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ADEQUACY OF THE METHODS USED TO APPROXIMATE THE VOLT-AMPERE CHARACTERISTICS OF DC ELECTRIC-ARC PLASMA GENERATORS

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The adequacy of power approximation of volt-ampere characteristics of a dc electric-arc generator is estimated. Using Fisher's ratio for the variances of the inadequacy and random error, it is shown that this approximation is acceptable. It is also shown that the power source has a slight effect on the characteristics of the arc.

At present, approximation of experimental data both in the form of simple empirical relations and with the use of generalized variables obtained by approximate similarity methods is widely used. However, in all cases a question arises about the adequacy of the approximation method chosen with a particular choice of independent variables. Power approximation is most suitable because it is very simple for processing of experimental data. It admits the use of linear regression to find the coefficient and exponents by the least-squares technique. To do this, it is only necessary to take the logarithm of the power expression. Estimation from the ratio of variances of regression and the standard deviation is the simplest one. Comparison of the calculated Fisher number with the tabulated one indicates whether the approximation used is adequate [1].

This method of adequacy estimation is convenient in that it can be applied to any set of experimental data. However, this method does not distinguish between a spread of points due to random factors and a spread due to inadequacy of the approximation expression itself. Therefore, to estimate the adequacy of the approximation used special experiments with recurrence of experimental points should be carried out. From these recurrences the error caused by random factors is calculated and the difference between the sum of the mean-square deviations from the regression and the sum of mean-square random deviations is attributed to the inadequacy of the approximation used. The approximation is adequate to the real relationship if the spread due to the inadequacy is within random deviations, which is estimated by the ratio of the corresponding variances.

The necessity of conducting special experiments with recurrence of experimental points makes the experimentation more complicated and, consequently, this more regorous estimation of the adequacy becomes inconvenient. In literature there are no reports of work, in which this approach was used to study the characteristics of electric-arc plasma generators. In order to fill this gap and to estimate the possibility of using simple power approximations for these purposes, special experiments were carried out, some results of which are considered in this work.

The studies were carried out on a dc plasma generator with a zirconium rod cathode and copper sleeve anode cooled by water from the outside. The inner diameter of the anode was 9.2 mm. The air flow rate was 1.27, 1.64, 2.05, 2.45, 2.57, 2.94, 3.83, and 4.27 g/sec. The current was varied in the range of 38-146 A. The power source provided stepwise stabilization of the current. Six steps were used in the experiments.

The experiments showed that voltage depends slightly on current (Fig. 1) and rather strongly on the air flow rate. It can be seen that as the air flow rate rises, the voltage increases and the region of the stable operation

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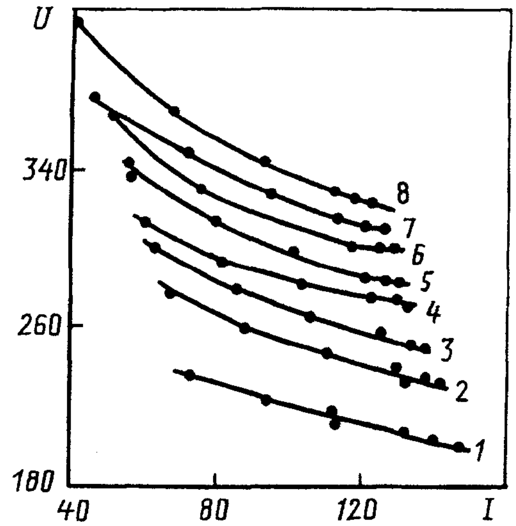

Fig. 1. Voltage across the arc of a plasma generator with a rod cathode versus current: 1) $G = 1.27$ g/sec; 2) 1.64; 3) 2.05; 4) 2.45; 5) 2.57; 6) 2.94; 7) 3.83; 8) 4.27 g/sec. U, V; I, C.

is shifted towards lower currents. Each experimental point was determined six times, although the required current could not be found in all cases. Therefore, the total number of points increased slightly in the presence of a smaller number of recurrences at some of them. At each flow rate, a power approximation of the form $U = AI^{\alpha}$ was used to describe the volt-ampere characteristics (VAC), and the expression $U = AI^{\alpha}G^{\beta}$ was used to describe the entire set of data. It is clear that in the latter case the inadequacy increases not only because of the choice of approximation expression but also due to a change in the slope of the VAC with the air flow rate.

The standard deviations caused by random factors were calculated as the sum of the squared deviations in every experiment due to repetitions. Then, the sum of the random mean square deviations was calculated by summation over all different points. The number of the degrees of freedom of the random deviations was determined in a similar way. (At each point it is equal to $n_i - 1$.) The sum of the squared deviations from the regression due to inadequacy was determined as the difference between the sum of the squared deviations and the corresponding sum of the squared random error. These calculations were carried out both for every air flow rate and for the entire set of data. The number of degrees of freedom of inadequacy was calculated similarly. In this case a number of degrees of freedom of the regression equal to the number of independent arguments was considered.

Table 1 contains data on the estimation of the exponential approximation. The ratio of variances of inadequacy and random deviations is small. In most cases for particular flow rates it is lower than the tabulated values. This indicates that the inadequacy is within the spread of the random error. This approximation can be considered perfect. In other cases, including the correlation of the form $U = AI^{\alpha}G^{\beta}$, the Fisher criterion of inadequacy exceeds only slightly the tabulated values and is a small fraction of the Fisher number for regression. Therefore, such approximations can be considered acceptable.

Changes in current can noticeably affect the VAC parameters of the arc discharge. At weak currents, they descend due to a sharp increase in the electric arc channel with temperature, while for heavy-current arcs these characteristics depend substantially on the conditions of discharge stabilization. In the case of good stabilization of the dimensions of the arc column, the VAC ascends as the current increases, unstabilized arcs have flat characteristics parallel to the axis of the currents. Plasma generators with stabilized blown arcs are used most often. Their VACs can contain descending and flat sections. Generalization of these characteristics by a single curve can give rise to noticeable deviations of real voltages in the regions of weak and heavy currents. However, the regions of stable arc combustion are usually confined to the region of slightly descending VACs, which are approximated by a single curve quite well.

The external parameters of the electric circuit have no marked effect on the VAC of the arc discharge, so this problem is not investigated thoroughly, although ordinary experimental data may give some relevant

TABLE 1. Analysis of the Adequacy of Power Approximations to Real Relations for Plasma Generators with a Rod Cathode and Longitudinal Vortex Air Flow Around the Arc

Air flow rate G, g/sec	Sum of squared deviations from the regression, $SS \cdot 10^3$	Number of degrees of freedom of total deviation from regression n	Sum of squared deviations caused by random factors $SS_{rn} \cdot 10^3$	Number of degrees of freedom of random factors n_{rn}	Sum of squared deviations of inadequacy $SS_{ia} \cdot 10^3$	Number of degrees of freedom of inadequacy n_{ia}	Variance of total deviation $S^2 \cdot 10^5$	Variance of random deviations $S^2_{rn} \cdot 10^5$	Variance of inadequacy $S^2_{ia} \cdot 10^5$	Fisher number of inadequacy F_{ia}	Tabulated values of Fisher numbers F_{tb}, %		Fisher number for regression F_r;	Ratio of Fisher numbers $(F_{ia}/F_r) \times 100\%$
											5	1		
4,27	1,334	34	0,145	21	1,190	13	3,925	0,688	9,155	13,3	2,23	3,12	1018	7,30
3,83	1,161	34	0,335	24	0,827	10	3,416	1,395	8,267	5,93	2,26	3,17	981	0,60
2,94	0,447	34	0,304	25	0,143	9	1,314	1,215	1,589	1,31	2,28	3,21	1579	0,08
2,57	1,413	34	0,176	25	1,314	9	4,210	0,471	14,60	31,0	2,28	3,21	709	4,40
2,45	0,333	34	0,206	26	0,128	8	0,980	0,791	1,594	2,01	2,32	3,29	1958	0,10
2,05	0,809	34	0,509	25	0,300	9	2,379	2,037	3,330	1,63	2,28	3,21	1046	0,16
1,64	0,796	34	0,472	22	0,324	12	2,341	2,144	3,600	1,68	2,23	3,12	1114	0,15
1,27	1,047	34	0,628	24	0,419	10	3,078	2,616	4,189	1,60	2,26	3,17	738	0,22
All G	937,8	286	2,774	192	935,0	94	327,9	1,445	994,7	688	1,32	1,48	167	412
All I	234,7	286	2,774	192	231,9	94	82,05	1,445	24,67	171	1,32	1,48	1552	11
All I, G	21,20	285	2,774	192	18,43	93	7,440	1,445	19,82	13,7	1,32	1,48	9829	0,01

TABLE 2. Estimation of the Possibility of Generalizing VAC by a Single Function over the Entire Current Range

Regression parameters	Parameter value
Sum of squared deviations for single VAC	0.02120411
Number of degrees of freedom for single VAC	285
Sum of squared deviations for all steps in correlation of VAC for each of them	0.01941057
Total number of degrees of freedom in correlation of VAC for each step	270
Total variance in correlation of individual steps	$7.189 \cdot 10^{-5}$
Sum of squared deviations due to separation of VAC of individual steps	0.0017935
Number of degrees of freedom of separation	15
Variance of separation of individual VAC	$1.176 \cdot 10^{-4}$
Fisher number for separation F_{ia}	1.66
Tabulated values of Fisher number (5%/1%)	1.72/2.14
Fisher number of regression F_p	9829
Ratio of numbers F_{ia}/F_r, %	0.02

information. If the total VAC is divided into individual sections with a narrower range of currents and approximated by separate curves for each section, then using the Fisher criterion for separation of individual curves, it is possible to estimate the validity of the method of generalizing the entire characteristic by a single curve. However, since the current is controlled by changing the parameters of the external circuit, this estimate can also reflect their effect. Such estimates are given in Table 2.

As can be seen from Table 2, the separation of the VAC of individual steps of current stabilization is within the spread of experimental points of the single curve. Therefore, generalization of the VAC of a plasma generator by a single expression over the whole current range is suitable for the plasma generator considered. It is evident that changes in the parameters of the external circuit have no noticeable effect on the characteristics of the plasma generator in controlling the current.

Thus, from the present analysis it can be concluded that the power approximation is quite suitable for description of the descending branch of the VAC of dc electric arc plasma generators. So, without complicating experiments, the adequacy can be checked from the ratio of the variances of regression and the total deviation. The power source was not found to have a noticeable effect on the characteristics of the arc.

NOTATION

A, constant; G, gas flow rate through the discharge channel of the plasma generator; I, current; u, voltage across the arc; F, Fisher's ratio for variances.

REFERENCE

1. N. R. Draper and H. Smith, Applied Regression Analysis, New York, London, Sydney (1966).