical distribution model of disconnector

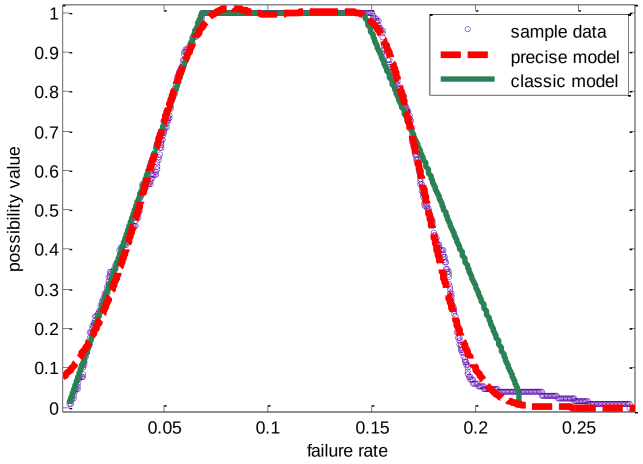

Fig. 5 Typical distribution model of overhead line

C. Distribution model of credibility

The possibility distribution is the foundation of credibility distribution. The relationship of possibility distribution can be met, according to equation (2):

$$pos\{\lambda_t \geq \lambda_s\} = \sup_{r \geq \lambda_s} \mu_{\lambda_t}(r) \tag{7}$$

Where symbol $\sup\limits_{r \geq \lambda_s}$ means the maximal possibility value when $r \geq \lambda_s$. λ_s is the set value, $\lambda_s \in [\lambda_{\min} \quad \lambda_{\max}]$.

On the basis of former equations (3) and (7), the credibility distribution can be determined as below.

$$Cr\{\lambda_t \geq \lambda_s\} = \frac{1}{2}\left(1 - \sup_{r<\lambda_s}\mu_{\lambda_t}(r) + \sup_{r\geq\lambda_s}\mu_{\lambda_t}(r)\right) \tag{8}$$

Therefore, the credibility distribution of triangular trapezoid and precise models can be shown as (9) and (10) on the basis of (4) and (5).

$$G_{Cr,\lambda}(\mathrm{x}) = \begin{cases} 1 & x \leq r_0 - \alpha \\ \dfrac{r_0 + \alpha - x}{2\alpha} & r_0 - \alpha < x \leq r_0 \\ \dfrac{r_0 + \beta - x}{2\beta} & r_0 < x \leq r_0 + \beta \\ 0 & x > r_0 + \beta \end{cases} \tag{9}$$

$$G_{Cr,\lambda}(\mathrm{x}) = \begin{cases} 1 & x \leq r_1 - \alpha \\ \dfrac{r_1 + \alpha - x}{2\alpha} & r_1 - \alpha < x \leq r_1 \\ \dfrac{1}{2} & r_1 < x \leq r_2 \\ \dfrac{r_2 + \beta - \mathrm{x}}{2\beta} & r_2 < x \leq r_2 + \beta \\ 0 & x > r_2 + \beta \end{cases} \tag{10}$$

Corresponding to the possibility distribution of these equipments, model-fittings of the classic and precise models are shown in figure.6 to figure.9.

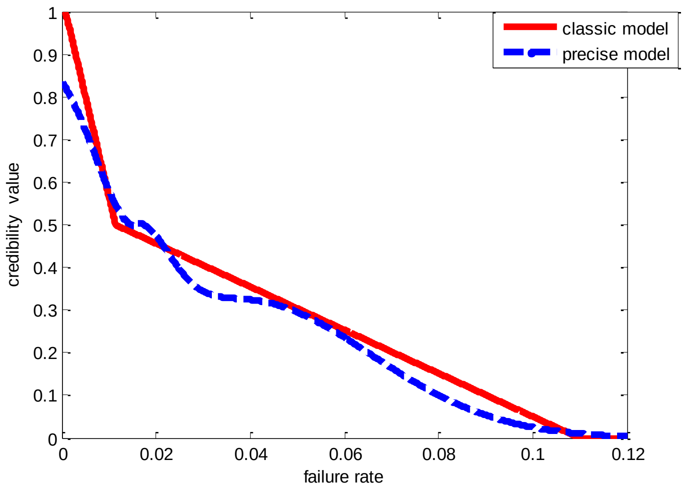

Fig. 6 Credibility distribution model of distribution transformer

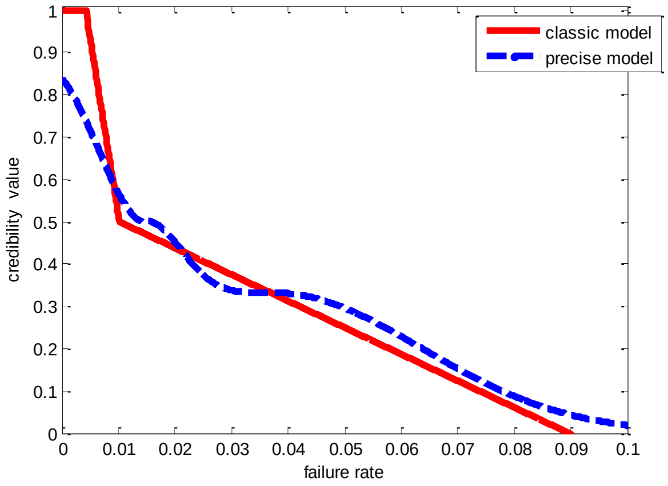

Fig. 7 Credibility distribution model of breaker

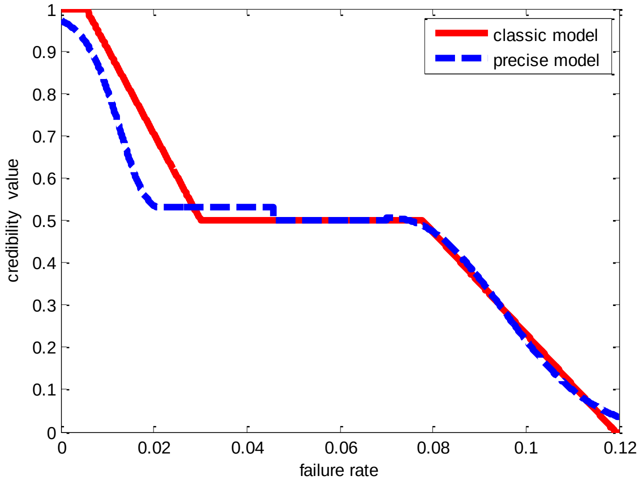

Fig. 8 Credibility distribution model of disconnector

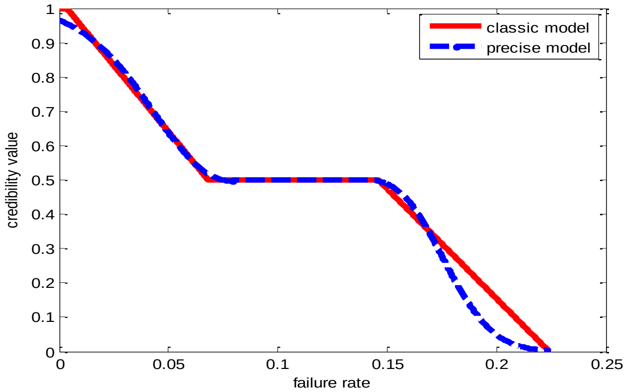

Fig. 9 Credibility distribution model of overhead line

D. Failure Rate Model

It is assumed that the failure rate lower and upper bounds of equipment i are successively λ_a and λ_b. The failure rate λ_i can be modeled as below, on the basis of credibility distribution of the matched equipment,

$$\lambda_i = \int_{\lambda_a}^{\lambda_b} Cr\left(\lambda \geq r\right)dr - \int_{-\lambda_b}^{-\lambda_a} Cr\left(\lambda \leq r\right)dr \tag{11}$$

Where the second term can be deduced from equation (7) and (8), with the possibility and credibility distribution models relation which describe uncertainty characters in distribution network.

III. Fuzzy Clustering Analysis of Equipment

As it can be noticed, a pivotal problem may be existed when the model above is applied in a complex distribution network, which would come into being overload calculated quantities because of the number magnitude of equipment, inevitably.

To solve this problem a fuzzy classified method is presented, named as fuzzy clustering analysis, in which the equipments could be classified according to their operating datum, such as operating voltage and load rate. This analytical method can be split into two parts: the standard model library and classification of equipment.

A. Standard Model Library

Firstly, it is presumed that original matrix $d_{n\times m}$ can be composed of n samples with m correlative parameters which should be composed by the unit of sample data in (4), representing the operating environment of the equipment. Hence the format of data matrix, $d_{n\times m}$ can be described as

$$d_{n\times m} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{12}$$

Secondly, the data matrix have to be standardized using the standard deviation method and named as standardized data matrix, $d'_{n\times m}$ where the matrix elements should meet with the constraint $x'_{ij} \in \left[0 \quad 1\right]$, which makes comparison between the parameters containing different dimensions convenient. Operating voltage and frequency couldn't compare with each other, since the former dimension is the voltage and the latter is the hertz, for example.

A third step, the fuzzy analogous matrix $R_{n\times n}$ can be defined as:

$$r_{ij} = \begin{cases} 1 & i = j \\ \dfrac{1}{M}\sum_{k=1}^{m} x'_{ik} \bullet x'_{jk} & i \neq j \end{cases} \quad r_{ij} \in R \tag{13}$$

Where x'_{ik} 、 x'_{jk} represent the k th matrix elements of equipment i and j ,separately. Then the constant M in equation (13) can be determined as

$$M = \max_{i\neq j}\left(\sum_{k=1}^{m} x'_{ik} \bullet x'_{jk}\right) \tag{14}$$

Thenceforward, fuzzy equivalent matrix R^* may be determined by inner product of R itself, which is commonly known as transitive closure mathematically. The formulation can be shown as

$$R \to R^2 \to \cdots \to R^{i^k} \tag{15}$$

When the relation of $R^{i^k} \circ R^{i^k} = R^{i^k}$ can be fulfilled, fuzzy equivalent matrix equivalent to inner product.

Ultimately, the n samples can be classified dynamically. If r_s is the threshold value and satisfied the inequality constraints, $r_{ij} \geq r_s$, $r_{ik} \geq r_s$, it means that the sample j and k belong to same classification. In this section, the r_s can be set to get different classifications, according to the actual conditions.

B. Classification of Equipment

The similar comparison method is applied to classify the undetermined equipment i with uncertainty by calculating the close degree δ_i .Assuming the clustering of standard model library has been done into p classifications named as B_j , $j = 1, 2, \cdots, p$, the close degree δ_i of an undetermined equipment i to B_j can be determined as

$$\delta_i(A_i, B_j) = \frac{2\sum_{k=1}^{m}\left(A_i(x_k) \wedge B_j(x_k)\right)}{\sum_{k=1}^{m} A_i(x_k) + \sum_{k=1}^{m} B_j(x_k)} \tag{16}$$

Where A_i 、 B_j are the standardized parameter set of equipment i and classification j . It is clear that $\delta_i \in [0 \quad 1]$ closing to 1 means the uncertainty between the undetermined equipment i and B_j tend to the same grade.

Successively the close degree δ_i with other classifications can be calculated in (16) and the classification of equipment i could be decided by the maximum of δ_i .

IV. Computational Algorithm

The calculation procedure of failure rate is adopted as shown in fig.10 which involves three aspects. Primarily the parameters of undetermined equipment i must be collected. Secondly the sort of equipment i can be determined by the close degree δ_i . At last the failure rate λ_i can be calculated in (11).

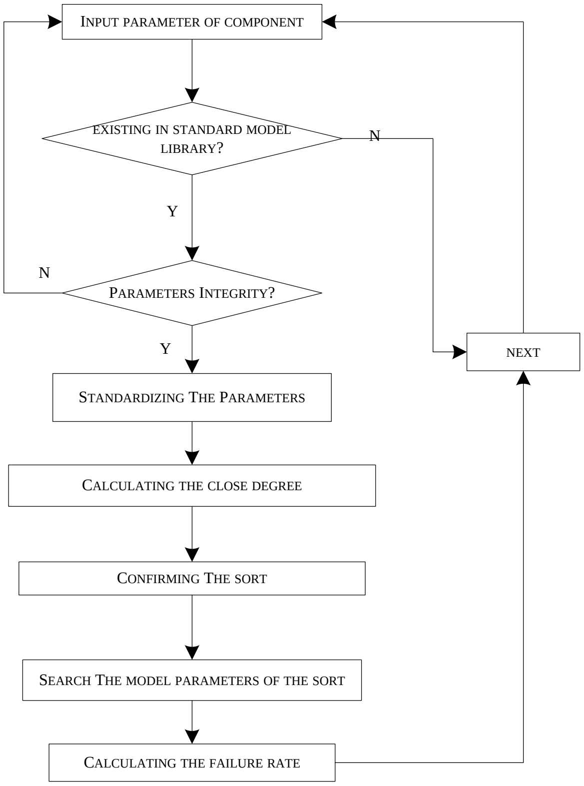

Fig.10 Flow chart for calculating failure rate

V. Application Example

A. Example System

An example distribution system of IEEE DRTS [5] is shown in Fig.11, which contains 7 feeders, 38 load points, 29 distribution transformers, 13 breakers, 45 disconnentors and 67 overhead lines, where all the equipments are assumed to be same type.

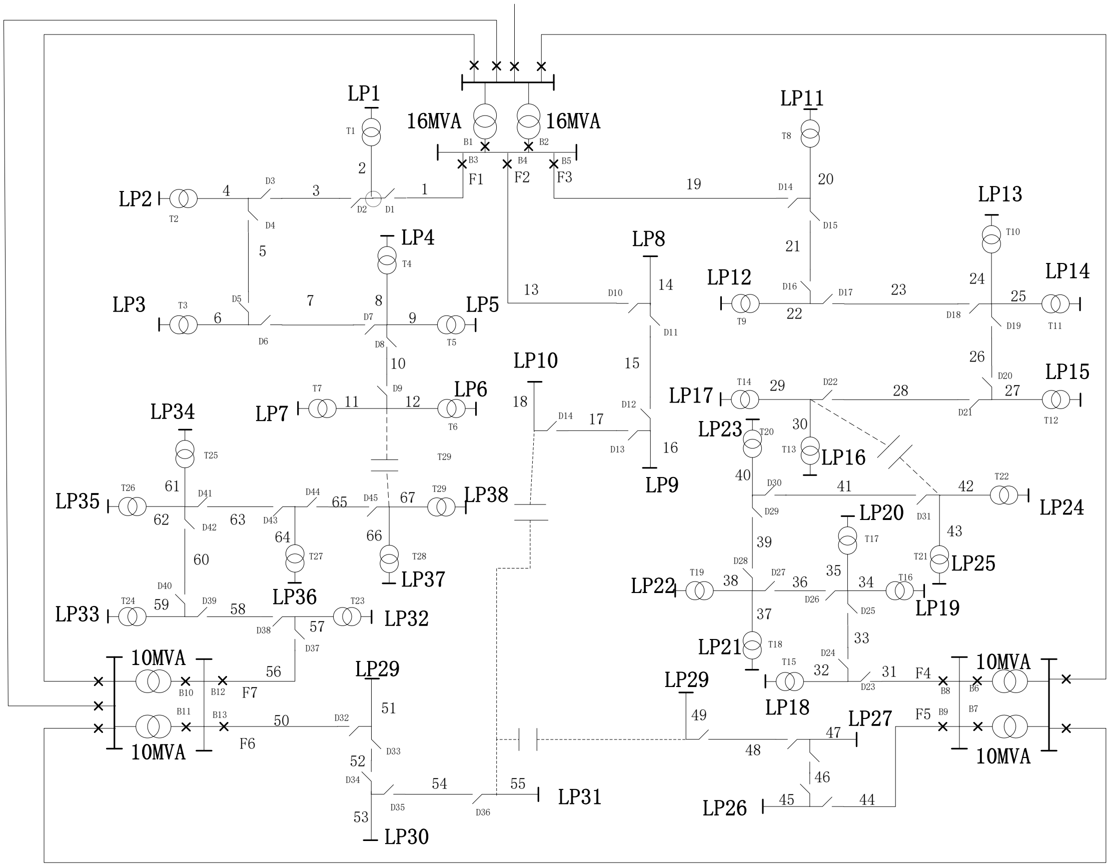

Fig. 11 Example of a distribution system

B. Calculation Procedure Of Failure Rate In Example System

As shown in Fig. 11 Example of a distribution system, the equipment failure rate in example distribution system can be calculated with the model presented primarily. Although the failure rate of different equipments has been modeled respectively, the calculation procedures of different equipments are the same. With the Consideration of the repeatability of calculating procedure, hence, the calculation procedure of distribution transformer is illustrated as an example in detail.

According to physical circumstance of sample transformers, the threshold is set as 0.8 in standard model library. Therefore the distribution transformer can be classified in five classes and the failure rate can be respectively calculated applying the classic and precise models in (11) with the matched interval value, as shown in Table.3.

Here the parameters of some undetermined transformers are shown in Table.4. It is worthwhile to note that the character parameter of transformers is adopted, like the temperature of Operating oil, unless the basic parameters.

Therefore the close degree of undetermined transformers can be calculated in (16). As shown in Fig.12, since T1 is much more similar with class IV in the close degree set, so it belongs to class IV. Likewise, T10, T16, T24and T29 belong to class III、II、V and IV in sequence. The undetermined equipment in example system can be classified in the same calculation procedure, as shown in Figure.13 to Figure.16.

Tab. 3 fuzzy clustering analysis of sample transformer

class	**features**	**Interval value**	**Failure rate (classic model)**	**Failure rate (precise model)**
I	load rate high	[0.062 0.11]	0.086	0.083
II	load rate above normal	[0.056 0.086]	0.064	0.059
III	load rate normal	[0.001 0.053]	0.034	0.04
IV	load rate under normal	[0.025 0.085]	0.048	0.045
V	load rate low	[0.035 0.094]	0.052	0.056

Tab. 4 parameters of the undetermined transformers

Distribution transformer	**Active time/y**	**Operating voltage/kV**	**Load rate/%**	**frequency/Hz**	**temperature of Operating oil /℃**
T1	4	10.036	35.3	50.085	53.4
T10	10	10.021	46.2	50.148	66.9

T16	6	10.066	65.3	49.959	73.9
T24	15	10.052	26.3	49.984	45.5
T29	2	10.055	30.2	50.135	48.6

Distribution transformer	**altitude/km**	**Temperature of air//℃**	**wind speed /（m/s）**	**humidity /%**	**weather**
T1	1.132	15	26	78	cloudy
T10	1.234	16	33	73	cloudy
T16	1.243	15	26	75	cloudy
T24	1.124	16	40	70	light rain
T29	1.232	13	30	65	cloudy

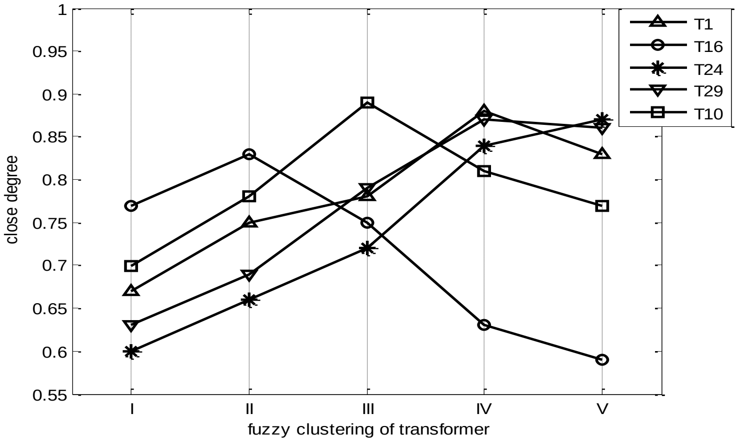

Fig. 12 Close degree of the undetermined transformers

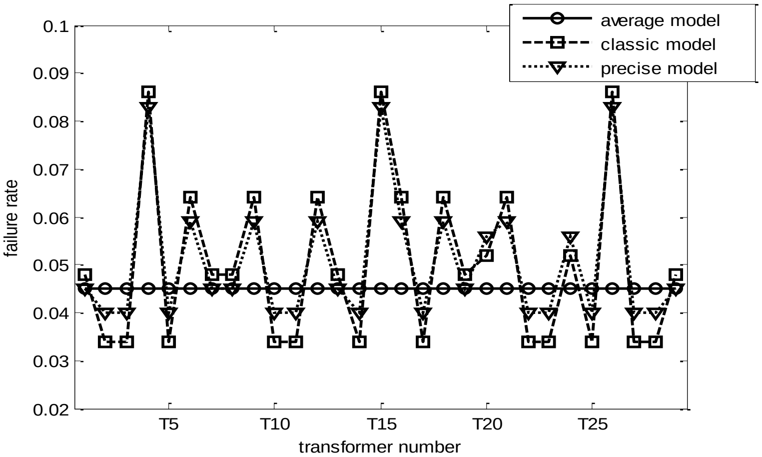

Fig.13 Clustering of the undetermined transformers

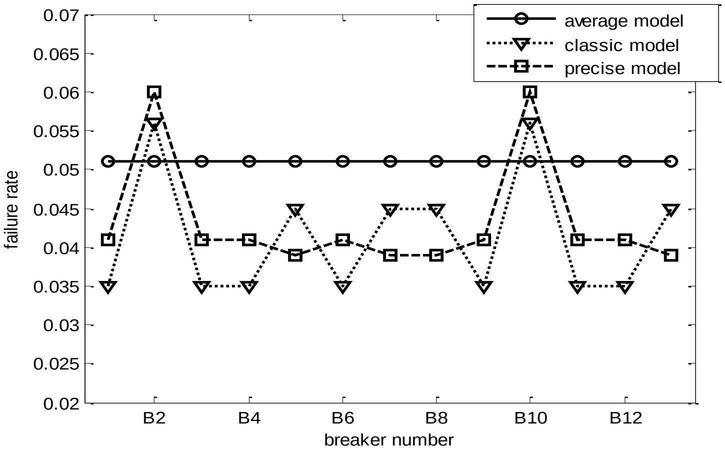

Fig. 14 Clustering of the undetermined breakers

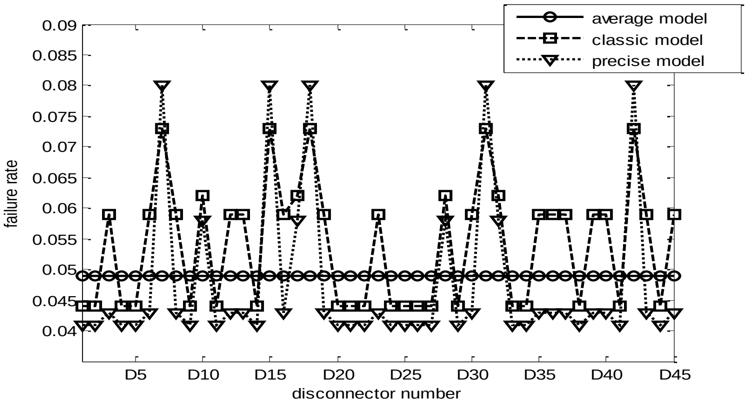

Fig.15 Clustering of the undetermined disconnectors

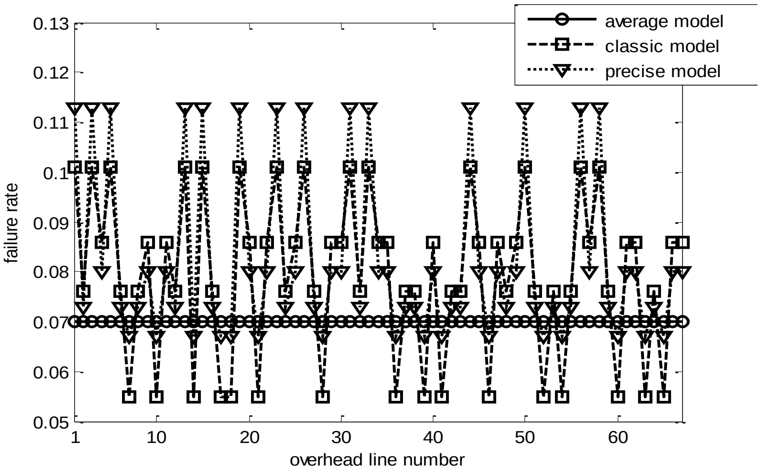

Fig.16 Clustering of the undetermined overhead lines

C. Comparative Analysis Of example distribution system Reliability

The reliability of example distribution system can be analyzed on the basis of the failure rates of equipments which have been determined above. At the same time, a contrast may be made among the system reliabilities with different failure rate models. The method of reliability calculation adopts the FMEA and the other reliability parameters used in example system can be referred to table.5.

Table 5: reliability Parameters used in distribution network

equipment	Average failure rate/（occ*y-1）	Repair time/h	Switching time/h
distribution transformer	0.045	15	1
breaker	0.051	3	0.5
disconnector	0.049	3	0.5
overhead line	0.07	6	1

As it can be seen in Fig.17, these differences of SAIFIs with three models are emerged. Especially for F2, F5, F6, the reason for these differences is that the load point in these feeders are industrial load which means their average load twice or triple to resident load and normally it would make the load rate of equipment in these feeders exceed other feeders’, relatively whose operating situation tends to be worse to affects the failure rate.

It is clear that The SAIDIs and CAIDIs in Fig.18-19 are nearly the same, but still there is tiny difference because of the definition of their formulas and the difference of failure rate. From Fig.20, the point can be illustrated that the ASAI with average model may lose sight of real situation of the distribution system and the ASAIs with classic or precise models can make the reliability level meet with the situation of system.

Besides, as it shown in Fig.17-20, the effect of classic and precise models made can be close to each other. Although the precise model gets the best accuracy, the classic can unite the accuracy and calculated quantity together which would produce a definite error that can be endured with.

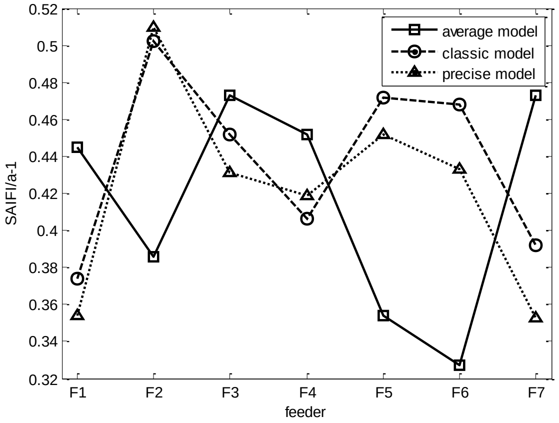

Fig.17 SAIFI of the feeders

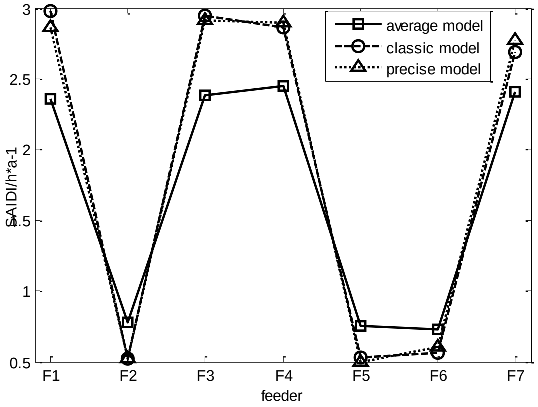

Fig.18 SAIDI of the feeders

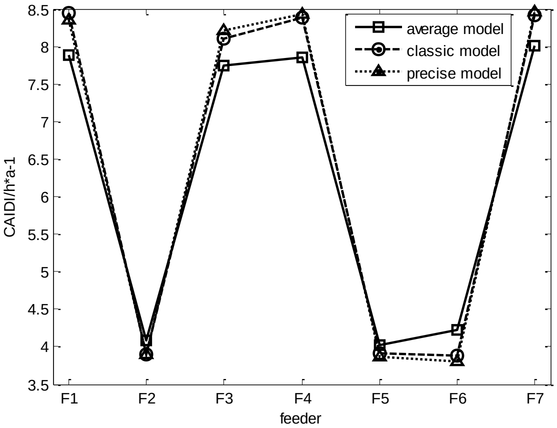

Fig.19 CAIDI of the feeders

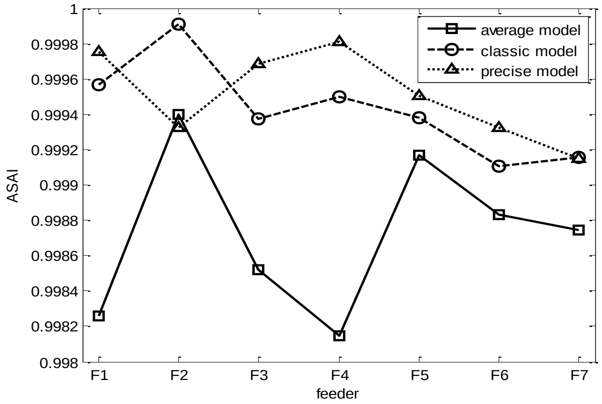

Fig 20 ASAI of the feeders

The system reliability indices with the three models mentioned are shown in Table.10 and it proves the argument that the system reliability evaluation with average model couldn't reflect the real operating situation in the distribution system with the deviation of system reliability indices between them.

In addition, the classic and precise models taking the uncertainty for failure rate into account make the results of the system reliability indices closer to real situation, since the accuracy of equipment failure rate can guarantee that the system reliability can be calculated veritably. Therefore, the uncertainty of failure rate should be considered when evaluating the system reliability and the classic model may be the better choice because of the accuracy and calculating efficiency.

Table 6: reliability indices of the example system

model	SAIFI	SAIDI	CAIDI	ASAI
Average model	0.4606	2.3995	7.8705	0.99842
Classic model	0.4054	2.8577	8.3374	0.99939
Precise model	0.3890	2.8535	8.3614	0.99959

VI. Conclusions

A novel model of the equipment failure rate for incorporating and weigh the effects of uncertainty factors in distribution network is proposed. On the basis of historical datum gathered, two approaches which mean to be classic and precise methods are introduced to model the possibility and credibility distributions of equipment that should be deemed to the kernel to weigh the uncertainty. Moreover, for the purpose decreasing the calculating amount, the fuzzy clustering analysis is presented. The application of the proposed model to example system has shown the system reliability level is closer to the real situation of distribution system. From the accuracy and calculating efficiency, as it can be known, the classic model is more recommended.

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