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Fuzzy Evaluation of the Uncertain Phenomena of AC Contactor's Dynamic Characteristics

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Abstract: AC contactors are widely used not only for motors but also in a huge number of automatic systems as a type of low-voltage electronic product. As the most frequently used electronic switch, the damages are mostly from the cauterization of contacts. During the start and break moment of the AC contactor, the bounce and the electro-arc of the contact result in shorten of the life-span. For the contacts' working conditions has a direct impact on the quality and the operational of the switch, it is necessary to value the dynamic characteristics of the contactor in order to find a appropriate working mode. In light of the situations, this paper presents a method for evaluating the dynamic characteristics of AC contactors. A single AC contactor is tested and the parameters which closely interrelated to the important performance of the AC contactor are obtained specialized with the closing process. The method is to deal with fuzziness to combine these dynamic parameters which affect the contact's dynamic response into one index that represent an overall estimate of how well the character was when evaluating the switch quality, namely the Fuzzy Evaluation of contact's Dynamic Characteristics. Both the stair evaluation and multi-level evaluation are introduced. In addition, fuzzy decision calculating system is designed and implemented by C program, and partly illustrated on the program frame.

Keywords: AC contactor, Fuzzy comprehensive evaluation, Dynamic characteristics, Closing making angle

1. Introduction

The AC contactor is mainly used for switching the AC power circuit. It is the indispensable low-voltage device for both the electric-drive system and the automatic system. As the most frequently used electronic switch, the damages are mostly from the cauterization of contacts. During the closing moment of the AC contactor, the bounce and electro-arc of the contact result in shorten of the lifespan [1-2].

It is obvious that, as the executed part, the contacts' working conditions has a direct impact on the quality and the operational of the switch. In order to improve the performance and upgrade the life span of the AC contactor, it is necessary to value the dynamic response condition using the parameters of the dynamic characteristics that affect the contacts' response. And according to this way, the foundation of designing high performance of the AC contactor is settled.

The theory and technology of electricity, magnetism, electrical contacts, thermal, mechanical, materials are involved in the operation process of the AC contactor, all these results presenting a nonlinear, complexity and uncertainty dynamic process. The parameters such as the voltage, circuit, displacement are variety at any moment during the closing process. The important properties of the evaluating system of AC contactor's dynamic characteristics are diverse and flexible with a certain degree of ambiguity that cannot be describe using the "low", "fair", "good" and so on to evaluate. Therefore, using fuzzy comprehensive evaluation technology will achieve a better result which is closer to the actual situation.

In this paper a method is presented to deal with fuzziness to combine these dynamic parameters which affect the contact's dynamic response into one index that represent an overall estimate of how well the character was when evaluating the switch quality, namely the Fuzzy Evaluation of Contact's Dynamic Characteristics. The ideology and the detailed step are set forth. By analyzing the AC contactor's dynamic characteristics with an important conclusion that for the certain dimension structure AC contactor, its dynamic characteristics are depend on the closing making angle of the voltage supply. Based on the theory, the evaluation model is structured answer for the fuzziness, comprehensive and multi-layer of the contactors' dynamic character. And the subjection degree function is established, so to calculate the value of the subjection degree. The valuation of the contactors' dynamic character with the different closing making angle is obtained. In addition, fuzzy decision calculating system is designed and implemented by C program, and partly illustrated on an example. This method lays the foundation of designing high performance of the AC contactor.

2. Analysis of the dynamic response of the contactor

Medium-small capacity AC contactors mostly employ the EE-core contact mechanism, and in this paper the EE-core CJ20-25 AC contactor is used as the study object. The framework of EE-core is shown in Figure 1.

The contact works as the actuator of the AC contactor. Its reliability and life-span are the main points. The critical factor of the electrical life is the wear of the contact which is largely depended on the vibration and bounce of the make contact.

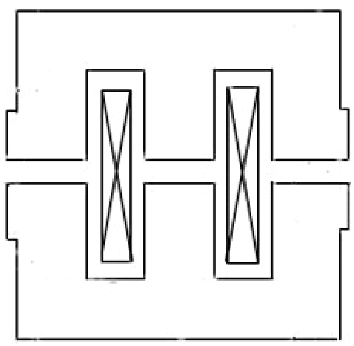

Figure 1. The framework of EE-core

The AC contactor's closing process is very complex, and how well the contactor's dynamic characteristic is mainly depended on the closing making angle, that is, the closing making angle plays the main role and has the crucial impact in the bounce time of the contact, the electromagnetic spring forces and core collision condition. And it is proved in large number of experiments that at the best closing angle, the cauterization of contacts can be minimized, also the mechanical life, the electrical life and the making capacity of the contacts can be improved in a large extent.

During the closing process of the AC contactor, the contactor coil electrified and the collision of two contacts for the first time which is resulted from the electromagnetic attraction of the core, the closing velocity of the moving contact determines the bounce of the contacts and the value of this speed has a directly influence on the electro-life and the making capacity of the contactor; later, the collision of the two cores occur with high impact and mechanical vibration, this brings a rebound of the contacts. The kinetic energy of the core is described as $E_k = 0.5mv^2$ and the closing velocity of the moving core affects the mechanical life of the contactor in a large extent. Besides, the current flow of the contact is bigger than the first time. All these can bring a serious electrical abrasion and result in the arc discharge and spark which cause the contact welding: a serious impact on the contactor's electro-life [3-4] .

3. Fuzzy evaluation of AC contactor's dynamic characteristics

The performance of a commercially available contactor CJ20-25 was evaluated using the electro-optical contactor dynamic testing device. The contactor is controlled to be closed at the different closing phase angle of the switching electromagnetic coil voltage to obtain the dynamic parameters which closely interrelated to the important performance of the AC contactor.

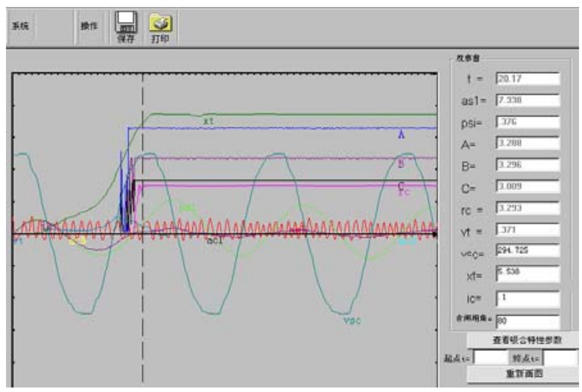

Figure 2. Closing dynamic characteristic image

The dynamic characteristic curves were

obtained by the electro-optical contactor dynamic testing device, the closing dynamic characteristic image and the dynamic parameters display interface are shown in Figure 2 and Figure 3.

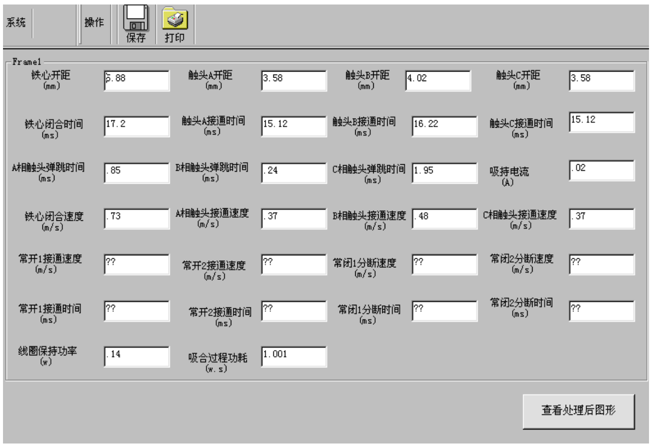

Figure 3. Dynamic parameters display interface

These curves shows the dynamic process intuitionistic according to an active coordinates which helps to record the dynamic parameters easily, at the same time, the device shows the important feature data at any certain time. By using the parameters, the valuation of the contactors' dynamic character with the different closing making angle is calculated to find the best.

The different responses are evaluated specialized with the closing process. Ten closing making angles are chosen from 0° to 180° with equal interval and the parameters of dynamic response characteristic at the these angles are recorded. These parameters are closing velocity of moving core v_r, closing velocity of moving contacts v_A, v_B, v_C, closing time of the cores t_r, closing time of the contacts T_A, T_B, T_C and bounce time of the contacts T_{tA}, T_{tB}, T_{tC}. The original data of sample's dynamic performances are given in Table 1.

Table 1. Original data of sample's dynamic performance

θ (°)	$T(ms)$			$T_t(ms)$			$v(m/s)$			t_r (ms)	v_r (m/s)
	A	B	C	A	B	C	A	B	C		
0°	15.8	16.05	15.93	0.49	0.86	1.11	0.43	0.54	0.49	17.78	0.7
20°	14.63	14.63	14.63	1.22	0.85	1.1	0.4	0.4	0.4	16.59	0.78
40°	14.51	14.63	14.63	0.85	0.85	1.34	0.44	0.44	0.44	16.83	0.65
60°	15.8	15.8	15.8	1.48	1.85	0.12	0.68	0.68	1.07	16.79	0.95
80°	16.83	17.68	16.83	0.98	1.95	0.02	0.71	0.69	0.71	19.15	0.56
100°	16.95	16.95	16.95	1.1	1.59	1.22	0.71	0.71	0.71	19.39	0.52
120°	20.12	20.12	20.12	0.85	1.46	1.1	0.46	0.46	0.46	21.59	0.86
140°	15.12	16.0	15.25	1.25	0.62	1.38	0.38	0.56	0.39	16.75	0.85
160°	16.51	16.63	16.63	0.96	1.33	1.57	0.38	0.38	0.38	18.55	0.73
179°	15.24	15.49	15.37	0.85	0.61	1.34	0.4	0.4	0.4	17.44	0.64

3.1 Build up the factor vector

According to the dynamic process analysis above, these parameters have close connection to the electro-life and the mechanical life of the AC contactor so they are chosen to build up the factor vector of fuzzy comprehensive evaluation.

$$U = \{u_1, u_2, \cdots, u_m\} = \{\overline{T}, \overline{T_t}, \overline{v}, t_r, v_r\}$$

Where:

$\overline{T}$ is the average closing time of three phase contacts;

$\overline{T_t}$ is the average bounce time of three phase contacts;

$\overline{v}$ is the average closing velocity of three phase contacts;

t_r is the closing time of the cores;

v_r is the closing velocity of the cores.

3.2 Build up the fuzzy set

Describing how well the contactor's dynamic responses are with a certain degree of ambiguity and flexible, then choose the conventional 5-level fuzzy set as the criteria performance of evaluation which is written as:

$$V = \{v_1, v_2, \cdots, v_n\} = \{VeryGood, Good, Medium, Low, VeryLow\}$$

3.3 Build up weighting vector

Above all the parameters, average bounce time of three phase contacts is the most important index, and the followings are the closing velocity of the cores, average closing velocity of three phase contacts, closing time of the cores, average closing time of three phase contacts.

On the basis of experts statistical method, the weighting vector is that:

$$A = (a_1, a_2 \cdots, a_m) = (0.10, 0.35, 0.20, 0.10, 0.25)$$

3.4 Build up the subject degree functions

Based on the characteristics of evaluation object, the subjection degree function of fuzzy comprehensive evaluation is built on the basis of real-number domain, at the same time the corresponding fuzzy sets of the actual measured influence factor have a linear characteristic when the AC contactor has no load. By using the basic fuzzy function model, the subject degree functions of evaluation indexes are built here.

The membership function of the five levels of linguistic variables is built up to assess the linguistic ratings of each parameter[5-6]. The function's chart is shown in Figure 4.

Upper and lower limits of each parameter can be determined by the Max and Min of the 10 groups' data of the dynamic response parameters. The abscissa of the corresponding grade is S_1, S_2, S_3, S_4, S_5 which equally plot the distance from Max to Min as seen in Figure 4.

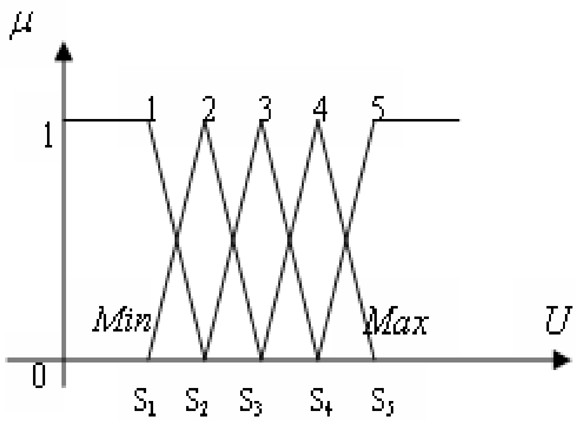

Figure 4. Membership function's Chart

The membership functions are listed as follows:

$$v_{1i} = \begin{cases} 1, & U_i \le S_1 \\ (S_2 - U_i)/(S_2 - S_1), & S_1 < U_i < S_2 \\ 0, & U_i > S_2 \end{cases} \quad (1)$$

$$v_{2i} = \begin{cases} 0, & U_i \le S_1 \\ (U_i - S_1)/(S_2 - S_1), & S_1 < U_i \le S_2 \\ (S_3 - U_i)/(S_3 - S_2), & S_2 < U_i < S_3 \\ 0, & U_i \ge S_3 \end{cases} \quad (2)$$

$$v_{3i} = \begin{cases} 0, & U_i \le S_2 \\ (U_i - S_2)/(S_3 - S_2), & S_2 < U_i \le S_3 \\ (S_4 - U_i)/(S_4 - S_3), & S_3 < U_i < S_4 \\ 0, & U_i \ge S_4 \end{cases} \quad (3)$$

$$v_{4i} = \begin{cases} 0, & U_i \le S_3 \\ (U_i - S_3)/(S_4 - S_3), & S_3 < U_i \le S_4 \\ (S_5 - U_i)/(S_5 - S_4), & S_4 < U_i < S_5 \\ 0, & U_i \ge S_5 \end{cases} \quad (4)$$

$$v_{5i} = \begin{cases} 0, & U_i \le S_4 \\ (U_i - S_4)/(S_5 - S_4), & S_4 < U_i < S_5 \\ 1, & U_i \ge S_5 \end{cases} \quad (5)$$

The grade of membership of each parameter attached to each grade is

$$R = \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix}$$

Subscript n of each element of the matrix stands for the number of the grade and subscript m stands for the number of the criteria.

The standard data of the grades are calculated by the dynamic response data as shown in Table 2.

Table 2. Standard data of the grades

Variable	Standard data				
	Very Good	Good	Medium	Low	Very Low
$\overline{T}$	14.63	16.0	17.37	18.74	20.12
$\overline{T_t}$	0.82	0.94	1.06	1.18	1.30
$\overline{v}$	0.38	0.49	0.60	0.71	0.81
t_r	16.59	17.84	19.09	20.34	21.59
v_r	0.52	0.63	0.74	0.85	0.95

Taking θ=0° as the example a single factor u1 is considered from the factor matrix U firstly.

According to Table 2 and Equations (1) (2), u1's function's grades data are calculated. S_1 is 14.63, S_2 is 16.0, S_3 is 17.37, S_4 is 18.74, S_5 is 20.12, and the degree of membership of u1 which is attached to vj (j=1, 2, 3, 4, 5) is also gained. The single factor value vector is gotten out:

$$r_1 = (0.05, 0.95, 0, 0, 0)$$

Follow the same steps, r_2~r_5 can be calculated, the combination of these five single factor's vector is the fuzzy evaluation matrix R_1 when θ=0° , that is:

$$R_1 = \begin{bmatrix} 0.05 & 0.95 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0.13 & 0.87 & 0 & 0 & 0 \\ 0 & 0.05 & 0.95 & 0 & 0 \end{bmatrix}$$

Similarly, the other nine fuzzy evaluation matrixes of R_2~R_{10} can be obtained.

3.5 Calculate comprehensive result

Select comprehensive evaluation model and work out the fuzzy comprehension evaluation vector.

There are five types evaluation model. And the model which used for evaluation is chosen according to the specific need. For the fuzzy comprehension evaluation of AC contactor's contact, there are multiple criteria affecting the response and the parameters also interacts each another in the system. While adopting model $M(\bullet,+)$, the result will not only take all the matters into consideration but also preserve the valuable information of single evaluation. Model $M(\bullet,+)$ would be the exact one for the AC contactor's fuzzy comprehensive evaluation.

Accordingly, the result of the comprehensive is: (e.g. θ=0°)

$$B_1 = A \circ R_1 = (b_1, b_2, \cdots, b_m)$$

$$= (0.10, 0.35, 0.20, 0.10, 0.25) \begin{pmatrix} 0.05 & 0.95 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0.13 & 0.87 & 0 & 0 & 0 \\ 0 & 0.05 & 0.95 & 0 & 0 \end{pmatrix}$$

$$= (0.268, 0.4945, 0.2375, 0, 0)$$

B2~B10 can be worked out in the same way.

For the grades Very Good, Good, Medium, Low, Very Low, each linguistic variable can be indicated using numbers as 5、4、3、2、1. Evaluate criteria is unitary for $\sum_{j=1}^{n} b_j = 1$, the fuzzy comprehension evaluation vector is dealing with the Weight Average Method,

$$v = \sum_{j=1}^{n} b_j v_j \tag{6}$$

The results are presented in Table 3.

Table 3. Result of the stair fuzzy comprehensive evaluation

Closing angle θ	Value of Comprehensive evaluation	Closing angel θ	Value of Comprehensive evaluation
0°	4.03	100°	2.14
20°	2.27	120°	3.15
40°	2.83	140°	3.22
60°	4.12	160°	2.04
80°	3.34	179°	3.02

From the table above, the highest value is 4.12. That means the contact's dynamic performance is the best when the closing making angle is 60°. And it is also approved in [7] through dynamic simulation of the contactor device, the contactor's closing time characteristic and the closing speed characteristic are the finest while the closing angle is 60° .

4. Multi-level fuzzy evaluation of AC contactor's dynamic characteristics

There may be some problems if all the eleven parameters in the Table 1 were considered when using stair evaluation. Firstly, the weight factor can not be distributed reasonably; secondly, some of the useful information would be lost for all the parameters in the weighting vector are so small. Besides, the parameters in the factor vector of the stair evaluation of contact's dynamic response are usually determined by other factor, so the multi-level evaluation method can be used [8-9].

The parameters in Table 1 are divided into two levels as shown in Figure 5.

The factor vector of evaluation is built up with these four parameters:

$$U = \{U_1, U_2, U_3, U_4\}$$

Where:

U_1 is the dynamic response of contact A;

U_2 is the dynamic response of contact B;

U_3 is the dynamic response of contact C;

U_4 is the dynamic response of the core.

and they are determined by the basic parameters.

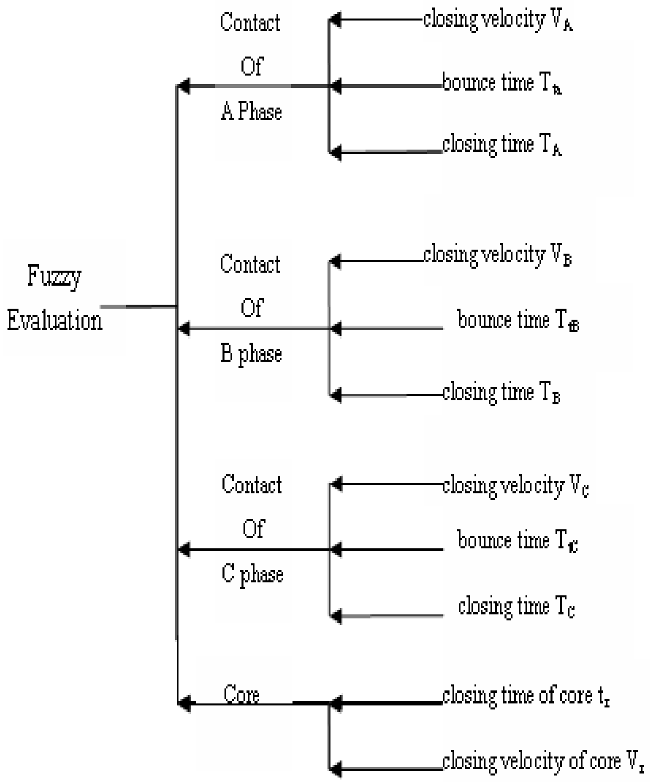

Figure 5. Fuzzy evaluation of the multi-level process

4.1 First level evaluation

For the dynamic response of contact A, the factor vector is built up with three parameters:

$$U_1 = \{u_{11}, u_{12}, \cdots, u_{1m}\} = \{T_A, T_{tA}, V_A\}$$

The criteria performance of evaluation of contact A is also given as a 5-level value written as:

$$V_1 = \{V_{11}, V_{12}, \cdots, V_{1n}\} = \{VeryGood, Good, Medium, Low, VeryLow\}$$

On the basis of statistical method, the weighting vector is:

$$A_1 = (0.30, 0.60, 0.10)$$

Taking $\theta = 0°$ for example, with the same membership function fuzzy evaluation matrix is calculated:

$$R_1 = \begin{bmatrix} 0.01 & 0.99 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0.38 & 0.62 & 0 & 0 & 0 \end{bmatrix}$$

Adopting model $M(\bullet, +)$, the fuzzy evaluation matrix B_1 is calculated,

$$B_1 = A_1 \circ R_1 = (0.041, 0.359, 0, 0, 0)$$

Following the same steps, dynamic evaluation of other two contacts when $\theta = 0°$ can be easily obtained.

For the contact of B phase, the factor vector is:

$$U_2 = \{u_{21}, u_{22}, \cdots, u_{2m}\} = \{T_B, T_{tB}, V_B\}$$

Criteria performance of evaluation is:

$$V_2 = \{v_{21}, v_{22}, \cdots, v_{2n}\} = \{VeryGood, Good, Medium, Low, VeryLow\}$$

The weighting vector is:

$$A_2 = (0.30, 0.60, 0.10)$$

The fuzzy evaluation matrix is:

$$R_2 = \begin{bmatrix} 0 & 0.63 & 0.37 & 0 & 0 \\ 0.24 & 0.76 & 0 & 0 & 0 \\ 0 & 0 & 0.87 & 0.13 & 0 \end{bmatrix}$$

So the fuzzy evaluation matrix B_2 is:

$$B_2 = A_2 \circ R_2 = (0.144, 0.645, 0.198, 0.013, 0)$$

And, for the contact of C phase, the factor vector is:

$$U_3 = \{u_{31}, u_{32}, \cdots, u_{3m}\} = \{T_C, T_{tC}, V_C\}$$

Criteria performance of evaluation is:

$$V_3 = \{v_{31}, v_{32}, \cdots, v_{3n}\} = \{VeryGood, Good, Medium, Low, VeryLow\}$$

The weighting vector is:

$$A_3 = (0.30, 0.60, 0.10)$$

The fuzzy evaluation matrix is:

$$R_3 = \begin{bmatrix} 0.05 & 0.95 & 0 & 0 & 0 \\ 0 & 0 & 0.82 & 0.18 & 0 \\ 0 & 0 & 0 & 0.64 & 0.36 \end{bmatrix}$$

So the fuzzy evaluation matrix B_3 is:

$$B_3 = A_3 \circ R_3 = (0.0150, 0.2850, 0.4920, 0.1720, 0.0360)$$

For the dynamic response of core, the factor vector is built up with two parameters:

$$U_4 = \{u_{41}, u_{42}, \cdots, u_{4m}\} = \{t_r, V_r\}$$

And the Criteria performance of evaluation is:

$$V_4 = \{v_{41}, v_{42}, \cdots, v_{4n}\} = \{VeryGood, Good, Medium, Low, VeryLow\}$$

The weighting vector is:

$$A_4 = (0.30, 0.70)$$

The fuzzy evaluation matrix is:

$$R_4 = \begin{bmatrix} 0.48 & 0.52 & 0 & 0 & 0 \\ 0 & 0 & 0.73 & 0.27 & 0 \end{bmatrix}$$

So the fuzzy evaluation matrix B_4 is:

$$B_4 = A_4 \circ R_4 = (0.1440, 0.1560, 0.5110, 0.1890, 0)$$

4.2 Multi-level fuzzy evaluation

The combination of B_1,B_2,B_3,B_4 is the fuzzy matrix of multi-level evaluation.

$$R_1' = \begin{pmatrix} B_1 \\ B_2 \\ B_3 \\ B_4 \end{pmatrix} = \begin{pmatrix} 0.041 & 0.959 & 0 & 0 & 0 \\ 0.144 & 0.355 & 0.198 & 0.013 & 0 \\ 0.015 & 0.285 & 0.492 & 0.172 & 0.036 \\ 0.144 & 0.156 & 0.511 & 0.189 & 0 \end{pmatrix}$$

The weighting vector of U is:

$$A = (0.30, 0.30, 0.30, 0.10)$$

Adopting model $M(\bullet,+)$, the fuzzy evaluation matrix B_1' is calculated,

$$B_1' = A \circ R_1' = (b_1', b_2', \cdots, b_m')$$

$$= (0.30,0.30,0.30,0.10) \begin{pmatrix} 0.041 & 0.959 & 0 & 0 & 0 \\ 0.144 & 0.355 & 0.198 & 0.013 & 0 \\ 0.015 & 0.285 & 0.492 & 0.172 & 0.036 \\ 0.144 & 0.156 & 0.511 & 0.189 & 0 \end{pmatrix}$$

$$= (0.1614, 0.4953, 0.2581, 0.0744, 0.0108)$$

$B_2' \sim B_{10}'$ can be worked out in the same way.

Multi-level evaluate criteria is unitary, and the grades are Very Good, Good, Medium, Low, Very Low, each linguistic variable can be indicated using numbers as 5、4、3、2、1. The fuzzy comprehension evaluation vector is dealing with the Weight Average Method as Equation (6) shows.

The result of the multi-level evaluation is presented in Table 4.

From the table, the contact’s dynamic performance is the best with the closing making angle 60°.

Compared the result of the multi-level fuzzy comprehensive evaluation with the stair fuzzy comprehensive evaluation, it can be found that the result scale of the multi-level fuzzy comprehensive evaluation is larger and finer. And the best closing making angles are identical. In practice, the reasonable pattern is chosen according to actual require.

Table 4. The result of the multi-level fuzzy comprehensive evaluation

Closing angle θ	Value of Comprehensive evaluation	Closing angel θ	Value of Comprehensive evaluation
0°	4.22	100°	2.24
20°	1.85	120°	2.87
40°	4.30	140°	3.98
60°	4.41	160°	1.60
80°	4.13	179°	4.01

5. C programming applications of fuzzy comprehensive evaluation

Computer programming application of fuzzy comprehensive evaluation can meet the evaluators’ needs such as the high calculating efficiency and exactness degree. Fuzzy decision calculating system is designed and implemented by C program and flow chart is shown in Figure. 6.

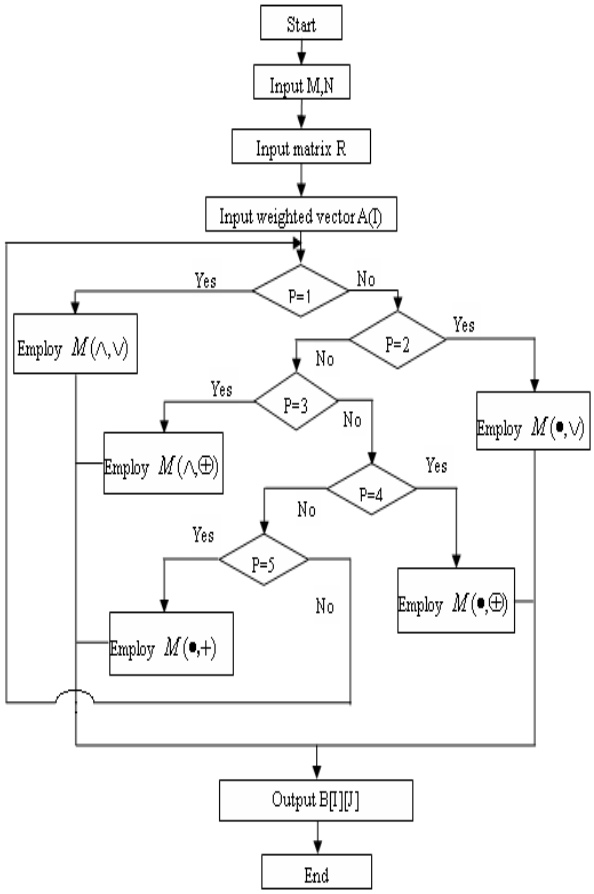

Figure 6. The flow chart of the fuzzy comprehensive evaluation program

The input data are listed below:

M is the number of the variables in the factor vector;

N is the number of evaluation grades;

MATRIX R is the fuzzy evaluation matrix;

MATRIX A is the weighting vector;

P=1, adopting $M(\wedge,\vee)$ calculating model;

P=2, adopting $M(\bullet,\vee)$ calculating model;

P=3, adopting $M(\wedge,\oplus)$ calculating model;

P=4, adopting $M(\bullet,\oplus)$ calculating model;

P=5, adopting $M(\bullet,+)$ calculating model;

Output of the program is B[J][I] in which the J is from 1 to N.

High flexibility and logicality are the advantages of the algorithm implementation by making use of the C program. More importantly, C language program can be implanted into VC + + program to further an object-oriented design programming.

6. Conclusions

In this paper a technique is presented to deal with fuzziness to combine some parameters which affect the contact's dynamic response into one index that represent an overall estimate of how well the character was when evaluating the dynamic characteristics, namely the Fuzzy Evaluation of contact's Dynamic Characteristics. Also, fuzzy decision making system is designed and implemented by visual C++. This method lays the foundation of designing high performance of the AC contactor and the successful value of this technology is the real meaning of innovation.

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