Model of residual resource of automotive alternators

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Abstract. The urgency of the problem under study is caused by the imperfection of methods for diagnosing automotive alternators, which do not reveal hidden defects, as a result of which the alternator failure is sudden and entails costs due to vehicle downtime in repair. The aim of the study is a method for predicting the residual life of automotive alternators, built on the results of diagnosing and assessing the operating conditions of a car, for the first time considering the magnitude of the fluctuation of the output voltage. Analytical expressions describe the dependence of the intensity of an alternator resource on the ambient temperature and operating time, considering its technical condition at the time of diagnosis and the degree of its change under the influence of factors operating conditions on the test run. The theoretical results were confirmed by experimental measurements. The presented results can be used for the full implementation of the life of automotive alternators in the conditions of road transport enterprises.

1. Introduction
In the field of machine diagnostics, prediction is used to predict changes in the parameters of the technical state of mates, assembly units and aggregates - the wear of parts and mates in the future.

The residual life is understood as the duration of operation (operating time) of the coupling, assembly unit or unit after diagnosis to their limit state, characterized by limiting wear, reduced quality of work, machine economy or safety requirements. In other words, the residual resource is the mileage (time) of the diagnosed coupling, assembly unit, and unit until the moment when their state parameters are reached.

At the same time, changes in the parameters, random for one object, are of a stable statistical nature for a group of objects. Moreover, there is a clear tendency towards monotony and smoothness, which is one of the decisive prerequisites for forecasting. Forecasting is possible if, in a random process characterizing a change in a parameter, a trend can be identified, that is, the principle basis for forecasting is the assumption of the existence of uniform patterns determining wear or aging.

When forecasting, in most cases it is impossible to measure the time of trouble-free operation, therefore it is important to determine the diagnostic parameter, i.e., such a value that adequately reflects the development of the diagnostic object's resource or the appearance of a defect leading to loss of its working capacity.

It is technically difficult to estimate the parameters of each element entering the object because of their large number, so they try to choose the minimum (in the limit - one) diagnostic parameters that provide the required accuracy of predicting the change in the state of the object [1-4, 7, 10, 11, 13-15].

As a result of the conducted analytical studies, it was established that for automotive alternators such a diagnostic parameter was the magnitude of the output voltage ripple [5, 6].
It is possible to perform a reliable prediction only when the conditions are known in which the object will be used. In this case, the terms are understood as: modes of use, the nature of the load, external factors (temperature, humidity, etc.) [8].

When predicting the residual life of an automotive alternator, let us consider it as a system (Figure 1). In this case, all the variables characterizing the system, are divide by:

– input parameters: X1, X2, ..., Xn, characterizing the external conditions (road, weather and climatic conditions, volumes and methods of maintenance;
– internal state variables: W1, W2, ..., Wn, characterizing the properties of the system (load current, winding temperature, vibration level, etc.);
– output variables: Y1, Y2, ..., Yn, which characterize the response to external influences (the magnitude and magnitude of the output voltage ripple, noise level, etc.).

![Figure 1. Automotive alternator as a system.](image)

2. Development of model of residual resource

Analytical studies aimed at establishing the relationship of structural and diagnostic parameters made it possible to establish that the magnitude of the output voltage ripple magnitude is determined by the electrical resistance of the stator winding, semiconductor diodes and the rotor winding of automobile alternators [5, 8, 9].

The resource of the alternator is due to the electrical resistances of its elements, the change of which is determined by the temperature $t$, operating time $L$, technological $FT$ and operational $FE$ factors [12]:

$$U_s = f(t, L, FT, FE),$$

where $U_s$ is the intensity of the resource change.

Upon receipt of the analytical dependence of the intensity of changes in the resource of the automotive alternator from the factors of operating conditions, we proceed from the following position:

$$\bar{U_s} = 1/(S_{lim} - S_{cur}),$$

where $S_{lim}$ is the limiting value of the diagnostic parameter, $V$; $S_{cur}$ - the current value of the diagnostic parameter, $V$; $\bar{U_s}$ – the average value of the intensity of change of the resource, %.

Thus, in its meaning, $\bar{U_s}$ is a generalized indicator of the intensity of change in the electrical resistance of the elements of an automotive alternator.

The analytical expression for determining the residual life of an automotive alternator on the $i$-th failure prevention pitch makes sense when the following condition is met - the current value of the diagnostic parameter $S_{cur}$ in the monitoring period should not exceed its limit value $S_{lim}$, that is:

$$S_{cur}(l_{i+1}) \leq S_{lim}(l_{i+1}).$$

The functional dependence of the intensity of the resource change on the ambient temperature and operating time, based on an analysis of previously completed studies, can be represented by the following equations:

$$U_s = \beta_1 + \beta_2 \cdot t_B - \beta_3 \cdot t_B^2,$$

$$U_s = \gamma_1 + \gamma_2 \cdot L,$$

where $\gamma_1, \gamma_2 = f(L)$; $\beta_1, \beta_2, \beta_3 = f(t)$ – relative sensitivity parameters of the intensity of the resource change in the operating time and the ambient air temperature.
Since in real conditions of operation, the ambient air temperature, operating time and other operational factors change independently of each other, it becomes necessary to develop a multifactor mathematical model that considers the cumulative effect of these factors, that is, the analytical dependence of expression (1).

To obtain a multifactor model, it is necessary to find such combinations of values $t$ and $L$ from expressions (4) and (5), at which the values of the intensity of change in the alternator resource will coincide, that is:

$$
\gamma_1 + \gamma_2 \cdot L = \beta_1 + \beta_2 \cdot t - \beta_3 \cdot t^2 .
$$

(6)

To determine the coefficients in expression (6), we find the third derivative of the left side of the equation for $t$. Then we have

$$
\gamma^{'''}_1 + \gamma^{'''}_2 \cdot L = \beta_2 - 2 \cdot \beta_3 \cdot t ,
$$

(7)

$$
\gamma^{''''}_1 + \gamma^{''''}_2 \cdot L = -2 \cdot \beta_3 ,
$$

(8)

$$
\gamma^{'''''}_1 + \gamma^{'''''}_2 \cdot L = 0 .
$$

(9)

From the last identity it follows that:

$$
\gamma^{'''''}_1 = 0 ,
$$

$$
\gamma^{'''''}_2 = 0 .
$$

(10)

Integrating these differential equations, substituting the values of the obtained coefficients into expression (6) and carrying out the transformations, we obtain the expression for the intensity of the change in the resource of the automotive alternator from the ambient temperature and operating time in the following form:

$$
U_s = \lambda_2 + \delta_2 \cdot L + \lambda_4 \cdot t - \lambda_3 \cdot t^2 ,
$$

(11)

where $\lambda_1, \lambda_2, \lambda_3, \delta$ – the coefficients that determine the operating conditions and technological features of the automotive alternator and are not dependent on $t$ and $L$.

Based on the expression (11), we define the extremum point of the function $U_s = f(t)$ for which we find the derivative and equate it to zero. Then we get the following equation:

$$
-2 \cdot \lambda_3 \cdot t - \lambda_4 = 0 .
$$

(12)

Solving equation (12), we get the critical point:

$$
M_0 \left( \frac{-\lambda_4}{2 \lambda_3} \right) , \text{ where } t_{OPT} = \frac{-\lambda_4}{2 \lambda_3} .
$$

(13)

To establish whether the point $M_0$ is an extremum, we determine the sign of the second derivative at the point $M_0$, that is:

$$
U''_s = -2 \cdot \lambda_3 .
$$

(14)

Depending on the sign of the quantity $\lambda_3$ we have $\lambda_3 < 0 \text{ if } M_0 \text{ then it is a minimum point, and } \lambda_3 > 0$. Therefore, $M_0$ is a maximum point.

To determine the coefficients in expression (11), we use the least squares method.

For practical use, instead of estimating $U_s$ by expression (11), it is necessary to use its value on the interval $\bar{U}_s$; for this we use the relations of probability theory:

$$
\bar{x} + \bar{y} = \bar{x} + \bar{y}, \quad \bar{c}x = c \cdot \bar{x}, \quad \bar{\bar{c}} = c, \quad \bar{\bar{c}}^2 = \bar{x}^2 + \sigma_x^2 .
$$

In accordance with these relations, expression (11) has the following form:

$$
\bar{U}_s = \bar{a}_2 \cdot \bar{L} + \bar{a}_4 \cdot \bar{t} + \bar{a}_3 \cdot t^2 - \lambda_3 \cdot \sigma_t^2 .
$$

(15)

For the purpose of further transformation, we write the expression as follows:

$$
\bar{U}_s = (\bar{\bar{a}}_3 \cdot t^2 + \bar{a}_4 \cdot \bar{t} + \bar{a}_3) - \lambda_3 \cdot \sigma_t^2 + \delta_2 \cdot L .
$$

(16)

The expression in parentheses is a square three-member, therefore selecting the full square in the expression in parentheses, denoting the coefficients $a_i$ and considering the resulting value $t_{OPT}$ from expression (13), we finally get:

$$
\bar{U}_s = a_1 + a_2 \cdot [(\bar{t} - t_0)^2 + \sigma_t^2] + a_3 \cdot L ,
$$

(17)

where $\bar{t}, \sigma_t^2$ – respectively, the average value of ambient air temperature and its dispersion for the period under consideration; $t_0$ – optimal ambient temperature, corresponding to the minimum intensity of change in the resource of the automotive alternator; $a_1, a_2, a_3$ – constants of the mathematical model.
Expression (17) is an additive model that establishes the dependence of the intensity of changes in the resource of a car alternator on the ambient temperature, operating time, operational and technological factors.

Since in real conditions there is a change in the factors of operating conditions; therefore, the magnitude of the intensity of the change in the life of the automotive alternator on the interval of interservice mileage also changes.

In this regard, the residual life of the automotive alternator must be adjusted by the adaptation coefficient \( K_a \) which shows how many times the average value of the intensity of the alternator resource change \( (\bar{U}_s) \) for given values of operating conditions factors, the predicted mileage differs from its optimal value \( U_0 \), that is:

\[
K_a = \frac{\bar{U}_s}{U_0}.
\]

From the expression (17) it follows that the more \( \Delta t = \bar{t} - t_{OPT} \), that is, the more \( \bar{t} \) deviates from, \( t_{OPT} \), the greater the magnitude of the intensity of change of the alternator resource. Similarly, the influence of ambient air temperature, characterized by magnitude, also affects \( \sigma_t^2 \). With the increase in operating time, the intensity of the alternator resource change increases linearly. Consequently, the magnitude of the resource change intensity will be minimal with the following values of the factors of operating conditions:

\[
\bar{t} = t_0, \quad \sigma_t^2 = 0, \quad L = 0, \quad \text{consequently,} \quad U_0 = \alpha_s.
\]

Then, the mathematical model of the residual life of automotive alternators in the final form is:

\[
R_s = \frac{[\alpha_t + \alpha_2 (\bar{t} - t_0)^2 + \sigma_2^2 + \alpha_3 L]}{\alpha_s}.
\]

To determine the residual resource in thousands of kilometers we use the expression:

\[
L_{oct} = L_0 \cdot \left( \frac{s_{lim} - s_{cur}}{s_{lim}} \right),
\]

where \( L_0 \) – time between failures, thous. km.

Thus, the constructed mathematical model of the residual life of the automotive alternator considers its individual technical condition at the time of diagnosis and the degree of its change from the factors of operating conditions on the predicted period.

3. Results
As a result of determining the diagnostic parameter - the pulse of the output voltage ripple of 60 alternators of VAZ cars, the optimum temperature was determined, \( t_{OPT} \) that is, at which the rate of change in the resource has a minimum value.

The value of the optimum ambient temperature was:

\[
t_0 = \frac{-\lambda_1}{2\lambda_2} = 4.67^\circ C.
\]

To build a regression model and estimate correlation coefficients, expression (17) is linearized by changing variables:

\[
U_S = a_0 + a_1 \cdot X_1 + a_2 \cdot X_2,
\]

where \( X_1 = (\bar{t} - t_0)^2 + \sigma_2^2 \); \( X_2 = L \).

As a result of the regression analysis, the numerical values of the coefficients of the previously obtained analytically mathematical model were obtained:

\[
\bar{U}_s = 0.062075 + 3.6 \cdot 10^{-6} \left[ (\bar{t}_0 - 4.67)^2 + \sigma_t^2 \right] + 9.44 \cdot 10^{-5} \cdot L. \quad (22)
\]

The resulting regression equation was subjected to statistical research, which included a statistical assessment of the significance of the regression coefficients and checking the resulting equation for adequacy. The significance of the regression coefficients was estimated using Student's t-test and is given in Table 1:

\[
t_{ct}^{EXP} = \frac{|\alpha_k|}{\sigma_{res} \sqrt{\chi^2_{k}}} \geq t_{ct}^{TABL} \left( k = n - m - 1 \right),
\]

(23)
where \( t_{st} \) is the coefficient of significance; \( \sigma_{res} \) – the standard deviation obtained by extracting the square root of the residual variance \( (\sigma_{ost}^2) \); \( C_{ii} \) – diagonal elements of the inverted information matrix; \( \alpha \) – significance level; \( n \) – number of observations; \( m \) – the number of significant coefficients of the model.

The information matrix \( X \) is composed of the coefficients of the system of normal equations:

\[
X = \begin{pmatrix}
a_{11} & a_{12} & a_{13} \\
a_{21} & a_{22} & a_{23} \\
a_{31} & a_{32} & a_{33}
\end{pmatrix}
\]  \( (24) \)

**Table 1.** Statistical estimation of regression coefficients

| The name of the characteristics | Numerical value |
|---------------------------------|-----------------|
| The calculated value of the Student's criterion \((t)\) for the coefficients \((a_k)\)      |                 |
| \( t_{a0} \)                  | 13.8            |
| \( t_{a1} \)                  | 1.73            |
| \( t_{a2} \)                  | 5.72            |
| The tabular value of Student's criterion \( t (0.10; 56) \) | 1.67            |

Analysis of the results of table 1 shows that the calculated value of Student's criterion for all coefficients is greater than the tabular one at a significance level of 0.10; that is, the coefficients of the regression model are significant.

To measure the closeness of the relationship between the two variables in question, paired correlation coefficients are used:

\[
r_{UST} = \frac{\overline{U}_S - T \overline{U}_T \overline{U}_S}{\sigma_{Us} \sigma_T}; \quad r_{USl} = \frac{\overline{U}_S - L \overline{U}_S}{\sigma_{Us} \sigma_L}; \quad r_{LT} = \frac{\overline{L} - T \cdot \overline{L}}{\sigma_L \sigma_T} .
\]  \( (25) \)

The cumulative multiple correlation coefficient is an indicator of the closeness of the relationship between the resultant and two or more factor signs.

In the case of a linear two-factor correlation, the cumulative multiple correlation coefficient can be calculated using the following formula:

\[
R_{Us,T,L} = \sqrt{r_{UST}^2 + r_{USL}^2 - 2r_{UST}r_{USL}r_{LT}} .
\]  \( (26) \)

The cumulative coefficient of multiple determination shows how much of the variation of the studied indicator is explained by the influence of the factors included in the multiple regression equation.

The validation of the obtained model for adequacy was performed using the multiple coefficient of determination \( R_{yx} \).

The partial elasticity coefficients show how much% on average the analyzed indicator changes with a change of 1% for each factor with a fixed position of other factors, and are calculated using the following formula:

\[
\beta_i = \alpha_j \cdot \frac{\overline{X}_j}{\overline{U}_S} .
\]  \( (27) \)

where \( \alpha_j \) – the regression coefficients at the j-th factor; \( \overline{X}_j \) – the average value of the j-th factor; \( \overline{U}_S \) – the average value of the dependent variable.

To test the significance of the regression model, Fisher's F-test is used.

If the calculated value with \( k1 = m \) and \( k2 = (n - m - 1) \) degrees of freedom, where \( m \) is the number of factors included in the model, is more than the table for a given level of significance, then the model is considered significant:

\[
F = \frac{R^2/m}{(1-R^2)/(n-m-1)} .
\]  \( (28) \)
Table 2 shows the main statistical characteristics of the regression model. According to the provisions of mathematical statistics, if the coefficient of multiple determination is $R_{yx}$, then the multiple regression equation is considered workable. Consequently, the “resource change intensity” regression model of car alternators is workable (that is, adequate), since the coefficient of multiple determination is 0.902.

Statistical assessment of the significance of this coefficient is made using Fisher criterion. The experimental value of the Fisher criterion is greater than the table value for the significance level of 0.10, which indicates the adequacy of the model to the process under study.

| The name of the characteristics | Numerical value |
|-------------------------------|----------------|
| Multiple correlation coefficient | 0.949 |
| Multiple determination coefficient | 0.902 |
| The experimental value of the Fisher criterion | 171.8 |
| The tabular value of the Fisher criterion F 0.10 | 2.18 |
| Coefficient of factors influence | |
| $\beta_T$ | 0.20 |
| $\beta_L$ | 0.75 |

In addition, the coefficient of multiple determination $R_{yx}[T, L] = 0.902$ indicates that the temperature of the ambient air and the operating time significantly affect the change in the life of automotive alternators and only 9.8% depend on other unaccounted factors.

Based on the numerical values of the coefficients of influence, it follows that the greatest influence on the intensity of change in the resource of automobile alternators is provided by the accumulation time ($\beta_L = 0.75$).

Based on the expression (22) in Figures 2 and 3, the effect of each variable $L, \bar{t}_n$ on the intensity of the resource change with fixed values of other variables is shown.

**Figure 2.** The dependence of the intensity of the alternator resource change on the ambient temperature.
From Figure 2 it follows that with an increase in the operating time, the intensity of the change in the resource increases, that is, when predicting the residual resource by expression (19), the magnitude decreases with the increase in the lead time $R_S$. The deviation of the ambient temperature from the optimal air also leads to an increase in the intensity of changes in the resource of automobile alternators.

**Figure 3.** The dependence of the intensity of the alternator resource change on the operating time.

In the final form, based on expressions (19) and (22), the expression for determining the residual life of automotive alternators is as follows:

$$R_S = \frac{0.062075}{0.062075 + 3.6 \cdot 10^{-6} \left[ (\bar{t}_a - 4.67)^2 + \sigma_T^2 \right] + 9.44 \cdot 10^{-5} \cdot L}.$$  \hspace{1cm} (29)

Figure 4 shows a graphical representation of the change in the residual life of automotive alternators during operation.

**Figure 4.** Impact of operating time and ambient temperature on the residual life of automotive alternators.

Analyzing the type of response surface, we can conclude that the ambient temperature has the greatest influence on the intensity of the resource change in the zone of small operating time. As the alternator operating time increases, the effect of temperature becomes insignificant relative to the operating time value.

4. Conclusion
The change in the alternator's service life is characterized by an additive two-factor mathematical model that determines the influence of the operating time and the ambient air temperature. As a result of diagnosing a group of automobile alternators in operation, the numerical values of the mathematical model were determined. Since the coefficient of multiple determination was $r_x = 0.902$, the regression model of the intensity of change in the resource is adequate.

The analysis of the mathematical model shows that with an increase in the operating time, the intensity of the resource change increases. The deviation of the ambient temperature from the optimal air also leads to an increase in the intensity of changes in the resource of automobile alternators.

Analyzing the contribution of the factors of the mathematical model, we can conclude that the ambient temperature has the greatest influence on the intensity of the resource change in the zone of small operating time. As the alternator operating time increases, the effect of temperature becomes insignificant relative to the operating time value.

Thus, extreme conditions, even with small runs, can lead to sudden failure of alternators, so this information should be considered during the technical operation of vehicles.

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