Forecasting of the 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 resource of automotive alternators, built on the results of diagnosing and assessing the operating conditions of an automobile. 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 resource of automotive alternators in the conditions of road transport enterprises.

1. Introduction
The alternator is the main source of electric power in an automotive feeding all power-consuming devices and charging the battery when the internal combustion engine is running.

At present, car maintenance does not involve technical state diagnostics of an automotive alternator. Therefore, its failure, as a rule, turns out to be a sudden event and leads to a significant loss of time [1, 2, 3].

Consequently, the task of forecasting the residual resource of an automotive alternator is rather relevant, as this would allow to reduce vehicle downtime due to sudden failures of alternators.

The following forecasting methods are best known:
- according to the permissible level of probability of failure-free operation of the unit under test [4];
- based on the results of the parameter change extrapolation in the operating time function [5];
- economic and probabilistic method based on the totality of realizations of parameters [6];
- statistical classification based on the pattern recognition theory [7];
- simulation modeling.

In the works of the founder of the theory of the adaptability of the car to the conditions of operation, Ph.D., prof. L.G. Reznik [8] provides a mathematical model that describes the effect on the residual resource of a vehicle’s aggregate ambient temperature:

\[ u = u_0 + S_T \cdot (t - t_0)^2 \]  

(1)

where \( u \) - the average intensity of resource use;
\( S_T \) - sensitivity parameter to changes in ambient air temperature;
Considering that the ambient temperature is a complex factor that considers the adverse effects of the environment and operating conditions on the performance of automotive alternators, we will take the equation (2) as the basis for developing a mathematical model of the residual resource.

2. Forecasting the residual resource

As a result of the analysis [9] carried out earlier, it has been found that the resource of the alternator is related to electrical resistances of its elements, whose change is determined by temperature \( t \), operation period \( L \), technological and operational factors.

The analytical dependence of the intensity of changes in the resource of the automotive alternator on the operating conditions can be confirmed in the following expression:

\[
\overline{U_s} = 1/(S_{EXT} - S_{CUR})
\]  

(2)

where \( S_{EXT} \) - the limiting value of the diagnostic parameter, V;
\( S_{CUR} \) - the current value of the diagnostic parameter, V;
\( \overline{U_s} \) - the average value of the intensity of change of the resource, %.

Oscillation of the output voltage was chosen as the most informative and sensitive diagnostic parameter in terms of changes in the technical state and operating conditions [10].

Based on the analysis of the previously completed studies and considering the most significant operational factors, let us present the intensity of the resource change as an additive model:

\[
\overline{U_s} = \alpha_1 + \alpha_2 \cdot [(\bar{t} - t_0)^2 + \sigma_t^2] + \alpha_3 \cdot L
\]  

(3)

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 maximum level of resource preservation of the automotive alternator;
\( \alpha_1, \alpha_2, \alpha_3 \) - model constants.

The mathematical model of the residual resource of the automotive alternator considers its technical condition at the time of diagnosis and the degree of its change from the factors of operating conditions on the forecasted period:

\[
R_S = \frac{(S_{EXT} - S_{CUR})}{S_{EXT}} = \frac{\alpha_1}{\alpha_1 + \alpha_2 [(\bar{t} - t_0)^2 + \sigma_t^2] + \alpha_3 L}
\]  

(4)

The method for estimating the residual resource of alternators is based on diagnostic information and is calculated using a mathematical model.

When determining the residual resource of the alternator by expression (4), it was found that the simplest solution is possible when the time of diagnostics coincides with the beginning of the month, the prediction interval corresponds to the vehicle’s monthly mileage (\( \Delta L = l_M \)) and the ambient temperature and its standard deviation correspond to monthly mean values. For predictions by a variable step (\( \Delta L = \text{var} \)), and the date of diagnostics which does not coincide with the beginning of the month, a universal algorithm was developed for determining the value \( \overline{U_S} \) for a given forecast interval:
where $U_{sn}$ - the change in the resource of the automotive alternator in the n-th forecast interval.

Forecasting the intensity of the alternator resource change by expression (5) at any forecast interval $\Delta L$ and, in the real range of factor changes $\bar{t}_a$, $\sigma_t$ and at the forecast step $\Delta l_i = \text{var}$, is illustrated in Figure 1.

**Figure 1.** Forecasting of changes in the alternator resource at a specified interval

Forecasting is conducted as of the given date, the first step of the forecast $\Delta l_1$ is taken in such a manner so that the end of this step falls on the beginning of the next month, the last step $\Delta l_n$ corresponds to the service hours from the beginning of the month to the end of the forecast date.

All other steps $\Delta l_i$ correspond to the average monthly mileages of the car. In this case, the change in the alternator residual resource is determined as follows:

$$U_{s1} = \alpha_1 + \alpha_2 \cdot [((\bar{t} - t_0)^2 + \sigma^2_t)] + \alpha_3 \cdot L_i$$

$$U_{s2} = \alpha_1 + \alpha_2 \cdot [((\bar{t} - t_0)^2 + \sigma^2_t)] + \alpha_3 \cdot (\Delta l'_1 + \Delta l_2)$$

The operation duration value, when the beginning or end of the forecast step does not coincide with the beginning of the month, can be obtained according to the formulas:

$$\Delta l_b = l_m \cdot \frac{D_e - D_i}{D_e}$$

$$\Delta l_e = l_m \cdot \frac{D_i}{D_e}$$

where $\Delta l_b$ - the operation duration corresponding to the first forecast step;

$\Delta l_e$ - the operation duration corresponding to the last forecast step;

$D_i$ - the number of days in a month corresponding to the beginning or end of the forecast, respectively, in the first and last step;

$D_e$ - the number of days of a month;

$l_m$ - average monthly car mileage.
3. Model of accounting of variation of ambient temperature

To carry out calculations using the above expressions, it is necessary to have the values of the average monthly ambient temperature $t_{\text{СС}}$ and its standard deviation. The change in the average monthly ambient temperature over several years is cyclical. It is known that the most preferred periodic function that approximates the cyclical change of indicators is a sine curve. In order to consider, the shift of the maximum (or minimum) temperature relative to the selected origin of coordinates, it is necessary to sum up of sine and cosine, providing a "phase shift". Since temperature fluctuations occur in relation to a certain non-zero value, it is necessary to introduce in the approximating expression an additive component corresponding to this “average” temperature.

As a result, the regression dependence of the change $t_{\text{СС}}$ during the year is calculated using the expression:

$$t_{\text{СС}} = v_0 + v_1 \cdot \cos \frac{2\pi N_m P_i}{\pi} + v_2 \cdot \sin \frac{2\pi N_m P_i}{\pi}$$

where $v_0, v_1, v_2$ - the regression factors;
$N_m$ - the number of time intervals (months);
$P_i$ - the serial number of the month.

Consequently, with the help of the obtained dependence, by substituting the values of time intervals, for example, $P_0, 7 = 0,7$, $P_2 = 2$, $P_3,4 = 3,4$, $t_{\text{СС}}$ can be forecasted for a specific interval. A graphical representation of the expression (8) for the city of Orenburg is shown in Figure 2, where the polygonal line shows the statistical data for the last 5 years, and the smoothed line shows their approximation.

![Figure 2. Change in average monthly air temperature (for example, in the city of Orenburg)](image)

To forecast the residual resource, it is necessary to consider fluctuations in ambient air temperature, which are determined by the standard deviation of temperature by months ($\sigma_t$). The approximation of the experimental values of the standard deviation of ambient temperature by months:

$$\sigma_t = b_1 \cdot e^{(-b_2 t)}$$

where $b_1, b_2$ - the regression factors.
4. Algorithm of forecasting of residual resource

The alternator residual resource forecasting algorithm contains an estimate of the current value of the resource, a breakdown of the forecast interval into monthly intervals, the calculation of the average monthly temperature and its deviations and an estimate of the predicted residual resource (Figure 3).

**Figure 3.** Algorithm of forecasting of residual resource

**Figure 4.** Graphic representation of the alternator resource change in the forecast interval

Figure 4 shows an example of using the method. The firm line passing through the $Db$ and $De$ points represents the results of determining the residual resource of the alternator according to the
diagnostic parameters. The polygonal line, the slope of which varies on each of the monthly intervals (I, II, ... XI), represents the results of the estimated residual resource forecast. Dashed lines indicate the confidence interval.

Verification of the accuracy of the method described above showed that the error in determining the residual resource of the alternator over the mileage interval corresponding to the maintenance of passenger cars is about 3.5%.

5. Conclusion
Analysis of existing methods of forecasting residual resource showed that they do not allow to consider changes in the factors of operating conditions of a diagnosed object, which negatively influences the accuracy of determining the residual resource in such a way. It has been established that the hours in service and the ambient air temperature greatly affect the value of the alternator residual resource. There was the mathematical model proposed for the residual resource of the automotive alternator considering its technical condition at the time of diagnosis and the degree of its change under the influence of the factors of operating conditions on the intercontrol mileage. To consider the ambient air temperature in forecasting the residual resource, there has been a regression model developed that approximates the statistical values of the ambient temperature variation. In addition, there has been an algorithm and an application program for estimating and forecasting the residual resource of automobile alternators based on the proposed model. Verification of the accuracy of the method described above showed that the error in determining the residual resource of the alternator over the mileage interval corresponding to the maintenance of passenger cars is about 3.5%, hence, its use will increase the efficiency of car operation due to the timely alternator failure forecasts and the reduction of periods when vehicles are out of operation due to repair works.

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