Reliability Measurement Method for Electrical Products Based on Grey Theory

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Abstract

One of the important indexes of products, reliability, has always attracted much attention. However, the traditional reliability analysis, based on probability theory and mathematical statistics, requires a lot of complete information, causing few applications in most cases. Grey theory can be accurately calculated in case of small data and poor information. Therefore, the concept of grey reliability is put forward based on grey number and grey level, and then, the feasibility of the model in terms of electrical reliability measurement is verified by the calculations on the basis of specific examples.

Keywords: electrical apparatus reliability, grey number, grey reliability

1. Introduction

With continuous improvement of automation of products, systems and equipments are increasingly developed towards large, complex, and integrated ways, while ensuring the reliability is the key technology to make these systems and devices practical. Reliability of electrical products refers to the ability of completing the required function under specified conditions and within the stipulated time [1]. As one of the important standards of product quality, the product's reliability is equally important with the performance, even in the military equipment, and aerospace equipment, because equipment failure will require extremely serious overhauling, or the replacement is very tedious. Therefore, it must be given priority to ensure the reliable performance of the product and the normal operation of equipment.

Currently, a reliability theory based on probability theory and mathematical statistics has been basically perfect. Conventional reliability theory considers random phenomenon in the field of engineering as starting points of researches, handles correlated variables into random variables, and describes the reliable state of products by the method of probability theory and mathematical statistics. A lot of problems about reliability in engineering practice are solved, and it has practical meaning. However, uncertain information in engineering practice is not all coming from randomness, fuzziness of information, uncertainty, and information that can not be fully trusted and can also lead to incompletion credibility [2]. The breakdown of products and components in engineering is accumulated and gradually varied, which doesn't have an obvious boundary, so it is a fuzzy process from fully intact to complete failure, of which reliability has been discussed widely and many methods have been developed. A new model of possibilistic reliability applied to possibility of structural failure when calculated stress and strength are fuzzy-valued has been established in literature [3] based on reliability theory and cut sets in fuzzy set. A new indicator of reliability which can measure security mechanical structure is presented in literature [4] based on cut set.

The present study focuses on the cases where large-scale experiment is not feasible, and only small mount of data sample is available. Based on grey theory, the concept of gray reliability is proposed as a feature for evaluating a product with a small set of samples. And a data processing method is introduced in detail.

2. Grey Theory and Grey Number

2.1 Introduction of Grey Theory and Grey Number

Grey theory was proposed by Professor Deng Julong in late 1970s and early 1980s, which has been widely used in all aspects of production and life [5]. The grey theory is proposed for the problem of small data and uncertainty, when only part information of a system is known, so the formation, development and final prediction of the poor information can be realized through the grey system theory [6]. After many years of development, the grey theory has developed a number of branches. Application scope and branches of the grey theory are shown as Figure 1.

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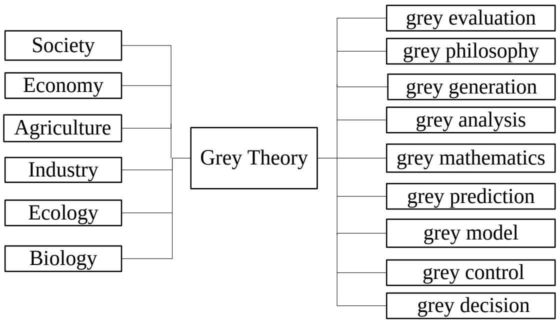

Figure 1: Application scope and branches of the grey theory

For a system or numerical arrays, when all the information is completely unaware, it is called black; when all the information is known, it is called white; and when a part of the information is known while the other is unknown, it is called grey. Grey number is only known about the range, but the value can not be determined exactly. Therefore, grey number is not an ordinary number, and also is not a fuzzy number; it is a value set whose range can be determined while the value cannot be determined [7].

At present there are two main types of the description methods of grey number, the description in the literature [8] is referred to as the "Deng's grey number", the grey number described in the literature [7] is referred to as the “interval grey number”. In literature [9], the common character of "Deng's grey number" and "interval grey number" are also studied, and it is summarized as a new way of expression -- "interval grey number". And further research is carried out in this paper. In the process of studying grey number, new methods of definition and calculation are proposed in literature [10].

2.2 Classification of Grey Number

There are many classification methods of grey number. According to the different ways of obtaining grey number, the grey number that can be obtained by infering is defined as default grey numbers; the grey number that can be obtained by measuring is defined as measured grey number.

Definition 2.1 To make ψ a proposition, $\psi(\theta)$ as domain of propositional information, D as number field, $\otimes$ is uncertain number in the sense of ψ, and make d° the only potential for $\otimes$, make $\tilde{\otimes}$ the default number for $\otimes$.

If satisfied

$$\forall\tilde{\otimes}\in\otimes\Rightarrow\tilde{\otimes}\in\wp$$

$$\wp=\{\tilde{\otimes}\big|\tilde{\otimes}\,\text{Apr}\psi(\theta),\exists d^{\circ}\,\text{Apr}\psi(\theta),$$

$$d^{\circ},\tilde{\otimes}\in\tilde{D}\subset D,$$

$$d^{*}\in\psi(d^{*}\text{is true value})$$

$$d^{*}\text{Occur}\Rightarrow d^{\circ}=d^{*},$$

$$d^{*}\text{Occur}\Rightarrow\tilde{\otimes},\otimes Vani\}$$

Then

$\otimes$ is called the default gray number in the sense of ψ;

$\tilde{\otimes}$ is called whiten number of $\otimes$;

$\tilde{D}$ is called numerical coverage of $\otimes$;

$\psi(\theta)$ and d° (or d^{*}) are information background of grey number $\otimes$.

Definition2.2 To make ψ a proposition, $\psi(\theta)$ as domain of propositional information, D as number field, $\otimes$ is uncertain number in the sense of ψ, d° is the only potential real value of $\otimes$, L^{*} is criterion to judge if d^{*} is true value or not.

If satisfied

$$\forall\tilde{\otimes}\in\otimes\Rightarrow\tilde{\otimes}\in\wp,$$

$$\wp=\{\tilde{\otimes}\big|\exists d^{\circ},\exists\tilde{\otimes}_{*}\to d^{*}\text{FORL}^{*},$$

$$\tilde{\otimes}\,\text{Apr}\psi(\theta),d^{\circ}\text{Apr}\psi(\theta),$$

$$\tilde{\otimes}\in\tilde{D}\subset D,$$

$$\tilde{\otimes}_{*},d^{*}\text{Occur}\Rightarrow d^{\circ}\text{Vani},$$

$$\tilde{\otimes}_{*},d^{*}\text{Occur}\Rightarrow\otimes\text{Vani}\}$$

Then

$\otimes$ is called the default gray number in the sense of ψ;

$\tilde{\otimes}$ is called whiten number of $\otimes$;

$\tilde{D}$ is called numerical coverage of $\otimes$;

The grey number can be divided into discrete grey number and continuous grey number by judging if the number is discrete or continuous.

Definition 2.3 Discrete grey number: Make $\tilde{D}$ is the numerical coverage of $\otimes$, if $\tilde{D}$ is a discrete set, $\otimes$ is called discrete grey number.

Definition 2.4 Continuous grey number: Make $\tilde{D}$ the numerical coverage of $\otimes$, if $\tilde{D}$ is a continuous set, $\otimes$ is called continuous grey number.

According to the problems to be studied and the abstract grey number is different, the grey number can be roughly divided into the following three categories

Definition 2.5 Upper unbounded grey number

For the grey number $G\big|_{\underline{\mu}(x)}^{\overline{\mu}(x)}$, $x\in R$, $E=\{x\big|\overline{\mu}_{G}(x)\neq 0,x\in R\}$, if $\inf E=a\in R$, $\sup E=+\infty$, then the $G\big|_{\underline{\mu}(x)}^{\overline{\mu}(x)}$ is called upper unbounded grey number.

For example, assume $\overline{\mu}_{G}(x)=\begin{cases}\sin^{2}x, & x\geq 0;\\ 0, & x<0,\end{cases}$, $\underline{\mu}_{G}(x)=0,\quad x\in R$, so $\inf E=0, \sup E=+\infty$, and $G|_{\underline{\mu}(x)}^{\overline{\mu}(x)}$ is upper unbounded grey number.

Definition2.6 Lower unbounded grey number

For the grey number $G|_{\underline{\mu}(x)}^{\overline{\mu}(x)}$, $x\in R$, $E=\{x|\overline{\mu}_{G}(x)\neq 0, x\in R\}$, if $\inf E=-\infty$, $\sup E=b\in R$, then $G|_{\underline{\mu}(x)}^{\overline{\mu}(x)}$ is called lower unbounded grey number.

For example, assume $\overline{\mu}_{G}(x)=\begin{cases}\sin^{2}x, & x\leq 0;\\ 0, & x>0,\end{cases}$, $\underline{\mu}_{G}(x)=0,\quad x\in R$, so $\inf E=-\infty, \sup E=0$, and $G|_{\underline{\mu}(x)}^{\overline{\mu}(x)}$ is called lower unbounded grey number.

Definition2.7 Bounded grey number

For the grey number $G|_{\underline{\mu}(x)}^{\overline{\mu}(x)}$, $x\in R$, $E=\{x|\overline{\mu}_{G}(x)\neq 0, x\in R\}$, if $\inf E=a\in R$, $\sup E=b$, and there exist real constants $a,b\in R$, and $G|_{\underline{\mu}(x)}^{\overline{\mu}(x)}$ is called bounded grey number.

The grey information, whose part information is known, can be described by two membership functions with a given scope of description. Make the unknown part locate between the two membership functions. This description method is called grey set description method.

Definition 2.8 Let G is a grey subset in domain U, and two mapping from U to closed interval $[0,1]$ is given,

$$\overline{\mu}_{G}:U\rightarrow[0,1], \mu|\rightarrow\overline{\mu}_{G}(\mu)\in[0,1]$$

$$\underline{\mu}_{G}:U\rightarrow[0,1], \mu|\rightarrow\underline{\mu}_{G}(\mu)\in[0,1]$$

$$\overline{\mu}_{G}\geq\underline{\mu}_{G}$$

$\overline{\mu}_{G}$ and $\underline{\mu}_{G}$ are called upper membership function and lower membership function of G; $\overline{\mu}_{G}(\mu)$ and $\underline{\mu}_{G}(\mu)$ are called upper membership degree and lower membership degree for element μ relative to G.

The set combines an upper membership function and a lower membership function and the area sandwiched between the two functions is called grey set.

The upper and lower membership degree of this set is known, but the exact membership degree is unknown. And this is the reflection of the connotation that "part is known, and part is unknown". The grey set visual diagram is shown as Figure 1, and the belt shaped area in the figure can be called grey band. When $\overline{\mu}_{G}=\underline{\mu}_{G}$, the grey band will become a line and is the image of a fuzzy subset.

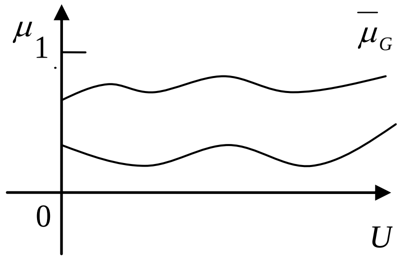

Figure 2: Grey set visual diagram

Definition2.9 Assume domain $U=R$, and then define grey set $G|_{\underline{\mu}(x)}^{\overline{\mu}(x)}$ $(x\in R, \underline{\mu}(x),\ \overline{\mu}(x)\in[0,1])$ as grey number. Grey number can be abbreviated as G. And the collection of grey numbers is recorded as $g(G)$, $E=\{x|\overline{\mu}(x)\neq 0, x\in R\}$ is called the gray domain of G. And the true grey domain of G is recorded as $e=\{x|\overline{\mu}(x)\neq\underline{\mu}(x), x\in R\}$.

3. Grey Reliability

3.1 Grey Degree

The information of gray number is incomplete and uncertain, so a measure is needed to characterize the degree of incomplete and uncertain; the measure that indicates the degree of grey number is called grey scale.

If the $\otimes$ is a discrete set of measured grey numbers, $\tilde{D}$ is the numerical coverage of $\otimes$, $POT.$ is discrete mapping, only when $h^{\circ}_{.r}=\ln POT.\tilde{D}$, $h^{\circ}_{.r}$ is called grey scale of $\otimes$.

Assume that $\otimes$ is a discrete set of measured grey numbers, and $\tilde{D}$ is the numerical coverage of $\otimes$.

When $\tilde{D}=\{30\}$, $h^{\circ}_{.r}=\ln POT.\tilde{D}=\ln 1=0$.

This indicates that there is only one white number in $\tilde{D}$. Therefore, the grey scale of measured grey numbers which has only one white number is 0.

When $\tilde{D}=\{29,30\}$, $h^{\circ}_{.r}=\ln POT.\tilde{D}=\ln 2$ $=0.693$, $\tilde{\otimes}$ must be one of the 29 or 30, or made up by them, so the grey scale is not 0.

3.2 Grey Reliability

The probability theory and mathematical statistics are always used to analyze the reliability, and the general level of the data is described by mean; the degree of variance is described by variance. Only when the mean value of two samples' feature is same, the two samples can be compared by a standard deviation. When the mean value of the two samples' feature is not same, a model of relationship between mean and variance can be built to eliminate the influence caused by different values.

The traditional reliability analysis methods need more samples and data, so it does not fit in most cases. In this article, the grey reliability degree is proposed to measure the reliability caused in small sample situation.

Because of the limitation of cognition, in the course of the study, only some of the characteristics of the object can be studied.

Suppose the number of characteristic to be studied is a, due to limitation of cognition only b (b<a) characteristics can be recognized. The upper membership function is d , and the lower membership function is c and c<b<d<a. The feature between a and d is the unknown feature of the research object. The value of grey reliability can be represented by the ratio of the value of c and d.

Then some specific calculation methods of grey reliability used in practical engineering are described.

In the reliability test, m samples are randomly selected from a batch of products in view of the specified feature firstly. Then the feature values of the feature are measured under specific conditions, and the testing process can be repeated for n times. And then under n different conditions, the above test is repeated using the m samples or selecting new m samples from the batch of products, and $m \times n \times t$ test data are obtained, and each data is recorded as $\chi_{ij}^{k}(1 \le i \le m, 1 \le j \le n, 1 \le k \le t)$.

Then in the j-th condition, the average and standard deviation of the h test dates of i-th samples are recorded as $\bar{\chi}_{ij}$ and S_{ij},

$$\bar{\chi}_{ij} = \frac{1}{t}\sum_{k=1}^{t}\chi_{ij}^{k} \quad (1)$$

$$S_{ij} = \sqrt{\frac{1}{t}\sum_{k=1}^{t}(\chi_{ij}^{k} - \bar{\chi}_{ij})^2} \quad (2)$$

N data sets can be obtained by the above calculation, and the j-th $(1 \le j \le n)$ data sets can be recorded as

$$X_j = \{\bar{\chi}_{ij} \mid i = 1, 2, \cdots, m\} \quad (3)$$

Then the difference Δx_j between the maximum and minimum data of X_j is calculated.

$$\Delta x_j = \max_{1 \le i \le m}\{\bar{\chi}_{ij}\} - \min_{1 \le i \le m}\{\bar{\chi}_{ij}\} \quad (4)$$

Then the grey number is generated by the following method according to the grey theory, and it is regarded as measured grey number $\otimes_{ij}$,

$$\otimes_{ij} = \begin{cases} \bar{\chi}_{ij} + S_{ij} \\ \bar{\chi}_{ij} \\ \bar{\chi}_{ij} - S_{ij} \end{cases} \quad (5)$$

It can also be recorded as

$$\begin{aligned} \otimes_{ij} &= \left(\bar{\chi}_{ij} + S_{ij}, \bar{\chi}_{ij}, \bar{\chi}_{ij} - S_{ij}\right) \\ &= \left(\otimes_{ij1}, \otimes_{ij2}, \otimes_{ij3}\right) \end{aligned} \quad (6)$$

Then the discrete grey number set $\tilde{\otimes}_j$ composed of N data is constructed.

$$\begin{aligned} \tilde{\otimes}_j &= \left\{\otimes_{ij} \mid i = 1, 2\cdots, m\right\} \\ &= \left\{\{\otimes_{ij1}, \otimes_{ij2}, \otimes_{ij3}\} \mid i = 1, 2\cdots, m\right\} \end{aligned} \quad (7)$$

Then all the data of $\tilde{\otimes}_j$ are arrayed in ascending order, and a new set of discrete numbers D_j can be modeled.

$$D_j = \{d_{js} \mid s = 1, 2, \cdots, 3m-1, 3m\} \quad (8)$$

The difference Δd_j between maximum data and minimum data in D_j can be recorded as

$$\Delta d_j = \max_{1 \le s \le 3m}\{d_{js}\} - \min_{1 \le s \le 3m}\{d_{js}\} \quad (9)$$

The data fluctuation can be denoted by the absolute ratio value of logarithm of Δx_j and logarithm of Δd_j, then stable condition can be recorded as

$$g_{s\,j}^{\circ} = 1 - \left|\frac{\ln \Delta x_j}{\ln \Delta d_j}\right|, 1 \le j \le n \quad (10)$$

The specific steps of the method are as shown in Figure 3.

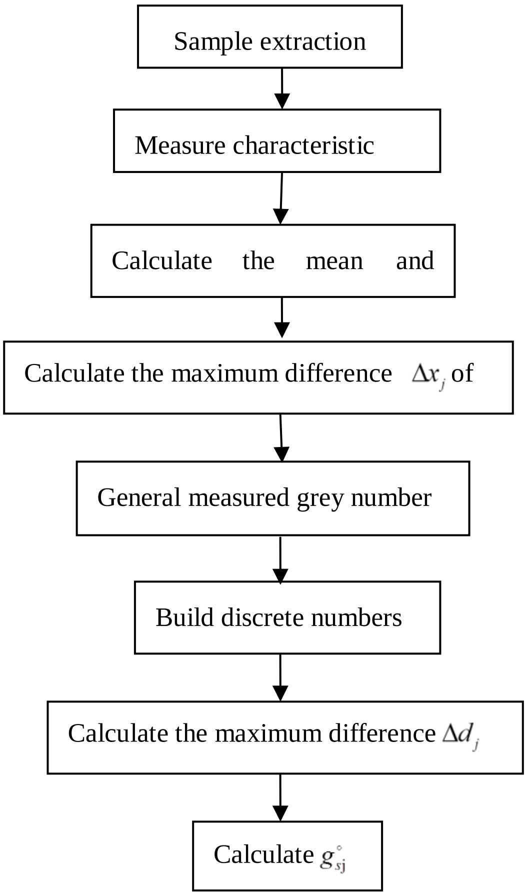

Figure 3: Flow chart of specific steps of the method

In the formula, g_{sj}° is the calculation result of grey reliability test at j-th test condition.

Grey reliability is measured to reflect the degree of fluctuate of the data in small quantity data condition; the higher the value of g_{sj}°, the higher the reliability of the research object.

4. Application Examples of Grey Reliability

Relay is the important connecting part of aviation, aerospace, power system, automation equipment and communication system. As an electrical control component, the electric current between electronic components, circuit, device or system is controlled by it, proving the guarantee of the system with a high efficiency. Therefore, the reliability of the relay directly affects the reliability of the whole system [11-13].

The relay is equivalent to a switching element, and the working principle is very simple: when an input is given, when it reaches the specified value of the system, the output circuit will be switched on or off through the relay [14-15]. The input is very extensive, including electrical and non electrical quantity. The electrical quantity includes current, voltage, frequency, power and so on; non electrical quantity includes temperatures, pressure, and speed and so on.

The working environment of relay is quite complex, in addition to its own factors, so it is affected by the combined effects of external factors; multiple factors cause some of the failure of the performance [16-17]. First of all, the temperature affects badly. The high temperature can make product performance parameters change, and insulation performance become worse; structural connections are damaged, and contact materials are oxidized gradually. And the humidity is also the influence factor, for the humidity will accelerate the speed of the corrosion of the coil, accelerating the speed of the oxidation of the contact surface materials and increasing the contact resistance. And another influence factor is mechanical stress, including vibration, impact, and collision, so they will cause a change of the electrical and mechanical properties of products, contact bounce, product structure destroyed, and movable armature to produce a false action [18].

Relay is one of the important basic components in all kinds of automatic control equipment, and the requirements of the equipments are generally very high. Therefore, it is important to focus on the reliability and failure of the relay. The practice data of electromagnetic relay failure mode shows that there are many different factors that eventually led to the relay failure, but accounted for 80 percent of the failure modes is contact failure. Therefore, the study of the evaluation of relay reliability has very important significance.

During the research of the problem of relay contact failure, static contact resistance (regard as $\mathrm{R_s}$) is an important indicator that should be examined in detail. [19-21]

$\mathrm{R_s}$ is the contact resistance value ($\mathrm{m\Omega}$) when the contact point is closed and the state is stable, it reflects the static contact performance of the contact [22].

In this paper, the HH52P type electromagnetic relay is taken as an example, three sets of data are measured in the environment of $-20^{\circ}\mathrm{C}$, $20^{\circ}\mathrm{C}$, $55^{\circ}\mathrm{C}$, and 5 data are measured in each group, a total of 15 sets of data. Then the mean and variance of the 15 sets of date are calculated, and the final results are shown in the table 1 to 3.

Table 1: The value of static contact resistance at $20^{\circ}\mathrm{C}$

number	a1	a2	a3	a4	a5
mean value	50.41	44.67	47.21	46.05	48.23
variance	5.71	4.65	3.98	3.62	2.64

Table 2: The value of static contact resistance at $-20^{\circ}\mathrm{C}$

number	b1	b2	b3	b4	b5
mean value	170.76	171.43	173.05	174.62	175.94
variance	3.72	2.14	3.05	3.71	3.92

Table 3: The value of static contact resistance at $55^{\circ}\mathrm{C}$

number	c1	c2	c3	c4	c5
mean value	196.43	198.56	200.49	202.94	205.71
variance	4.21	3.89	4.21	4.37	4.65

Take the environment of $20^{\circ}\mathrm{C}$ as an example, and the data is processed following the steps in section three.

Data set X_1 is constructed firstly,

$$X_1 = \{44.67, 46.05, 47.21, 48.23, 50.41\}$$

Then the difference Δx_1 between the maximum data and the minimum data is calculated:

$$\Delta x_1 = \max_{1\le i\le m}\{\bar{\chi}_{ij}\} - \min_{1\le i\le m}\{\bar{\chi}_{ij}\} \\ = 50.41 - 44.67 = 5.74$$

And the contact a1 to a5 are calculated by the formula (5). The calculation results are shown below.

$$\mathrm{a1}\begin{cases}50.41+5.71=56.12\\ 50.41\\ 50.41-5.71=44.70\end{cases} \quad \mathrm{a2}\begin{cases}44.67+4.65=49.32\\ 44.67\\ 44.67-4.65=40.02\end{cases}$$

$$\mathrm{a3}\begin{cases}47.21+3.98=51.19\\ 47.21\\ 47.21-3.98=43.23\end{cases} \quad \mathrm{a4}\begin{cases}46.05+3.62=49.67\\ 46.05\\ 46.05-3.62=42.43\end{cases}$$

$$\mathrm{a5}\begin{cases}48.23+2.64=50.87\\ 48.23\\ 48.23-2.64=45.59\end{cases}$$

Then the discrete grey number set $\tilde{\otimes}_1$ is constructed:

$$\tilde{\otimes}_1 = \begin{pmatrix}56.12, 50.41, 44.70\\ 49.32, 44.67, 40.02\\ 51.19, 47.21, 43.23\\ 49.67, 46.05, 42.43\\ 50.87, 48.23, 45,59\end{pmatrix}$$

Then all the data in $\tilde{\otimes}_1$ are arranged in ascending order, and a new discrete number set D is shown below:

$$D = \begin{pmatrix}40.02, 42.43, 43.23\\ 44.67, 44.70, 45.59\\ 46.05, 47.21, 48.23\\ 49.32, 49.67, 50.41\\ 50.87, 51.19, 56.12\end{pmatrix}$$

And the difference $\Delta d1$ between the maximum data and minimum data is shown below:

$$\Delta d1 = \max_{1\le s\le 3m}\{d_{js}\} - \min_{1\le s\le 3m}\{d_{js}\} \\ = 56.12 - 40.02 \\ = 16.10$$

And the grey reliability in $20^{\circ}\mathrm{C}$ is

$$g_1^{\circ} = 1 - \left|\frac{\ln \Delta x_i}{\ln \Delta d_j}\right| = 1 - \left|\frac{5.74}{16.1}\right| = 0.3712,$$

And the grey reliability in $-20^{\circ}\mathrm{C}$ and $55^{\circ}\mathrm{C}$ can be calculated in the same way.

$$g_2^{\circ} = 1 - \left|\frac{\ln \Delta x_i}{\ln \Delta d_j}\right| = 1 - \left|\frac{5.38}{13.02}\right| = 0.3443$$

$$g_3^{\circ} = 1 - \left|\frac{\ln \Delta x_i}{\ln \Delta d_j}\right| = 1 - \left|\frac{\ln 9.28}{\ln 18.14}\right| = 0.2313$$

Conclusions can be drawn by above calculation that $g_3^{\circ} < g_2^{\circ} < g_1^{\circ}$, and this means the performance of the static contact resistance in $20^{\circ}\mathrm{C}$ is relatively stable, and resistance volatility is less. And the performance of the static contact resistances in $55^{\circ}\mathrm{C}$ and $-20^{\circ}\mathrm{C}$ are instable, and the resistance volatility is bigger.

5. Conclusions

In this paper, a method of reliability measurement for electrical products based on grey theory is proposed. At first, the general situation of grey theory, grey number and the classification of grey number related to this paper are introduced. Based on grey number and gray scale, the concept of grey reliability for the experiment of little information and poor data is proposed, and the calculation process is illustrated in detail. And finally the theory is verified according to the experimental data.

The calculation results show that the performance of static contact resistance at $20^{\circ}\mathrm{C}$ is relatively stable, and resistance volatility is less. In practical application, due to the low temperature ($-20^{\circ}\mathrm{C}$), the contact hardness is large, the effective contact area is small, and the contact resistance is relatively small. However, when the temperature is too high, it is easy to form an oxide film on the contact surface, and the resistance of oxide film is large, so the contact resistance is also large.

For the type of HH52P electromagnetic relay, the contact resistance at temperature $20^{\circ}C$ is lower than that at the temperature $-20^{\circ}C$ and $55^{\circ}C$, and the performance of contact is better and more stable. The actual situation is the same as the calculation result, which shows that the method has practical application value.

Acknowledgments

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