


Lavrov V.A., Durnev A.V.

METHODS AND MEANS OF DIAGNOSTIC CONTROL OF LOW-CURRENT ELECTROMAGNETIC RELAYS

The article covers the methods and means of quality control and identification of dependable low-current electromagnetic relays based on the diagnostic value of properties. Software is suggested for selection of the most informative parameters and dependability classification of relays.

Keywords: *relay diagnostics, relay control, relay characteristics, potentially undependable relay, informative relay parameters.*

The quality of electronic equipment (EE) used in various industries and special technology (military, space, medical, etc.) largely depends on the used electronic components [1, 2]. One of the widest and longest used EE components is the electromagnetic low-current hermetically sealed relay (further referred to as relay), the production of which has been on the rise over the last years [3, 4]. That is why it is important to have diagnostic tools able of identifying the quality of manufacture and forecast their operational dependability.

Today's manufacturing procedures still let faulty relays go to the consumers. The defects (a defect should be understood as a relay parameter outside the standard value set forth in the technical specifications) are uncovered at each lifecycle step of relays, namely delivery, acceptance test and operation. The most common defect is non-compliance of pick-up and drop-off voltage (current) with the standard values set forth in the technical specifications. They are followed by defects due to excessive time parameters, circuit resistance of contacts and short disruptions of field circuits. Given the application area of relays we can say that the problems related to the development and implementation of efficient measures of prevention and identification of the above defects and elimination of their marketing are of utmost importance to the improvement of product quality [5].

Practical experiments have shown that identifying relays with excessive values of actuation level, time parameters and circuit resistance of contacts must be performed by means of multiple measurements of those parameters. Each measurement is performed during or upon completion of switching actions. 20 to 30 switching actions are optimal. It should be noted that regulatory documents [6] prescribe a single measurement of those parameters. It has been found that deviations of one or another parameter (even if it is within the standard prescribed in technical specifications) from measurement to measurement indicates that the relay will be unstable in further operation. Those factors play a great role in identifying potentially undependable relays. As an example, tables 1 and 2 show the parameters of two faulty relays of REK60 and RPS45 types. Actuation levels (sensitivity) were measured 10 times, while circuit resistance of contacts was measured 30 times.

As control results show (Tables 1, 2), excessive circuit resistance values of NC and NO contacts Rc (100 mOhm is normal) were identified at the third, fifth and from the nineteenth to twenty-third, while pick-up voltages Upu1 and Upu2 (14,5 V is normal) at the fifth and

Table 1. Results of REK60 relay contacts resistance measurements

Contacts' resistance, mOhm				
No. of test	NZ 1	NP 1	NZ 2	NP 2
1	50	82	53	56
2	68	58	51	55
3	101	62	52	55
4	67	53	52	55
5	54	601	51	55
6	52	71	52	55
7	93	93	53	55
8	60	53	52	55
9	51	54	51	55
10	52	53	52	55
11	50	53	52	55
12	51	53	52	55
13	51	53	53	55
14	50	53	53	55
15	51	53	53	55
16	50	53	52	55
17	51	53	53	55
18	51	53	52	55
19	51	85	53	55
20	234	173	52	55
21	54	649	53	55
22	138	93	53	55
23	140	55	53	55
24	53	59	53	55
25	53	53	52	55
26	51	53	52	55
27	50	53	53	55
28	51	55	52	55
29	53	58	53	55
30	52	62	53	55
31				

nineteenth measurements respectively. With a single measurement of the parameters those defects could not be uncovered, and the relays identified as fit would have made it to the consumers. The acceptance test [7] would not identify anything either if performed once. In fact, excessive pick-up voltage and circuit resistance of contacts indicates that in some switching actions the relay did not perform its functions (did not comply with the technical specifications).

As it is well known there are two main approaches to identifying the condition of a system (in this case a relay): deterministic and probabilistic ones [8, 9].

Paper [10] covers discriminant analysis methods that can be attributed to the deterministic approach to classification and choice of the most informative parameters. As the diagnostic indicators the authors use eight time parameters of relays obtained by manual oscillographic method. The main disadvantage of the method is the limited range of covered indicators for classification. The authors, in particular, did not use electric parameters of relays. Diagnostic procedures based on this range of measured parameters with single measurement can result (as shown above) in as significant reduction of classification accuracy. The values of time parameters within normal limits do not guarantee normal values of electrical parameters. For example, REK60 and RPS45 mentioned above have normal time parameters. One of the possible ways to improve the quality and accuracy of diagnostics based on this method is the extension of the list of covered indicators and automation of the measurement of electric and time parameters of relays.

It should be also noted that in order to obtain the time parameters the authors used the labor intensive manual oscillographic method that practically does not allow for multiple measurements. Although back then that method of obtaining the values of parameters was completely justified.

Over the last few years the equipment used in the diagnostics and quality control of low-current electromagnetic relays has experienced significant changes. In particular, a number of automated installations have been developed for the purpose of measuring electrical and time parameters of relays using computer technology and enabling multiple measurements of electric and time parameters of relays with subsequent statistical processing.

This article explores the possibilities of using the statistical probabilistic method in identifying the technical condition of relays. The authors consider various methods, devices and software for identification of the technical condition and classification of relays by values of electric and time parameters, as well as their evolution over multiple measurements using information theory methods.

Relays dependability classification and evaluation of informative value of indicators has been performed based on a priori statistics of diagnostics with calculation of diagnostic weights and diagnostic value of the inspection.

The most reliable information regarding switching longevity of low-current electromagnetic relays is provided by wear tests. In order to define a relay's lifespan it is required to identify a range of properties that describe its technical condition in the best possible way.

Electric and time parameters of relays are used as diagnostic indicators. A diagnosis is the number of fault-free switching actions performed in a certain electrical mode.

It should be noted that the generation of the diagnostic matrix, identification of the most informative parameters and classification of relays by diagnostic weights must be performed individually for each type of relay depending on its operating mode.

In the given example the diagnostic weight of the RES47 relay indicators is identified. The set of diagnostic indicators K_{js} includes 12 relay parameters defined before the wear tests.

The experiment featured 96 RES47 relays with a set of electric and time parameters (indicators). During the wear tests with active load on contacts (36 V, 3 A, direct current) the follow-

Table 2. Results of RPS45 relay pick-up voltage measurements

Sensitivity checkup						
No. of test	Upu1 V	Upu2 V		No. of test	Upu1 V	Upu2 V
1	11,77	11,53		6	13,78	11,54
2	12,83	11,52		7	14,16	11,54
3	13,4	11,53		8	14,35	11,45
4	13,3	11,52		9	15,34	11,56
5	14,75	11,55		10	14,17	11,54

ing diagnoses were made (categories of technical conditions) based on the numbers of fault-free switching actions:

- S1, up to 7 thousand;
- S2, from 7 to 15 thousand;
- S3, from 15 to 23 thousand;
- S4, above 23 thousand.

As per [9], the formula for diagnostic weight evaluation is as follows:

$$Z_{S_i}(K_{js}) = \log\frac{P(K_{js}/S_i)}{P(K_{js})}, \qquad (1)$$

where $P(K_{js}/S_i)$ is the probability of the interval S of indicator K_j for a system components with condition S_i; $P(K_{js})$ is the probability of simultaneous occurrence of each interval of each indicator in each condition considered. The value $P(K_{js})$ is calculated using the following formula:

$$P(K_{js}) = \sum_{i=1}^{n} P(S_i)P(K_{js}/S_i), \qquad (2)$$

where $P(S_i)$ is the a priori probability of a condition.

By plugging formula (2) into formula (1) we get formula (3)

$$Z_{S_i}(K_{js}) = \log\frac{P(K_{js}/S_i)}{\sum_{i=1}^{n} P(S_i)P(K_{js}/S_i)}. \qquad (3)$$

In order to calculate values $Z_{S_i}(K_{js})$ the diagnostic matrix was generated as shown in Table 3.

The results of diagnostic weights calculation $Z_{S_i}(K_{js})$ according to formula (3) and probabilities of simultaneous occurrence of each interval of each indicator in each considered condition $P(K_{js})$ defined using formula (2) are given in Table 4.

As the table shows, the diagnostic weight $Z_{S_i}(K_{js})$ can be either positive or negative. A negative diagnostic weight means the negation of the diagnosis. For example, $Z_{S_3}(K_{13}) = -0{,}38$ means the negation of diagnosis S_3 for the third interval of the first indicator. Thus are identified the intervals and characteristics that are the most valuable for uncovering defects and undependable relays.

Table 3

No	Diagnostic indicators	K_{js}	Indicator intervals	$P(K_{js})$	S_1	S_2	S_3	S_4
					$P(S_1) = 0,19$	$P(S_2) = 0,28$	$P(S_3) = 0,39$	$P(S_4) = 0,14$
					$P(K_{js}/S_1)$	$P(K_{js}/S_2)$	$P(K_{js}/S_3)$	$P(K_{js}/S_4)$
1	Pick-up voltage *Upu, V*	K_{11}	6,8-7,5	$P(K_{11})$	0,12	0,16	0,26	0,38
		K_{12}	7,5-8,4	$P(K_{12})$	0,82	0,82	0,73	0,61
		K_{13}	8,4-9,4	$P(K_{13})$	0,06	0,02	0,01	0,01
2	Return voltagea *Ureturn, V*	K_{21}	2,5-3,1	$P(K_{21})$	0,05	0,16	0,17	0,24
		K_{22}	3,1-3,9	$P(K_{22})$	0,93	0,72	0,71	0,6
		K_{23}	>3,9	$P(K_{23})$	0,02	0,12	0,12	0,16
3	Resistance of contact circuits, *Rc, mOhm*	K_{31}	13-36	$P(K_{31})$	0,9	0,96	1.0	1,0
		K_{32}	36-960	$P(K_{32})$	0,1	0,04	-	-
4	Action time, *tact, ms*	K_{41}	1,3-1,9	$P(K_{41})$	0.73	0,76	0,86	0,84
		K_{42}	>1,9	$P(K_{42})$	0,27	0,24	0,14	0,16
5	Return time, *treturn, ms*	K_{51}	0,9-1,2	$P(K_{51})$	0,81	0,73	0,71	0.69
		K_{52}	1,2-1,8	$P(K_{52})$	0,19	0,27	0,29	0,31
6	Flyover time, *tfly, ms*	K_{61}	0,08-0,18	$P(K_{61})$	0.54	0.63	0,9	0,89
		K_{62}	0,18-0,8	$P(K_{62})$	0,46	0,37	0,1	0,11
7	Bounce time, *tb, ms*	K_{71}	0,01-0,1	$P(K_{71})$	0,02	0,07	0,24	0,22
		K_{72}	0,1-0,3	$P(K_{72})$	0,06	0,09	0,38	0,43
		K_{73}	0,3-0,7	$P(K_{73})$	0,08	0,16	0,26	0,24
		K_{74}	0,7-1,4	$P(K_{74})$	0,84	0,68	0,12	0,11
8	Deviation of pick-up voltages from minimal values, ДUpu, V	K_{81}	0,1-0,3	$P(K_{81})$	0,56	0,48	0,51	0,43
		K_{82}	0,3-0,6	$P(K_{82})$	0,44	0,52	0,49	0,57
9	Deviation of return voltages from minimal values, *ДUreturn, V*	K_{91}	0,01-0,1	$P(K_{91})$	0,24	0,48	0,65	0,73
		K_{92}	0,1-0,25	$P(K_{92})$	0,76	0,52	0,35	0,27
10	Deviation of contact circuit resistance from minimal value, *ДRc, mOhm*	K_{101}	1-10	$P(K_{101})$	0,03	0,08	0,31	0,17
		K_{102}	11-20	$P(K_{102})$	0,09	0,24	0,58	0,69
		K_{103}	20-949	$P(K_{103})$	0,88	0,68	0,11	0,14
11	Follow time, *tfol, ms*	K_{111}	0,03-0,12	$P(K_{111})$	0,86	0,75	0,38	0,16
		K_{112}	0,12-0,3	$P(K_{112})$	0,14	0,25	0,62	0,84
12	Armature start time, *tstart, ms*	K_{121}	0.67-0,9	$P(K_{121})$	0,72	0,78	0,84	0,83
		K_{122}	0,9-1,5	$P(K_{122})$	0,28	0,22	0,16	0,17

Table 4

№	Diagnostic indicators	K_{js}	Indicator intervals	$P(K_{js})$	S_1	S_2	S_3	S_4
					Z_{S1}	Z_{S2}	Z_{S3}	Z_{S4}
1	Pick-up voltage *Upu, V*	K_{11}	6,8-7,5	0,222	-0,653	-0,142	0,068	0,233
		K_{12}	7.5-8,4	0,756	0,035	0,355	-0,015	0,093
		K_{13}	8,4-9,4	0,022	0,429	-0,047	-0,348	-0,348
2	Return voltagea *Ureturn, V*	K_{21}	2,5-3,1	0,153	-0,485	0,019	0,046	0,196
		K_{22}	3,1-3,9	0,747	0,113	-0,015	-0,022	-0,095
		K_{23}	>3,9	0,101	-0,705	0,051	0,051	0,176
3	Resistance of contact circuits, *Rc, mOhm*	K_{31}	13-36	0,969	-0,032	-0,004	0.013	0,013
		K_{32}	36-960	0,031	0,519	0,122	-	-
4	Action time, *tact, ms*	K_{41}	1,3-1,9	0,804	-0.042	-0,024	0,028	0,018
		K_{42}	>1,9	0,196	0,140	0,089	-0,14	-0,08
5	Return time, *treturn, ms*	K_{51}	0,9-1,2	0,732	0,044	-0,001	-0,03	-0.025
		K_{52}	1,2-1,8	0,268	-0,149	0,003	0,073	0,102
6	Flyover time, *tfly, ms*	K_{61}	0,08-0,18	0,755	-0.145	-0.078	0,076	0,071
		K_{62}	0,18-0,8	0,245	0,272	0,178	0,407	-0,348
7	Bounce time, *tb, ms*	K_{71}	0,02-0,1	0,148	-0,86	-0,32	0,21	0,172
		K_{72}	0,1-0,3	0,245	-0,611	-0,43	0,19	0,244
		K_{73}	0,3-0,7	0,195	-0,386	-0,085	0,125	0,09
		K_{74}	0,7-1,4	0,412	0,309	0,217	-0,53	-0,575
8	Deviation of pick-up voltages from minimal values, ДUpu, V	K_{81}	0,1-0,3	0,499	0,05	-0,017	0,0173	0,065
		K_{82}	0,3-0,6	0,501	-0,055	0,017	-0,008	0,056
9	Deviation of return voltages from minimal values, Д*Ureturn, V*	K_{91}	0,01-0,1	0,535	-0,348	-0,012	0,088	0,134
		K_{92}	0,1-0,25	0,465	-0,214	0,014	-0,02	-0,235
10	Deviation of contact circuit resistance from minimal value, Д*Rc, mOhm*	K_{101}	1-10	0,173	-0,757	-0,33	0,253	-0,007
		K_{102}	11-20	0,407	-0,655	-0,229	0,153	0,229
		K_{103}	20-949	0,420	0,321	0,209	-0,58	-0,477
11	Follow time, *tfol, ms*	K_{111}	0,03-0,12	0,544	0,198	0,139	-0,155	-0,531
		K_{112}	0,12-0,3	0,456	-0,512	-0,26	0,133	0,265
12	Armature start time, *tstart, ms*	K_{121}	0.67-0,9	0,79	0,04	-0,005	0,027	0,026
		K_{122}	0,9-1,5	0,21	0,125	0,02	-0,118	-0,041

According to [9], the concept of diagnostic weight of realization of each particular indicator is applicable only to the given diagnosis as its confirmation or negation, which does not yet indicate the diagnostic value of studies based on that indicator. The diagnostic value of studies according to indicator K_j for diagnosis S_i that is characterized by the amount of information introduced by all realizations of indicator K_j in the establishment of diagnosis S_i (4)

$$Z_{S_i}(K_j) = \sum_{s=1}^{m} Z_{S_i}(K_{js}) P(K_{js} / S_i)$$

$$Z_{S_i}(K_j) = \sum_{s=1}^{m} P(K_{js} / S_i) \log \frac{P(K_{js} / S_i)}{\sum_{i=1}^{n} P(S_i) P(K_{js} / S_i)}, \quad (4)$$

where m is the resolution of the indicator.

$Z_{S_i}(K_j)$ is a specific diagnostic value of study based on indicator K_j, because it refers to a single specific condition.

The overall diagnostic value of study [6] or the amount of information introduced by the study in the system of diagnoses is calculated according to formula (5):

$$Z_s(K_j) = \sum_{i=1}^{n} Z_{S_i}(K_{js}) P(S_i). \quad (5)$$

In other words, that is the average value of information introduced by the study for the purpose of establishing the a-priori unknown diagnosis. The specific and general diagnostic values of study of an experimental batch of relays are given in Table 5

Based on general and specific diagnostic values of a study the conclusion can be made that the most informative indicators for the considered case are *tb, ΔRc and tfol.*

It should be noted that values $Z_{S_i}(K_j)$ can be used to identify the diagnostic value of the study depending on the number of intervals.

Now when realizations of a complex of indicators are known, relays can be classified using the Bayesian approach K_{compl} [9]. For the considered case let us take a relay to be classified that has the following values of the most informative parameters (set of indicators):

tb = 0,26 ms; ΔRc= 19 mOhm; tfol =0,06 ms.

The probability of occurrence of the set of indicators $K_{compl} = (K_{72}, K_{122}, K_{132})$ given the presence of diagnosis S_i is calculated using formula 6) [9].

Table 5

№	Indications	$Z_{S_1}(K_j)$	$Z_{S_2}(K_j)$	$Z_{S_3}(K_j)$	$Z_{S_4}(K_j)$	$Z_{S_5}(K_j)$
1	Pick-up voltage,*Upu*	0,023	0,222	0,0033	0,036	0,072
2	Return voltage,*Ureturn*	0,071	0,0012	0,0015	0,018	0,019
3	Resistance of contact circuits, *Rc,*	0,023	0,00065	0,013	0,013	0,011
4	Action time, *tact*	0,023	0,00312	0,0045	0,023	0,01
5	Return time, *treturn*	0,0075	0,00005	0,012	0,014	0,02
6	Flyover time, *tfly*	0,047	0,017	0,011	0,024	0,059
7	Bounce time, *tb*	0,259	0,076	0,22	0,101	0,166
8	Deviation of pick-up voltages from minimal values, Д*Upu*	0,004	0,00077	0,005	0,06	0,035
9	Deviation of drop-off voltages from minimal values, Δ*Ureturn*	0,099	0.0029	0,005	0,034	0,005
10	Deviation of contact circuit resistance from minimal value, Д*Rc*	0,2	0,068	0,103	0,09	0,107
11	Follow time, *tfol*	0,098	0,039	0,141	0,138	0,103
12	Armature start time, *tstart*	0,064	0,00011	0,003	0,01	0,014

$$P(K_{compl}/S_i) = \\ = P(K_{compl1}/S_i)P(K_{compl2}/S_i).....P(K_{complN}/S_i). \quad (6)$$

Then the generalized Bayesian formula is as (7)

$$P(S_i/K_{compl}) = \frac{P(S_i)P(K_{compl}/S_i)}{\sum_{s=1}^{n} P(S_i)P(K_{compl}/S_i)}, \quad (7)$$

For the considered case formula (6) is as:

$$P(K_{compl}/S_i) = P(K_{72}/S_i)P(K_{122}/S_i)P(K_{132}/S_i)$$

By inserting the numerical values we will find the probability of set of indicators occurring for each diagnosis

$P(K_{compl}/S_1)$ = 0,06·0,09·0,14= 0,00076,
$P(K_{compl}/S_2)$ = 0,09·0,24·0,25= 0,0054,
$P(K_{compl}/S_3)$ = 0,38·0,58·0,62= 0,137,
$P(K_{compl}/S_4)$ = 0,43·0,69·0,84= 0,249.

As the result of calculation using the generalized Bayesian formula (6) we deduce the following values of a-posteriori probabilities of the four considered conditions $P(S_1/K_{compl})$ = 0,00159; $P(S_2/K_{compl})$ = 0,0168; $P(S_3/K_{compl})$ = 0,594; $P(S_4/K_{compl})$ = 0,387.

The maximum value of entropy (initial) of the a-priori entropy of the diagnoses can be calculated according to formula 8).

$$H(S) = -\sum_{i=1}^{n} P(S_i)\log P(S_i), \quad (8)$$

Then it is not difficult to calculate that for this case

$H(S)$ = –((0,19)×(–0,721)+0,28×(–0,552)+0,39××(–0,408)+0,14×(–0,853) = 0,137+0,154+0,159+0,149=0,569.

After the realization of the set of indicators the entropy of such element will be as follows:

$$H(S/K) = -\sum_{i=1}^{n} P(S_i/K_i)\log P(S_i/K_{compl}).$$

$$H(S/K) = -(0{,}00159\cdot\log 0{,}00159 + 0{,}0168\cdot\log 0{,}0168 + \\ +0{,}594\cdot\log 0{,}594 + 0{,}387\cdot\log 0{,}387 = 0{,}00444 + 0{,}03 + \\ +0{,}1343 + 0{,}16 = 0{,}328$$

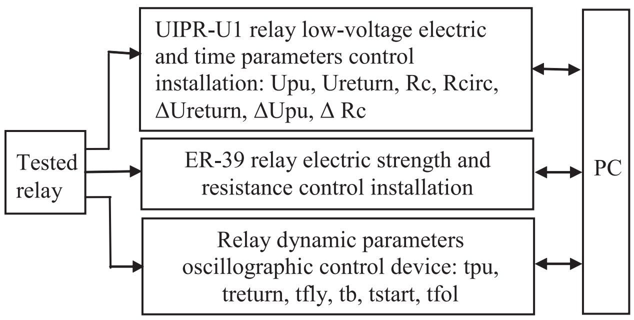

Fig. 1. Architecture of relay electric and time parameters identification system

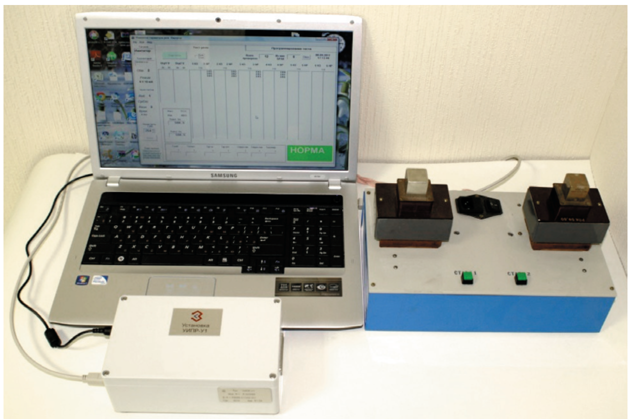

Fig. 2. UIPR-U1 relay low-voltage parameters control installation

The degree of uncertainty or residual entropy will amount to 0,569-0,328=0,241. Thus, we can conclude that the system is quite determined and the relay must be included in the third category of technical condition .

The measurement of electric and time parameters determined through relay diagnostics is performed using purpose-designed monitoring and measuring devices (fig.1): UIPR-U1 and ER-40 installations and the automated device for relay dynamic characteristics control depicted in fig. 2 – 4[11].

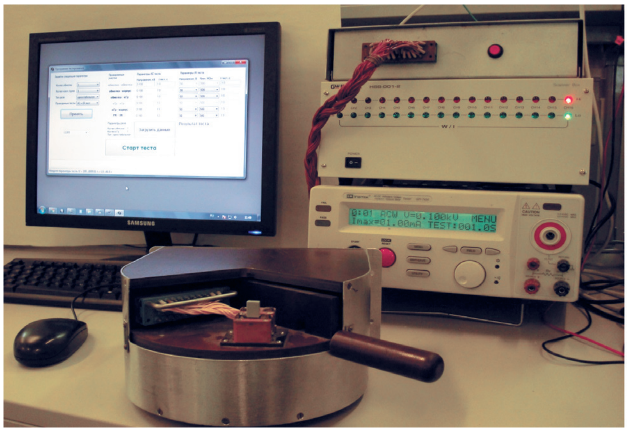

Fig. 3. ER-40 relay high-voltage parameters control installation

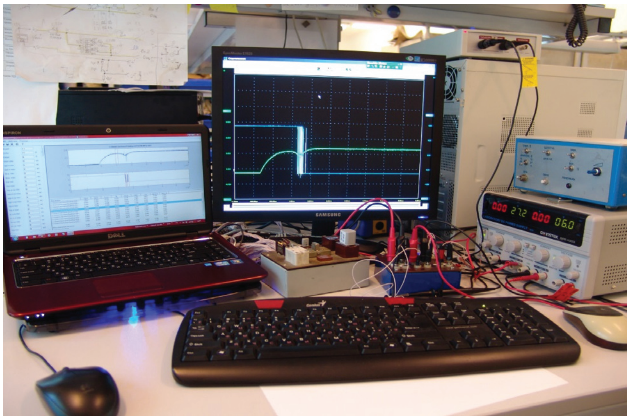

Fig. 4. Automatic oscillographic relay time parameters control device

It should be noted that the above installations are automated and have a PC interface. Their operating principle is a topic apart that is beyond the subject area of this article.

Software has been developed for relay classification and selection of the most informative parameters. Fig. 5 shows the relay classification window.

There are three logical parts: classification coefficients, calculation data and summary table with relay parameters and control results.

The software downloads and displays in the window the classification algorithm data obtained as the result of training, then fills it with measured parameter values. The program also performs calculations for relay classification and saves the results in an Excel file. It is possible to modify the list of parameters used in the classification operation (fig. 6).

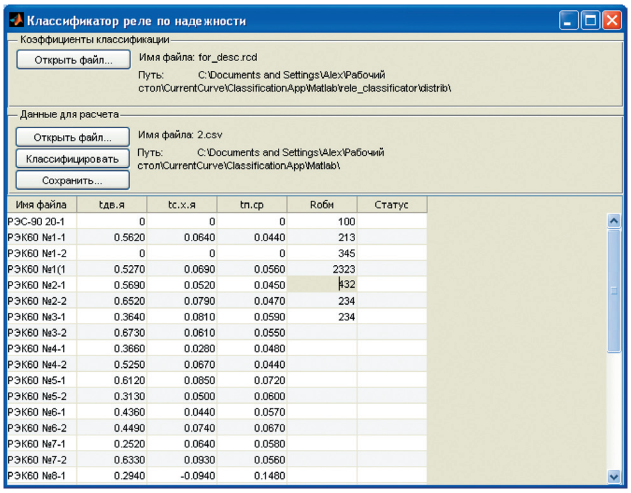

Fig. 5. Classification window

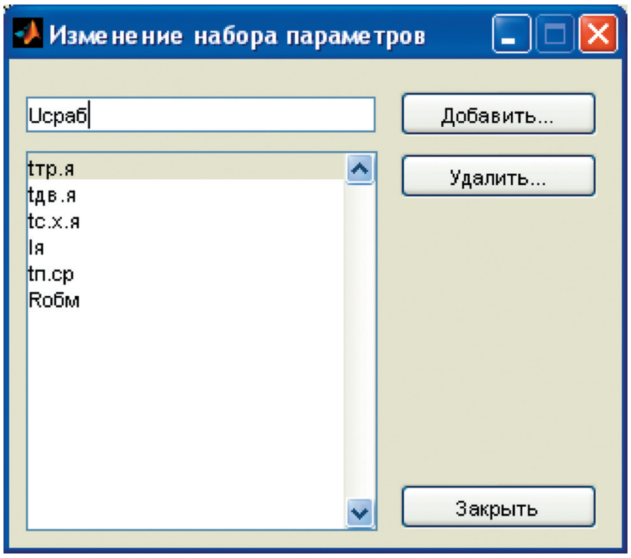

Fig. 6. Parameters list modification window

In this window the list of relay parameters for calculation can be modified, highlighted parameters can be deleted and new ones added. The parameters table in the classification window will change according to the new list.

In order to establish the diagnosis, RES47 relays were classified based on the most informative parameters with subsequent durability testing. The errors (first type), misclassifications of fit relays amounted to and the errors (second type) did not exceed 4%.

The experimental studies have shown that the use of automated installations and control devices allows classifying relays with the required level of accuracy, as well as reduces the overall labor intensiveness of control operations and relay diagnostics. It should also be noted that this equipment can be used for classification of relays by electrical and time parameters using either the probabilistic or deterministic approach to relay technical condition identification.

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