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Physical modeling of failures of the automotive alternator

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Physical modeling of failures of the automotive alternator

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Abstract. The relevance of the problem of automotive alternator diagnosis is associated with the imperfection of existing methods due to their significant complexity and lack of information. In order the accelerate the process of electrical failures diagnosis, the article considers their physical modelling method, the advantages of which are significant acceleration of the experiment, the possibility of modelling several failures, as well as the establishment of a clear boundary between the serviceable and non-serviceable states of the alternator. Adequately simulating the processes occurring in the alternator, physical modelling is implemented by means of serial or parallel connection to the alternator elements of adjustable active resistance. Experimental data show that the most informative and sensitive to the process of failures development is the temperature increase which can serve as the basis for on-board monitoring system aimed at determining the technical condition of an automotive alternator.

1. Introduction

The automotive alternator is the main source of electrical energy on board of transport vehicles. Mean time between failures of the alternator is largely determined by operating conditions. The most common in operation are electrical faults of the alternator [1, 2, 3, 4, 5] which account for about 70% of all failures.

Electrical failures include breakages and short circuits in the windings and diodes of the rectifier unit, as well as voltage regulator failures.

Diagnostic parameters of automotive alternators can be:

- output voltage parameters: mean value and voltage fluctuation, amplitude-frequency characteristic [6, 7];
- analysis of the current velocity properties [8];
- analysis of the thermal condition [9, 10, 11, 12, 13,14, 15, 16, 17, 18, 19];
- noise and vibration analysis [20];
- external magnetic field parameters [21, 22, 23, 24];
- changing of the brake torque, etc.

The structural and consecutive diagram of the relationship between the technical condition parameters and the typical faults of the alternator is shown in Figure 1.

The diagnostic parameter analysis provided in Figure 1 shows that all of them can be used to determine the electrical failures of an automotive alternator. However, methods using these diagnostic parameters differ in terms of information content, sensitivity and efficiency.

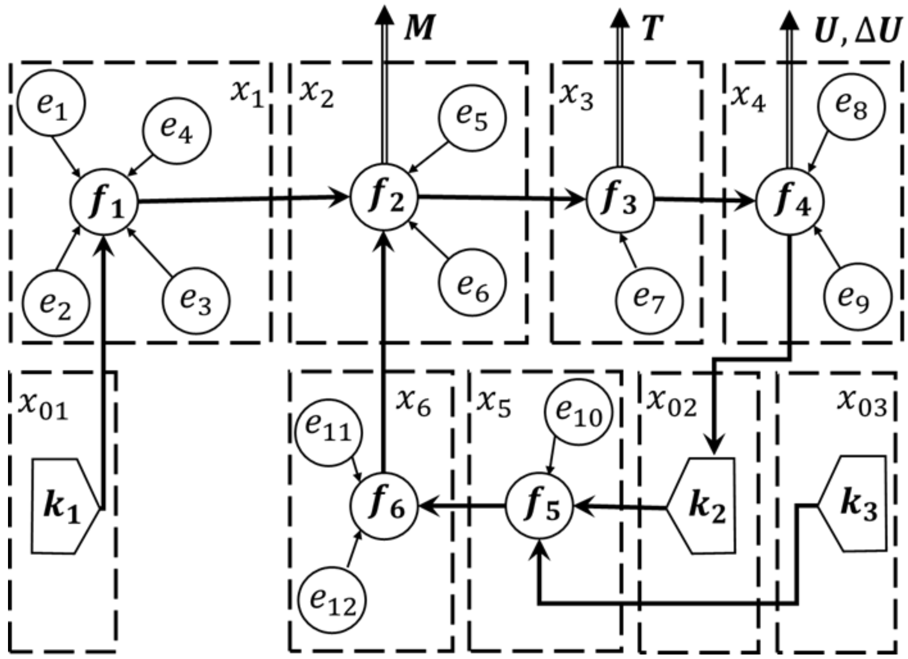

Figure 1. Structural and consecutive diagram of the automotive alternator (e1 – drive belt tension; e2 – drive belt defects; e3 – pulley overrun clutch defects; e4 – bearings defects; e5 – excitation winding defects; e6 – oxidation and wear of slip rings; e7 – stator winding defects; e8 – rectifier unit diodes defects; e9 – short circuit of rectifier unit plates; e10 – the voltage regulator defects; e11 – brush spring defects; e12 – wear and hang-up of brushes; f1 – rotation frequency of the alternator shaft; f2 – magnetomotive force of the excitation winding; f3 – electromotive force of the stator winding; f4 – the output voltage of the rectifier; f5 – the voltage at the input of the voltage regulator; f6 – the voltage on the excitation winding; k1 – rotation frequency of the internal combustion engine crankshaft; k2 – battery voltage; k3 – frequency signal of the internal combustion engine; x01 – rotational movement of the crankshaft; x1 – transmission of rotation to the alternator; x2 – generation of rotating magnetic field; x3 – generation of AC voltage; x4 – rectification of the AC voltage; x5 – transfer of DC voltage to the brushes; x6 – transfer of DC voltage to the excitation winding; x02 – battery; x03 – electronic control unit of the internal combustion engine; M – magnitude of the external magnetic field; T – temperature of the stator winding; U, ΔU – mean value and fluctuation of the output voltage)

2. Physical modeling of failures

Modelling of electrical failures is a process of simulating real processes occurring with the insulation of alternator windings and semiconductor crystals of the rectifier unit.

The difference between the simulation and the actual process is the duration of the failure's development. Aging of the insulation and degradation of the semiconductor crystal usually occurs as a result of a prolonged operation, overloads and similar abnormal conditions. This process takes a long time, and to track it you need many measurements with a large interval between them.

To accelerate the information obtainment process there are methods of physical and simulation modelling used, which assume a significant acceleration of the experiment, the possibility of modelling the aggregate number of faults and the establishment of a clear boundary between the serviceable and non-serviceable condition of the alternator. The paper deals with the physical modelling of automotive alternator failures.

Physical modelling of winding or diodes breakage of the rectifier unit is carried out by means of the forced increase of resistance of the tested element by sequential connection of the regulated active resistance (rheostat *R2*, Figure 2).

In the process of modelling the diode circuit or alternator winding breakage, the processes occurring in the alternator do not differ from those typical for the natural origin of the defect.

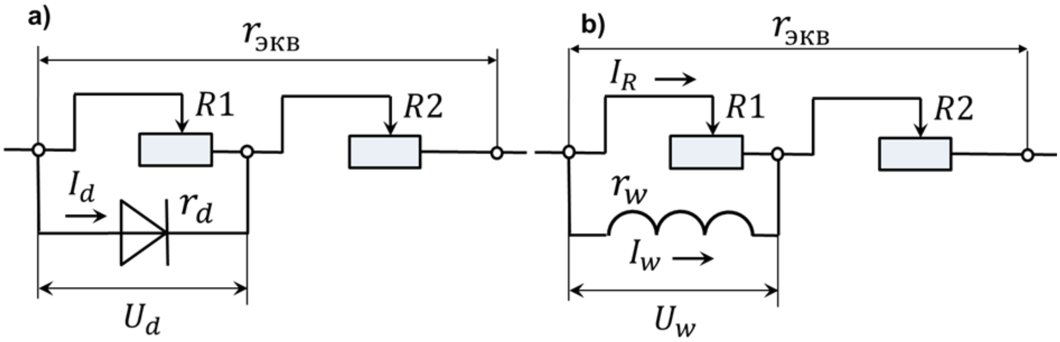

Figure 2. Connection of an adjustable resistance (of the rheostat) in the process of physical modelling of automotive alternator failures: a) modelling of failures of the rectifier unit diodes; b) modelling of failures of the stator winding

To carry out modelling of turn-to-turn short circuits of windings, short circuits of diodes and the short circuit between phases of the stator winding, resistance of these elements is decreased by means of a parallel connection of the adjustable active resistance (rheostat *R1*, Figure 2).

The main failures of the rotor winding include: turn-to-turn short circuits, short circuits to frame ("ground fault"), the winding breakage and contact failure in the area of soldering of the rotor winding terminals to the contact rings (in fact, the initial stage of the fault leading to the winding breakage). These faults are accompanied by a change in the electrical resistance of the winding, which decreases during short circuits and increases in other cases.

The main difference between the stator winding and the already considered rotor winding is its multiphase, and hence the possibility of a short circuit between phases. Since the stator winding is placed fixed and has no cover insulation, it becomes possible to simulate turn-to-turn short circuits and short circuits to frame by soldering the rheostat to the winding turns.

Artificial short circuits in the stator windings are created using special outputs previously brought out from the front part of the stator winding. For modelling of the transition resistance of the insulating layer at the point of circuit, these outputs are circuited through an adjustable active resistance. This allows adjusting the value of the current in the short-closed loop and obtaining different degrees of severity of the damage studied, which are created by changing the current in the short-closed loop.

The rectifier unit is a serial and parallel connection of a group of semiconductor diodes (usually not less than six). Therefore, diode faults can be divided into two groups: related to one of the diodes and group faults. Diode faults are mainly internal circuit breakages (resistance tends to infinity) and short circuits (resistance tends to zero).

The group faults include the simultaneous failure of two diodes of one phase ("phase burning"), failure of three diodes of a positive or negative polarity as well as combination of short circuits ("breakdowns") and circuit openings of all diodes of the rectifier.

When modelling short circuits, it was found that most diagnostic parameters respond adequately to the process of the failure’s development except for the stator winding temperature. The fact is that with the natural origin of the defect, the heat released in short-circuited turns leads to the heating of all elements of the alternator. When simulating a failure, this heat is released on the external adjustable resistance distorting the picture of what is happening.

Adjustment of the temperature measurement results is based on the following assumptions (the following symbols are shown in Figure 2).

$$\Delta T = T_w - T_a \approx \sqrt{P_W} \tag{1}$$

where ΔT is the temperature increase, °C; T_w - stator winding temperature, °C; T_a - ambient temperature, °C; P_w - power released in the stator winding, W.

$$P_W = I_W \cdot U_W \tag{2}$$

where I_w is the stator winding current, A; U_w - voltage at the stator winding outputs, V.

$$P_R = I_R \cdot U_W \tag{3}$$

where P_R is the power released in the rheostat, W; I_R - rheostat current, A.

$$\Sigma P = U_W \cdot \left(I_W + I_R\right) \tag{4}$$

where ΣP is the total power, W.

Then the adjusted value of the winding temperature will be

$$\Delta T_{real} = \Delta T \cdot \left(1 + \left(\frac{\Sigma P}{P_W}\right)^{1/2}\right) \tag{5}$$

3. Experimental procedure

The general scheme of physical modelling of failures is shown in Figure 3 which provides the connection points of rheostats to the elements of the automotive alternator. The parameters of the output voltage were recorded directly with the help of a digital oscilloscope and a Hall sensor was connected to the oscilloscope to measure the magnitude of the external magnetic field. The temperature was measured with a semiconductor sensor mounted on the surface of the stator winding.

During the experiment, changes in the above-mentioned diagnostic parameters was recorded: stator winding temperature T, magnitude of the external magnetic field *M*, the average value *U* and fluctuations *ΔU* of the output voltage in the process of the failure development.

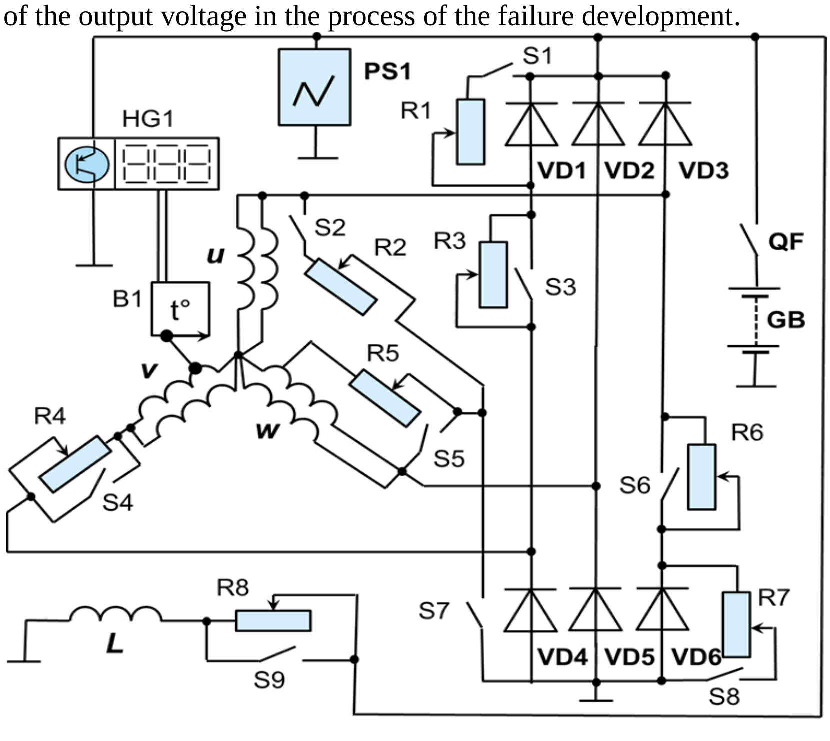

Figure 3. Modelling diagram of the automotive alternator failures (u, v, w - phases of the stator winding; B1 - stator winding temperature sensor; HG1 - temperature sensor indicator; PS1 - digital

oscilloscope; L - rotor winding; GB - battery; QF - general switch; S1 - S9 - fault input switches; R1 - R8 - rheostats of physical modeling of failures; VD1 - VD6 - rectifier unit diodes).

4. Analysis of experimental results

Table 1 shows the results of the experiment on the example of physical modeling of the short-circuited diode while Figure 4 gives a graphical representation of the relations

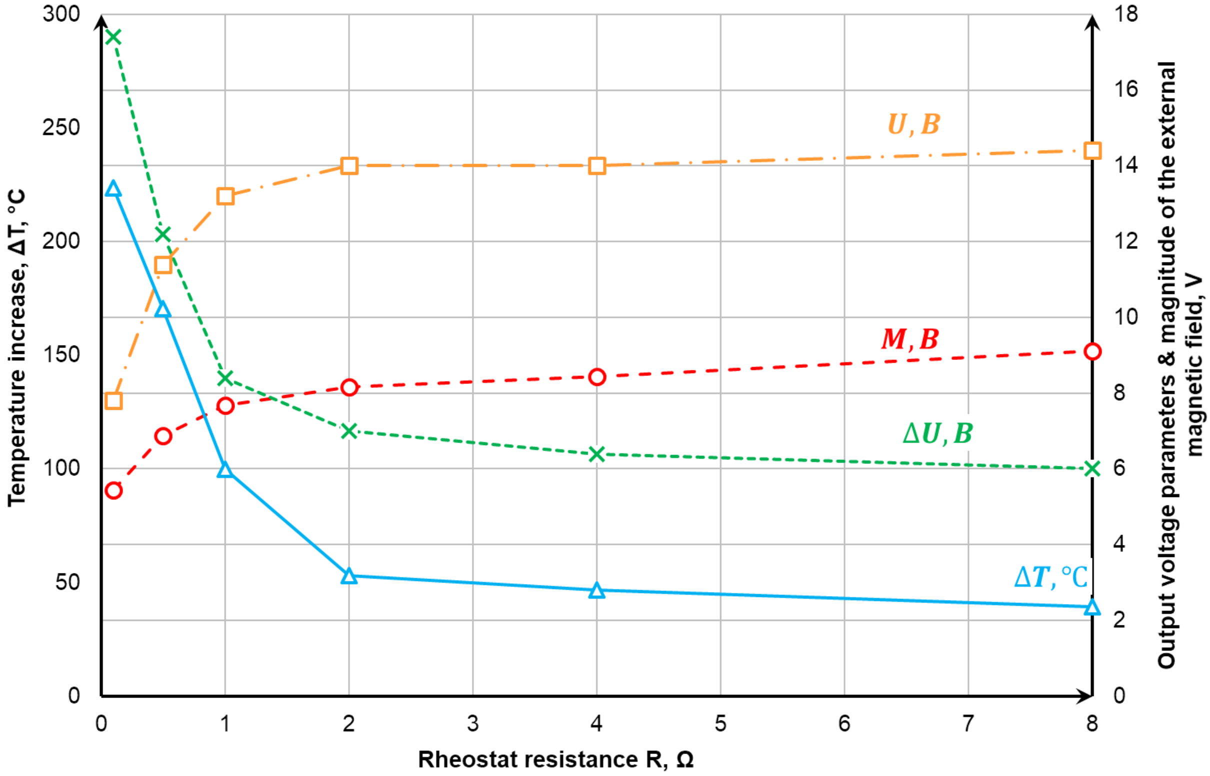

Figure 4. - Changing of diagnostic parameters of the automotive alternator in the process of the diode short circuit modelling.

Table 1. Diagnostic test of the alternator in the failure development (on the example a short circuit diode).

Failure stage	rheostat resistance	over temperature	external magnetic field magnitude	voltage fluctuation	average voltage
	Ω	°C	V	V	V
final stage	0,1	223,7	5,44	17,4	7,8
	0,5	170,4	6,88	12,2	11,4
intermediate stage	1,0	99,8	7,68	8,4	13,2
initial stage	2,0	52,9	8,16	7,0	14,0
	4,0	46,8	8,44	6,4	14,0
	8,0	39,2	9,12	6,0	14,4

The analysis results showed that reducing the resistance of a parallel-connected rheostat from the perpetuity to 2.0 Ohm leads to a slight change in the test parameters of the alternator. That can be considered the initial stage of failure.

The decrease in resistance from 2.0 to 1.0 Ohm is characterized by a 2.5-fold increase in temperature, while the remaining test parameters change by 9-40%. That is an intermediate stage of failure development.

Further reduction of the resistance of the rheostat leads to the inability of the alternator to perform the objective function, which is the final stage of the failure development.

The criterion of failure of the automotive alternator is to reduce the output voltage to a level at which it becomes impossible to charge the battery. The operation of a battery charged at less than 50% is prohibited, therefore, the alternator output voltage must satisfy the relation:

$$U_{per} \le U_{bat}^{50\%} = 12,2V \tag{6}$$

The final stage of failure development is accompanied by acoustic noise (hum) and a significant change in test parameters: the average value of the voltage and the magnitude of the external magnetic field are reduced by 84% and 67%, respectively. Voltage fluctuations and temperature rises increase 2.9 and 5.7 times.

Consequently, the excess temperature has the greatest sensitivity to electrical faults of the alternator.

Based on the results of the experiment, a mathematical model describing the relationship between the temperature rise of the alternator and its parameters can be represented as

$$\Delta T = \frac{\sqrt{P}}{n} \cdot \left(a + \frac{b \cdot r_{dir}}{r_{dir} + r_{rev}} \right) \tag{7}$$

where r_{dir} – is the resistance of the diode in the forward direction, Ohm; r_{rev} - is the resistance of the diode in the opposite direction, Ohm; a and b – are the coefficients of the mathematical model; n – is the frequency of rotation of the generator rotor, rpm.

Using equation (7) we can calculate the temperature rise with both healthy and faulty rectifier diodes with various combinations of load power and rotor speed.

5. Conclusions

The failures which can be diagnosed basing on the output voltage parameters, external magnetic field, and thermal state are the most common electrical failures in automotive alternators. Physical modeling of electrical failure is performed by connecting elements of adjustable resistance in series or in parallel to the alternator. Failures simulation adequately models the processes occurring in the alternator, with the exception of the thermal state, that is to be corrected. Experimental data obtained due to physical modeling show that temperature is the most sensitive to failures development. The information provided can be used for operational monitoring of the technical condition of the on-board network of emergency vehicles, as well as for improving the automotive alternator elements' design.

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