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Reliability testing and reliability analysis of the over-load protective relay*

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Abstract: The over-load protective relay is widely used for motor protection. The reliability of the over-load protective relay directly affects the safe running of a motor. The reliability testing and reliability analysis of the over-load protective relay is an important way to improve the reliability of products. In this paper, the reliability test method of the over-load protective relay is studied, and the reliability tests of the typical products are carried out on a reliability tester developed by authors. In terms of the testing results, the reliability analysis is finished. The failure reasons are found and the measures are put forward to improve the reliability of the products.

Key words: Over-load protective relay, Protective success ratio, Sampling and checking plan, Reliability testing, Reliability analysis

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INTRODUCTION

The over-load protective relay is an important low-voltage apparatus in power control. It is mainly used with AC contactor to protect motor from over current.

The structural diagram of an over-load protective relay is shown in Fig.1. The core part is the bimetals. Once over-load current happens in motor, the increased bending of bimetals releases the AC contactor controlled by the auxiliary contact, so the main circuit breaks and the motor is protected.

One of the reasons why the failures of over-load protective relay increase, which results in major economic loss, is the low reliability. Reliability evaluation has attracted more and more attentions at home and abroad. The reliability testing and reliability analysis of over-load protective relay is an important way to quantitatively evaluate the reliability and insure the quality. In this paper, the reliability test method of over-load protective relay is studied and the reliability testing and the reliability analysis for the typical product of JR36-20 are carried out. In addition, in terms of the reliability analysis of JR36-20, the corresponding measures are put forward to improve the reliability of the products.

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RELIABILITY TEST METHOD OF OVER-LOAD PROTECTIVE RELAY

Reliability characteristic value

For over-load protective relay, four trip points of over-load current, that is, 1.05, 1.2, 1.5, and 7.2 times current are considered in the reliability testing. During the reliability testing, the main types of failure modes of over-load protective relay are as follows:

(1) When over-load current is up to a serious degree, the over-load protective relay cannot operate timely (refuse operation).

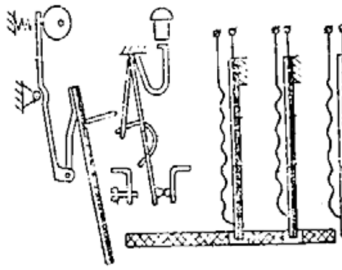

Fig.1 Structural diagram of over-load protective relay

(2) When the motor works normally, the over-load protective relay operates to cut the circuit because of its operation characters changing or some kinds of jamming signals existing (misoperation).

(3) Reset time exceeds the stated time.

(4) After the over-load protective relay trips, the *a*-contact cannot reliably close or the *b*-contact cannot reliably open.

In terms of the non-frequent-operation characteristic and the main types of failure modes of the over-load protective relay, the protective success ratio R is chosen as the reliability characteristic value (Zhao *et al.*, 2006). For the over-load protective relay, R is the probability of non-failure during the operations. R can be calculated with the following formula:

$$\hat{R} = (n_1 - r)/n_1, \tag{1}$$

where $\hat{R}$ is point estimated value of protective success ratio; n_1 is total test runs; r is total failure runs.

During the reliability test of the over-load protective relay, when a sample's failure runs reach up to 2, it is dismissed from the reliability testing.

Sampling and checking plan

In terms of reliability sampling theory, when protective success ratio R is less than the unacceptable protective success ratio R_1, the reliability test should be accepted with lesser probability (probability less than β named as consumer risk) (Lu and Wang, 2004). Fig.2 shows the sampling and checking plan of over-load protective relay with two parameters R_1 and β which can indicate the reliability level of the products. The acceptable probability $L(R)$ of the sampling and checking plan in Fig.2 refers to the qualification probability, which is judged by checking a batch of products with some sampling and checking plan.

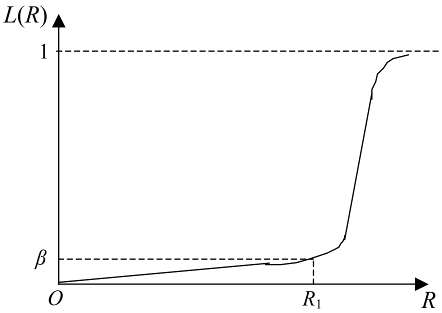

Fig.2 Sampling and checking characteristic curve

To be reality, for the over-load protective relay, it is recommend the protective success ratio R be graded into five levels in terms of the unacceptable protective success ratio R_1, seeing Table 1.

Table 1 Name of protective success ratio level and values of R_1 for over-load protective relay

Name of protective success ratio level	Values of R_1
Level I	0.99
Level II	0.98
Level III	0.97
Level IV	0.96
Level V	0.95

The sampling and checking plan adopted in the reliability test of over-load protective relay is one-time count sampling and checking plan (Fig.3).

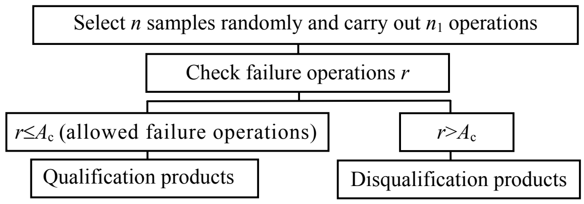

Fig.3 Diagram of one-time count sampling and checking plan

$L(R)$ of the sampling and checking plan should be equal to the sum of the probabilities when r is 0, 1, …, A_c respectively. On the assumption of the total number of a batch of products N>10n, by use of binomial probability formula, seen from Fig.2, the reception condition can be written as:

$$L(R_1) = \sum_{r=0}^{A_c} C_{n_1}^r R_1^{n_1 - r} (1 - R_1)^r \le \beta \, . \tag{2}$$

After the values of A_c, R_1 and β are given by producer and user, the minimum value of the reliability test operations (that is, n_f: the minimum cumulative test operations required by judgment) in the time or failure curtailed test of over-load protective relay can be solved by Eq.(2) and the sampling and checking plan with the two parameters of R_1 and β can be acquired (Luo *et al.*, 1999). So the result judgment of the reliability test of over-load protective relay is when the cumulative test operations n_Σ satisfies $n_\Sigma \geq n_f$ and the cumulative failure operations r satisfies $r \leq A_c$, the test plan will be accepted; when n_Σ satisfies $n_\Sigma \leq n_f$ and r satisfies $r > A_c$, the test plan will be refused.

For the sampling and checking plan with two parameters R_1 and β, the calculation software is programmed by VC++ (Bates *et al.*, 1998). Table 2 shows the different sampling and checking plans of protective success ratio with different protective success ratio levels and β=0.1.

Table 2 Different sampling and checking plans of protective success ratio (β=0.1)

R_1	n_f								
	A_c=1	2	3	4	5	6	7	8	9
0.95	77	105	132	158	184	209	234	258	282
0.96	96	132	166	198	230	262	292	323	333
0.97	129	176	221	265	308	349	390	431	471
0.98	194	265	333	398	462	525	587	648	708
0.99	388	531	667	798	926	1051	1175	1297	1418

During the reliability test of over-load protective relay, because the trend of the sampling and checking characteristic curve is the same with different values of the curtailed operations of each sample n_z, the value of n_z from 40 to 80 is recommended. So the number of the samples in reliability test can be acquired by the following equation:

$$n = n_f / n_z + A_c. \tag{3}$$

RELIABILITY TESTING OF OVER-LOAD PROTECTIVE RELAY

Reliability tester of over-load protective relay

The reliability tester of over-load protective relay developed by authors is shown in Fig.4. The tester allows 3 samples testing at the same time.

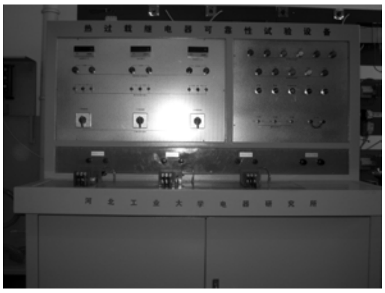

Fig.4 The reliability tester of over-load protective relay

Procedure of reliability testing

In this paper, the reliability testing for the typical products—JR36-20 is carried out.

1. Test conditions

(1) Environment condition: Temperature is 15~25 °C; Altitude is ≤2000 m.

The samples are placed in the environment stated above for a sufficient time period (not less than 8 h), so as to reach the balance.

(2) Installation condition: The samples are installed in the normal position in service.

(3) Power source condition: The frequency of the constant-current source is 50 Hz with a tolerance less than +5%.

2. Procedure of reliability testing

(1) Choose β=0.1, R_1=0.95, A_c=1. From Table 2, n_f=77 can be acquired.

(2) Choose n_z=40. In terms of Eq.(3), the number of the samples n can be acquired.

$$n = n_f / n_z + A_c = 77/40 + 1 \approx 3. \tag{4}$$

(3) Three samples of JR36-20 are randomly selected from a batch of qualified products.

(4) By use of the reliability tester, the reliability testing of JR36-20 is carried out and the result judgment is acquired.

1) Test program

(a) Normal operation current testing: The initial temperature is the environment temperature. 1.05 times setting current flows through the samples.

(b) 1.2 times over-load current testing: When the samples reach to a thermal balance, 1.2 times setting current flows through the samples.

(c) 1.5 times over-load current testing: When the samples reach to the thermal balance, 1.5 times setting current flows through the samples.

(d) 7.2 times over-load current testing: The initial temperature is at the environment temperature. 7.2 times setting current flows through the samples.

The maximum numbers of test runs of a sample for Test a, b and c are $0.5n_z$, $0.25n_z$ and $0.25n_z$ respectively. Test d is only a validation test to be done 1 operation.

2) Setting of test parameters

The action limit of over-load protective relay JR36-20 (tripping level is 10 A) in GB14048.6-1998 is shown in Table 3 (GB14048.6-1998, 2001).

The reset types of JR36-20 include automatic reset (reset time is less than 300 s) and manual reset (reset time is less than 120 s).

The setting of test parameters for JR36-20 is shown in Table 4 and the setting of test process is shown in Table 5.

3) Result judgment of reliability testing

When any of the followings happens, the failure is included in the relevant failures:

(a) The samples operate within 2 h when 1.05 times setting current flows (misoperation).

(b) The samples do not operate within 2 h when 1.2 times setting current flows (refuse operation).

(c) The samples do not operate within 2 min when 1.5 times setting current flows (refuse operation).

(d) The samples cannot operate between 2 s and 10 s (misoperation if the samples operate within 2 s, or refuse operation if the samples operate during the time more than 10 s) when 7.2 times setting current flows.

Table 3 Action limit of over-load protective relay

Times of setting current	Tripping time t_p	Original condition	Environment temperature
1.05	≥2 h	Cold state	20 °C
1.20	<2 h	Heat balance	
1.50	<2 min	Heat balance	
7.20	2 s≤t_p≤10 s	Cold state	

(e) Reset time exceeds the stated time.

(f) After the over-load protective relay trips or resets, the voltage between closing contacts is more than 10% of the voltage of contact open circuit and the voltage between opening contacts is less than 90% (The power source in contact circuit is 24 V DC, the current is 1 A and the load is resistant).

When the test operations arrive at 8, two failure operations have occurred. That is, when $n_\Sigma=8<n_f=77$, $r_\Sigma=2>A_c=1$, so the products cannot achieve Level V.

RELIABILITY ANALYSIS OF OVER-LOAD PROTECTIVE RELAY

Because of the structure characteristics of over-load protective relay, there are a lot of failure factors. In order to make further analysis on JR36-20, after the conclusion of the reliability testing for JR36-20 is acquired, the number of allowed failure operations is modified, the testing moves on. The testing results are shown in Table 6.

Failure analysis

The failure modes of JR36-20 include the loose contact and the misoperations. By reliability analysis, the failure causes are considered as follows.

1. Influence of contact resistance

When the current flows through the mechanical

Table 4 Setting of test parameters

Parameters	Values
Type of product	JR36-20
Setting current (A)	20.00
Choice of samples	1, 2, 3
Cooling time (s)	7200
Number of testing cycle	7
Number of testing process	3
Allowed failure operations	1

Table 5 Setting of test process

	Test process 1	Test process 2	Test process 3
Test state	Cold	Cold	Cold (7.2 times)
Testing current 1 (A)	21	21	144
Testing time 1 (s)	7200	7200	2
Criterion of judgment (1)	Non-action	Non-action	Non-action
Testing current 2 (A)	24	30	144
Testing time 2 (s)	7200	120	10
Criterion of judgment (2)	Action	Action	Action

Table 6 Testing results

Sample No.	Times of setting current			
	1.05	1.2	1.5	7.2
1	14 operations are normal	Loose contact occurs continuously	Loose contact occurs continuously	Tripping at 7.9 s
2	14 operations are normal	7 operations are normal	7 operations are normal	Tripping at 7.3 s
3	2 misoperations occurred within 14 operations	6 operations are normal	6 operations are normal	Tripping at 6.9 s

contacts, the contact resistance which includes film resistance and contraction resistance, will occur on the contact surfaces. It can be calculated by the following equation:

$$R_j=\frac{\rho}{2n_2a_p}+\frac{\sigma}{\pi n_2 a_p^2}, \quad (5)$$

where ρ is resistivity of contact material; σ is surface resistivity of film; n_2 is number of conductive points; a_p is mean radius of conductive points.

For the contacts of over-load protective relay, the roughness of contact surface, the oxide layer, the corrosion and the contamination can reduce the number and the radius of conductive points and increase the contact resistance to result in loose contact (Li *et al.*, 2000; Hu *et al.*, 2004).

2. Problem of thermal synchronization of bimetallic system

Fig.5 shows the action process of bimetallic system.

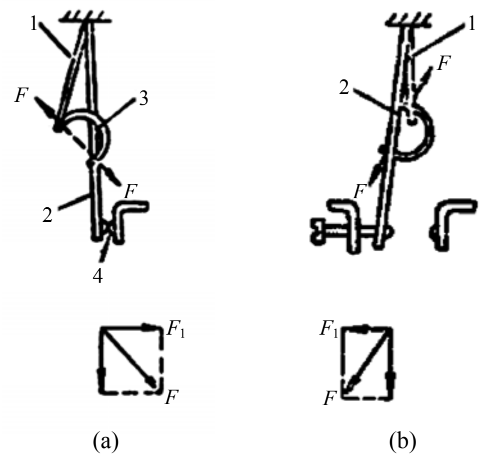

Fig.5 The action process of bimetallic system. (a) Before action; (b) After action

1,2: leaf spring; 3: semielliptic spring; 4: contact; F: elastic force; F_1: horizontal component of F

The performances of three phases in bimetallic system are approximately the same but with some differences. When the bimetals and the thermal parts of three phases are heated, the directions of the forces generated by the bimetals are different to cause the reduction of contact force of the contacts. The relationship between contact force F and contact resistance can be expressed by the following equation:

$$R_j=\rho K_j/(0.1F)^m, \quad (6)$$

where m is coefficient related with the contact modes; K_j is coefficient related with the contact material, surface condition and contact modes, and so on.

Seen from Eq.(6), the reduction of contact force can make contact resistance increase to result in loose contact.

3. Problem of product stability

For Sample 3, two misoperations occurred among 14 operations at the 1.05 times setting current condition. The time of 2 misoperations is 1841.34 s and 1964.62 s respectively. The data show that there are problems in the cooperation of operation frameworks and the performance of the key parts, which are generally determined by the compositions and the consistency of material, thus to cause the worse stability of products.

4. Problem of processing and assembly

The action time of Sample 2 and Sample 3 under the 1.2 and 1.5 times setting current is shown in Figs.6a and 6b respectively.

It can be seen from Fig.6 that the action time is quite different for the same sample or the different samples. It shows the deficiencies in the precision of processing and the standard of assembly, and so on.

Measures of improving the reliability of over-load protective relay

In terms of the reliability analysis, the following

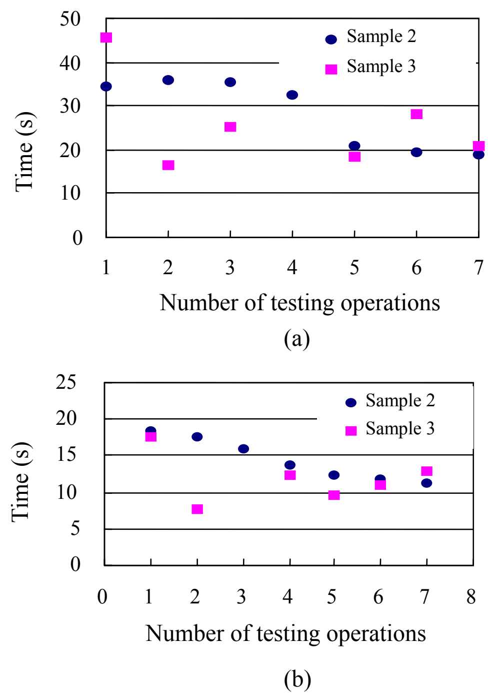

Fig.6 Action time of Sample 2 and Sample 3 under the 1.2 (a) and 1.5 (b) times setting current

measures can be adopted to improve the quality and reliability of the over-load protective relay.

(1) Silver-based material has good performances such as well-electric and well-heat performance (Wu *et al.*, 2005). With the development of material, hope a better material be applied in the contacts. At the same time, enough attention should be paid to maintain the cleanness of the contact and assuring enough contact force to reduce contact resistance.

(2) Reinforce the performance of key parts in over-load protective relay. For the bimetallic system, the temperature, time and times of the heat-treating must be chosen correctly, and such tests as the measurements of bending coefficient and spring coefficient need to be completed to assure that the material is uniform with a controlled dimension tolerance (Zhou, 2000; He, 2000). At the same time, the resistance of thermal parts needs to be strictly controlled. In addition, it is important to reinforce the performance and the cooperation of operation framework.

(3) Try the best to adopt the automatic equipment to process and assemble the products to maintain the precision and the consistency of the products. In addition, keep some allowances for some key parts to improve the reliability.

CONCLUSION

The reliability testing and the reliability analysis are of importance on improving the quality and reliability of the over-load protective relay. Firstly, by taking protective success ratio as the reliability characteristic value and adopting the one-time count sampling and checking plan with two parameters R_1 and β, the reliability test method of over-load protective relay is studied in this paper. Subsequently, by using of the reliability tester developed by authors, the reliability testing for the typical product JR36-20 is carried out. The testing results show that the reliability of the batch of products is lower. Based on the testing results, the reliability analysis is finished. The failure reasons are found from the aspects of contact resistance, thermal synchronization of bimetallic system, stability of products, processing and assembly, and so on. Lastly, in terms of the reliability analysis, the improvement measures are put forward.

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