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Diagnosing of Failures of Automotive Alternators Based on Amplitude of Fluctuations of Voltage

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***Abstract*— Automotive alternators problems constitute about 21 % of total automotive electrical faults. Fault in automotive alternator can cause different implications, ranging from fault in battery accumulator or electronics through road traffic accident. Fluctuation of output voltage is accepted as the main diagnostic parameter as being the most sensitive to faults in automotive alternators. Disadvantage of existing methods for determining the fluctuation of output voltage is a smoothing effect of battery accumulator and absence of methods for interpreting the obtained quantitative data. It is suggested to improve the diagnostic method using an oscilloscope through the exclusion of smoothing effect of battery accumulator. The developed diagnostic method makes it possible to assess the technical condition alternators without dismounting them from a car based on the parameters of output voltage through the comparison of the obtained value of output voltage fluctuation with the allowable value. It is found that fluctuation of output voltage of serviceable alternators increases monotonically with increasing time in service without reaching limit or allowable values. Voltage fluctuation in alternators with electrical problems significantly exceeds allowable values that makes it possible to use this parameter for the determination of technical condition. Fluctuation of output voltage used as a diagnostic parameter makes it possible to assess the residual operation time of automotive alternators. Determination of residual operation time of automotive alternators can improve the operational efficiency of cars by means of decrease in standby time during repair.**

Keywords*— *automotive alternator, diagnostic parameters, voltage fluctuation, residual resource

I. Introduction

Operational life of other electrical elements and traffic safety depend on the reliable operation of automotive alternators. In the conditions of abundance of automotive electrical and electronic systems, including traffic safety systems, the probability of road traffic accidents increases by 9 % (for example, fault in alternator leads to tripping of electric power assisted steering) [8].

Consequently, assurance of automotive alternators serviceability in operation is an ongoing challenge.

According to empirical data, the problems [1, 2, 3, 4, 6, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 23] (see Figure 1) are the most common for automotive alternators.

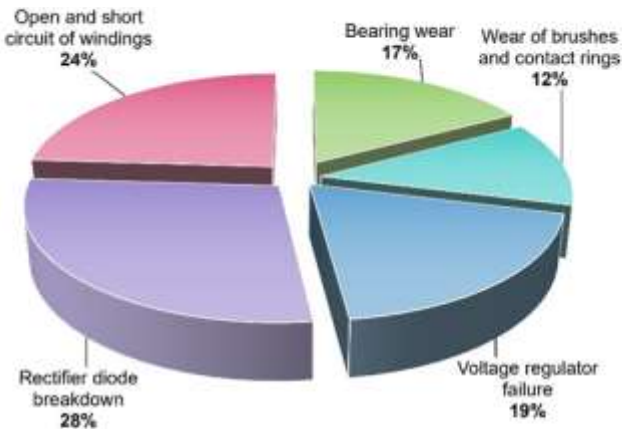


Fig. 1. Diagram of automotive alternators problems according to the rate of occurrence

These faults result in excessive heating of alternator (12 %), excessive noise during operation (15 %), zero (7 %) or low output voltage (40 %), increase in output voltage (26%) [7].

Analysis of the causes of automotive alternators problems showed that only 29 % of problems are related to mechanical elements and other problems are caused by faults in electrical elements.

Analysis of diagnostic methods showed that the most effective methods regarding accuracy, efficiency and high information value are the diagnostic methods based on the recording of oscillating processes (oscillographic methods) suggesting the determination of shape and parameters of output voltage waveform displayed in oscilloscope.

Advantages of oscillographic methods [5, 21, 22] include efficiency, proper accuracy, possibility of automatic measurement of diagnostic parameters.

II. Model of automotive alternator serviceability

Generally, output voltage waveforms displayed by oscilloscope are assessed according to mean value and output voltage fluctuation determined through the following equations:

$$U_d = U_{\text{phase}} \cdot k_{\text{circuit}} \cdot k_{\text{в}} \cdot k_{\gamma} - \Delta U_{\text{fwd}}, \qquad (1)$$

where U_{phase} – alternator phase voltage (EMF), V; $k_{circuit}$ – rectification circuit factor $k_{\text{circuit}} = 2cos(\pi/2m)$; m – number of rectifier (alternator) phases, $m = 3$; k_{rect} – rectification factor $k_{\text{rect}} = \left(2m\sqrt{2}/\pi\right) \cdot sin(\pi/2m)$; k_γ – commutation factor $k_\gamma = (1 + cos\gamma)/2$; γ – commutating angle, degrees. According to [20] $\gamma = 15°$. ΔU_{fwd} – forward pressure drops on diode, V.

$$\Delta U_{fwd} = U_0/2 + I \cdot R_{dfwd}, \tag{2}$$

where U_0 – threshold voltage, $U_0 = 0.6 - 0.8$ V; I – alternator current intensity, A; R_{dfwd} – forward diode resistance, Ohm.

After calculations and substitution of the values in the equation (1), the following equation is derived

$$U_d = 2.3 \cdot U_{\text{phase}}.$$

No-load voltage induced in the stator winding

$$U_{\text{phase}} = 4 \cdot k_{\text{shape}} \cdot k_{\text{o}} \cdot \left(\frac{p \cdot n}{60}\right) \cdot w_{\text{phase}} \cdot \Phi, \tag{3}$$

where k_{shape} – factor dependent on field curve shape, $k_{shape} = 1.11$; p – number of pairs of alternator poles, $p = 6$; w_{phase} – number of turns per phase; k_{o} – winding factor; n – alternator rotary speed, min^{-1}; Φ – magnetic flux, Wb.

After substitution of the values of phase voltage and losses in rectifier in the equation (1), the following equation is derived

$$U_d = 2.3 \cdot 4.44 \cdot \left(\frac{p \cdot n}{60}\right) \cdot R_{\text{sw}} \cdot \text{C}_{\text{c}} - 2 \cdot (U_0/2 + I \cdot R_{\text{dfwd}}), \tag{4}$$

where R_{sw} – stator winding resistance, Ohm; C_c – constant factor determined by the rotor winding parameters.

Since the alternator current intensity is inversely proportional to the resistance of the stator winding and rectifier diodes and considering the need for finding relation between structural and diagnostic parameters, we corrected the equation (4) as follows

$$U_d = \varphi_1 \cdot R_{\text{sw}} - \varphi_2 \cdot R_{\text{dfwd}}/(R_{\text{sw}} + R_{\text{dfwd}}), \tag{5}$$

where φ_1, φ_2 – factors, which are independent of R_{sw} and R_{dfwd} determined by alternator speed operation mode and load operation mode, respectively.

According to [20], alternator voltage fluctuation is expressed as follows

$$\Delta U = \sqrt{2} \cdot U_{\text{phase}} \cdot 2cos(\pi/2m) \cdot \left(1 - cos\gamma \cdot cos(\pi/2m)\right), \tag{6}$$

where ΔU – alternator voltage fluctuation, V.

Considering the behavior of voltage fluctuation occurred in case of electrical faults, we corrected the equation (6) as follows

$$\Delta U = \mu_1 - \mu_2 \cdot U_d, \tag{7}$$

where μ_1, μ_2 – factors determined by the technical condition of alternator.

The equations (5) and (7) show that problems associated with the change in electrical resistance of the stator winding and semiconductor diodes lead to the decrease in mean value and increase in output voltage fluctuation confirming the reasonability in choosing diagnostic parameters.

III. AUTOMOTIVE ALTERNATORS DIAGNOSTIC METHOD

Based on the analysis made [7], it was decided to accept the fluctuation of output voltage (ΔU) as the main diagnostic parameter as being the most sensitive to alternators faults.

The key factor that affects the information value of this diagnostic parameter is a smoothing effect of battery accumulator (see Figure 2).

For the exclusion of this factor, according to the paper [21], it is suggested to apply non-inductive load to alternator while disconnecting it from the battery. Disadvantage of this method is the absence of such load in the conditions of motor transport enterprises.

For the determination of diagnostic parameters, we suggest reading data from oscilloscope at alternator power output after disconnecting it from the battery accumulator (see Figure 3). This makes it possible to exclude the smoothing effect of battery accumulator on the shape of output voltage waveform and improve its information value [8].

Diagnosis is performed as follows: automotive alternator power cable connected to the positive side of the battery accumulator should be disconnected; positive probe of portable oscilloscope should be connected to alternator power output and negative probe of oscilloscope should be connected to the negative side of battery accumulator or to any other point having reliable contact with the body (earth) of a car of a tractor; engine of a car or a tractor should be started; a portable oscilloscope should be switched on and a waveform of alternator output voltage should be recorded to oscilloscope memory or flash drive.

The developed diagnostic method makes it possible to assess the technical condition of alternators without dismounting them from a car based on the parameters of output voltage through the comparison of the obtained value of voltage fluctuation with the allowable value.

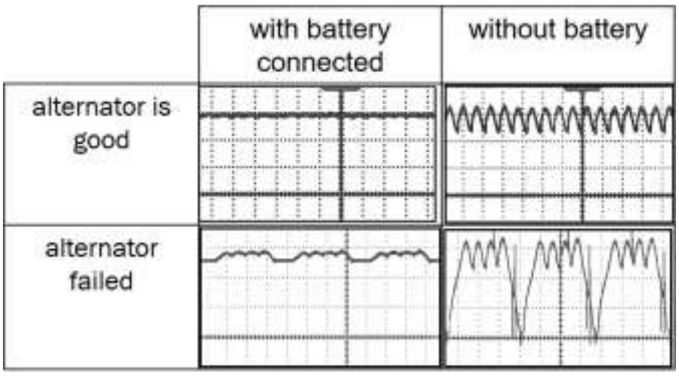
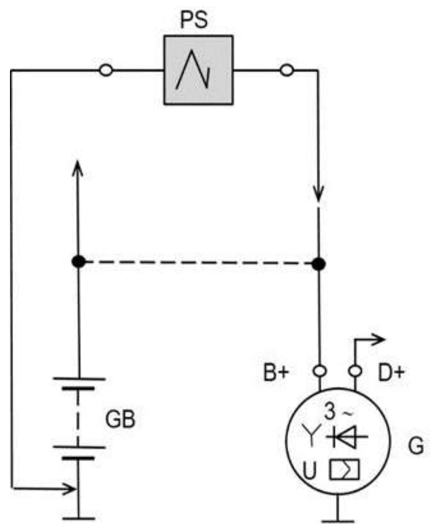


Fig. 2. Battery accumulator effect on the information value of automotive alternator output voltage waveform displayed in oscilloscope



B+ – alternator power output, D+ – output to control light, G – automotive alternator, GB – battery accumulator, PS – digital oscilloscope

Fig. 3. Suggested layout for alternator diagnosis

The method under consideration can be attributed to rapid methods based on minimum labor intensity (less than three man minutes) and limited number of diagnostic parameters (mean value and fluctuation of output voltage).

Experimental studies aimed at obtaining data on changes in the diagnostic parameters of automotive alternators considering the ambient temperature conditions and time in service were carried out in the conditions of automotive service enterprises. Time in service was determined based on the readings of the factory-installed odometer and it ranged from 1,000 to 270,000 operational kilometers. Data on ambient temperature conditions at the time of diagnosis was obtained from the reports of Orenburg meteorological station.

VAZ cars were used as the units under test. All the cars under test were equipped with domestically produced alternators with rated current of 90 A, 105 A and 110 A of the same design.

IV. Alternators Diagnosis Results

The results of automotive alternators diagnosis using the suggested method are presented in Figure 4 in ascending order. It is found that fluctuation of output voltage of serviceable alternators increases monotonically with increasing time in service without reaching limit or allowable values [8]. Voltage fluctuation in alternators with electrical problems significantly exceeds allowable values that makes it possible to use this parameter for the determination of technical condition.

Spread in diagnostic parameter values in alternators with failures is attributed to the difference in the form of failures and randomness of their development.

Now, consider the case when one parameter x is monitored and its lower and upper limit values (x_{min}, x_{max}) are known.

When the measurement result is $x_{measured}$, then the product will be ready for operation at $x_{min} \leq x \leq x_{max}$.

$$x_{measured} = x + \Delta_x, \tag{8}$$

where x – measured parameter value; Δ_x – parameter measurement error.

TABLE I. THE RESULTS OF EXPERIMENTAL STUDIES OF DIAGNOSTIC PARAMETERS IN OPERATING CONDITIONS

Make and model of vehicle	**Operating time, km**	**Average voltage, V**	**Amplitude of fluctuations of voltage (ΔU), V**	**Diagnosis**
1. VAZ 2172	1000	14,0	2,4	Good
2. Lada Granta	1711	14,4	2,0	Good
3. Niva	4000	14,2	2,8	Good
….	….	….	….	….
20. Lada Granta	47800	14,6	3,2	Good
21. Lada Largus	50000	14,0	4,4	Good
22. Lada Kalina	52900	14,6	3,6	Good
….	….	….	….	….
32. Niva	92605	14,2	3,8	Good
33. VAZ 2172	94000	14,2	8,6	Interturn closure of the stator winding
34. VAZ 2172	100000	14,2	5,2	Good
….	….	….	….	….
37. Lada Kalina	119000	15,4	15,6	Open circuit diode
38. VAZ 2114	119023	14,0	4,6	Good
39. Lada Kalina	120000	14,2	5,0	Good
….	….	….	….	….
51. Lada Kalina	153400	14,0	5,5	Good
52. VAZ 2170	157000	15,6	18,2	Short circuit diode
53. VAZ 21099	158500	14,5	6,0	Good
….	….	….	….	….
73. Niva	270000	14,8	7,0	Good

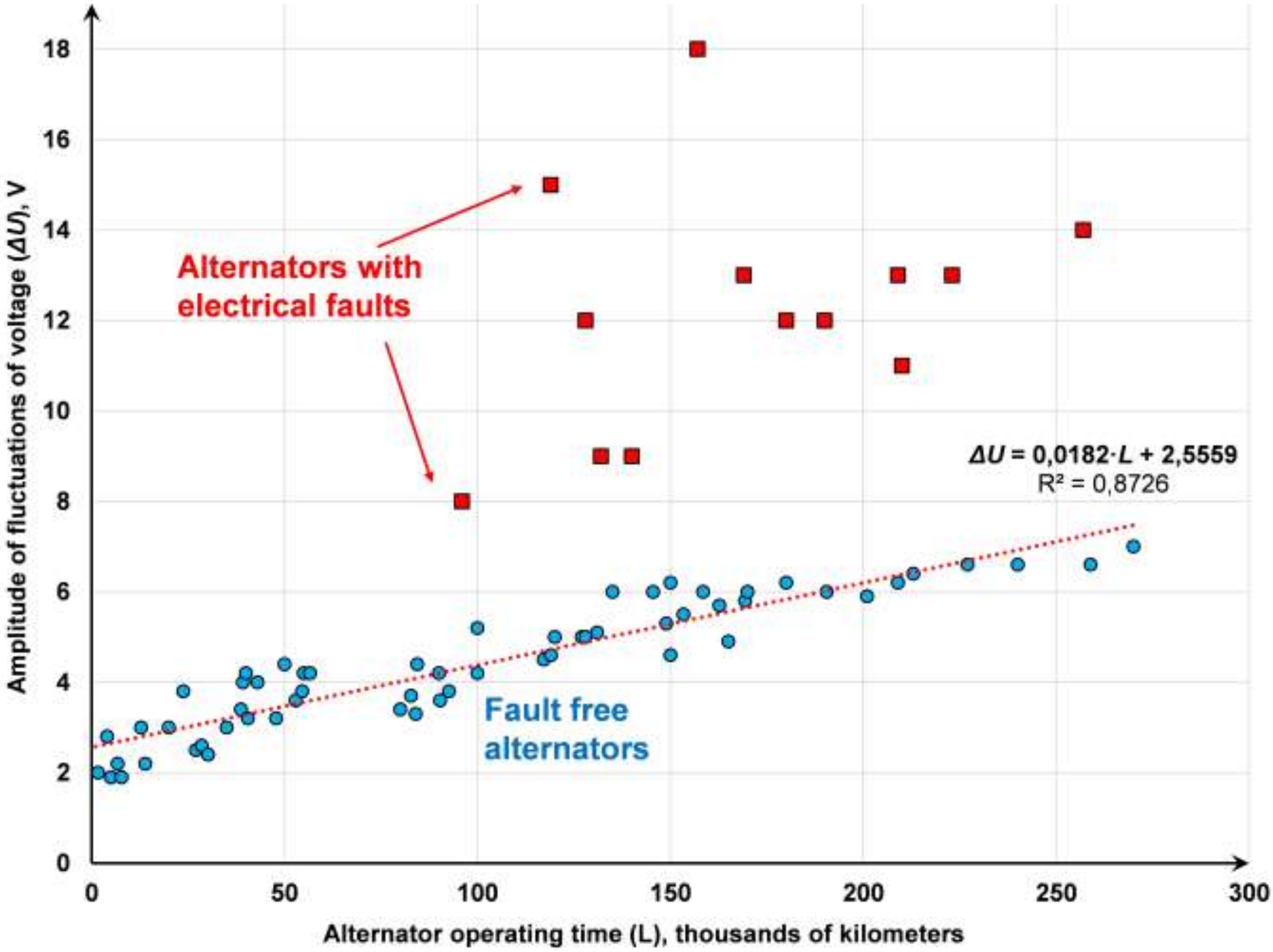


Fig. 4 – Change in voltage fluctuation with the increase of time in service

Two independent events are possible:

– the value of control parameter was within the range of $x_{min} \leq x \leq x_{max}$;

measurement error is very high, and the result lies within one of the ranges $(-\infty \leq x \leq x_{min}; x_{max} \leq x \leq \infty)$.

Due to the measurement error, there are two zones *I* and *II*, which lead to the rejection of serviceable alternators or pass of non-serviceable ones.

Diagnosis accuracy is numerically determined by the following formula:

$$\mathrm{D} = 1 - (P_I - P_{II}), \tag{9}$$

where P_I and P_{II} – probability of errors of the first kind (valid parameter is found invalid) and the second kind (invalid parameter is found valid).

In general terms, probability of errors of *I* and *II* kind can be determined by the following formulas:

$$P_I + P_{II} = \int_{-\infty}^{\infty} P(x) f(x) dx, \tag{10}$$

where $f(x)$ – probability density function of distribution of cars coming for diagnosis.

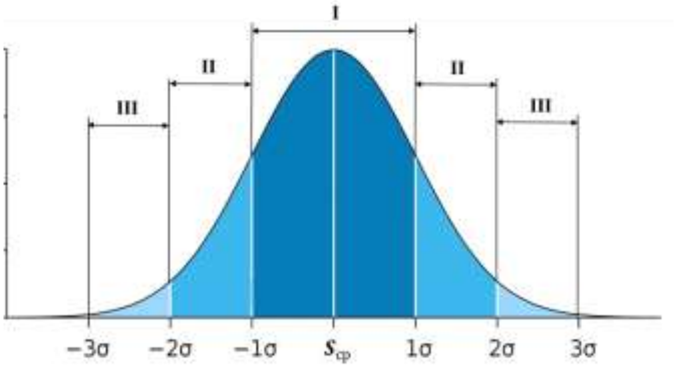


Fig. 5 – Ranges of diagnosis errors determination

Diagnosis accuracy can be approximately determined as [24]:

$$D = 1 - 0.314 \cdot \beta_1 - 0.083 \cdot \beta_2 - 0.007 \cdot \beta_3, \tag{11}$$

where β_j – relative number of cars, which fell into j range (see Figure 5)

$$S_{mean} - j \cdot \sigma \leq S_i \leq S_{mean} - (j-1) \cdot \sigma \quad (12)$$

According to the central limit theorem [25], measurement (diagnosis) errors occur under the influence of several weakly dependent random factors; their distribution is considered normal.

For the normal law of measurement errors, mean square measurement error is as follows:

$$\sigma = 300^{-1} \cdot \delta \cdot (X_2 - X_1), \quad (13)$$

where δ – accuracy of measuring tool, %. Accuracy of digital oscilloscope Hantek DSO1062B, according to datasheet specifications, is δ=3%, $(X_2 - X_1)$ – scale range of diagnostic tool, which corresponds to the variation range of diagnostic parameter, $(X_2 - X_1) = 40\ V$.

$$\sigma = 300^{-1} \cdot \delta \cdot (X_2 - X_1) = 300^{-1} \cdot 3 \cdot 40 = 0.4 \text{ V}$$

$$\beta_j = m_j / n, \quad (14)$$

where m_j – number of cars fell into j range. According to the diagnostic parameter distribution, mean value – $S_{mean} = 4.37$ V, number of cars, which fell into j range, was $m_1 = 12$, $m_2 = 12$, $m_3 = 7$; n – total number of cars under test, $n = 60$.

$\beta_1 = 12/60 = 0.2$; $\beta_2 = 12/60 = 0.2$; $\beta_3 = 7/60 = 0.117$.

Diagnosis accuracy (11) was as follows:

$$D = 1 - 0.314 \cdot 0.2 - 0.083 \cdot 0.02 - 0.007 \cdot 0.117 = 0.92$$

V. DETERMINATION OF ALTERNATORS RESOURCE

Since a trend can be identified in a random process being indicative of change in diagnostic parameter, it is possible to use the results of diagnosis by the suggested method for the forecasting of residual operation time of automotive alternators [24].

In the course of assessment of residual operation time of automotive alternators, we proceed from the following condition:

$$R_S = (S_{lim\,it} - Scurrent)/S_{lim\,it}, \quad (15)$$

where R_S – residual resource of automotive alternator, %; S_{limit}– limit value of diagnostic parameter, V; $S_{current}$ – current value of diagnostic parameter, V.

To determine residual resource in thousand operational kilometers, we use the following equation:

$$L_{res} = L_0 \cdot R_S, \quad (16)$$

where $Lres$ – residual operation time of alternator, thousand km; L_0 – time between failures, thousand km.

$$L_0 = \sum_{i=1}^{n} L_i \,/ \sum_{i=1}^{n} r_i, \quad (17)$$

where L_i – time between failures of i alternator, thousand km; r_i – total number of alternators faults; n – total number of alternators under test.

Figure 6 shows the graphic presentation of residual operation time of automotive alternators during operation.

VI. CONCLUSIONS

1. Analysis of diagnostic methods showed that the most effective methods regarding efficiency, accuracy and high information value are the diagnostic methods based on the recording of oscillating processes (oscillographic methods) suggesting the determination of shape and parameters of output voltage waveform displayed in oscilloscope.

2. The faults associated with the change in electrical resistance of the stator winding and semiconductor diodes lead to the decrease in mean value and increase in output voltage fluctuation confirming the reasonability in choosing diagnostic parameters.

3. A rapid method for the determination of technical condition of alternator based on output voltage fluctuation was developed. According to the diagnosis results, this parameter makes it possible to forecast the change in the technical condition of alternator under the influence of operation conditions. This method has improved the diagnosis accuracy up to 92 %.

4. The use of the suggested diagnostic parameter, i.e. output voltage fluctuation, makes it possible to assess the residual operation time of automotive alternators that will improve the operational efficiency of cars and tractors by means of decrease in standby time during repair.

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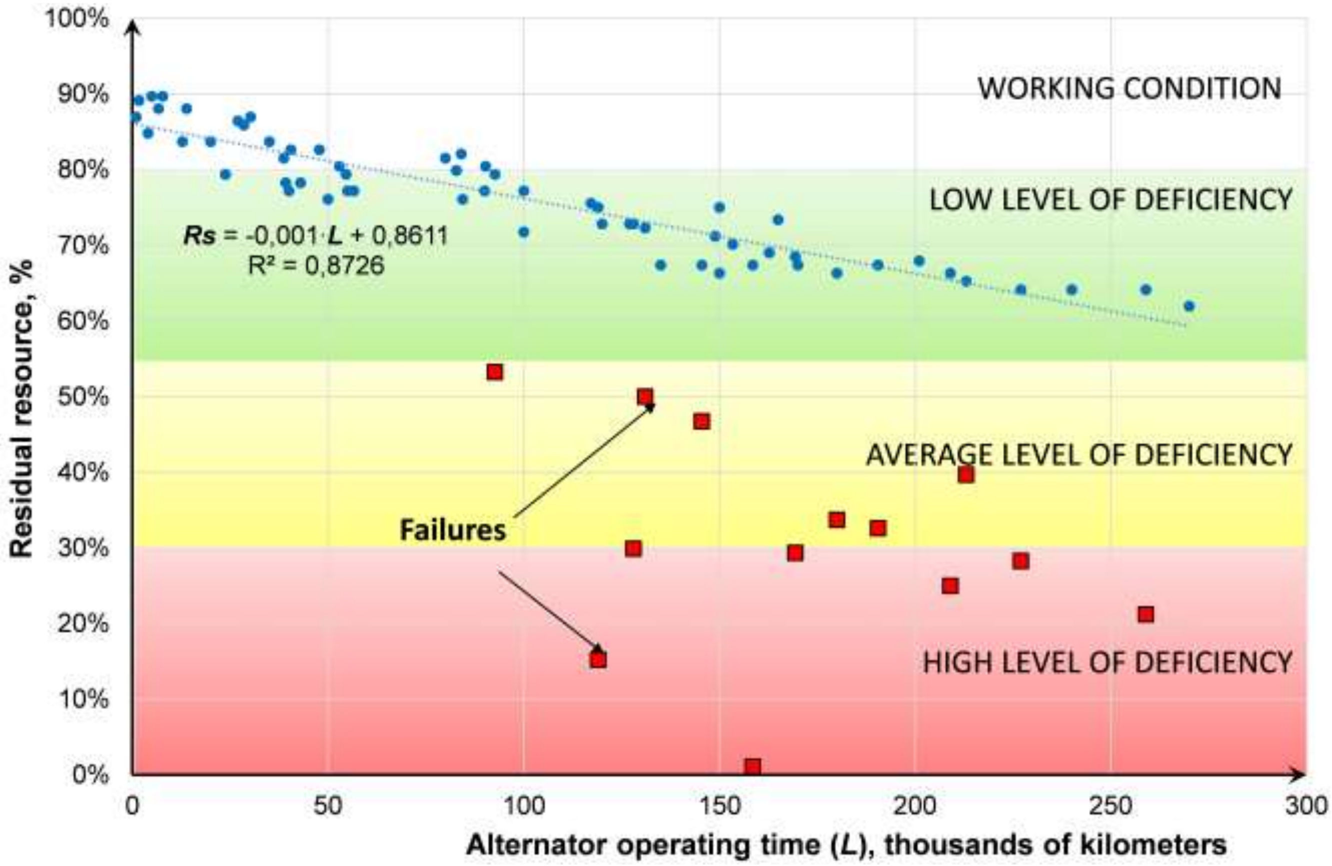

Fig. 6. Change in residual operational time with the increase of alternator time in service

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