Modeling of failures of the starter electric motor

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Abstract. Failures of automotive starters make it impossible to reliably start internal combustion engines, which, under adverse circumstances, may cause a risk of road traffic accidents. A significant part of starter failures is associated with electrical faults in electric motors. The occurrence and development of failures causes a change in the torque produced by the starter. A mathematical model of the starter’s performance dependant from the magnitude of the electrical resistance of its windings was developed. Physical modeling of failures was carried out using an adjustable active resistance connected in series and parallel to the armature winding. Critical values of electrical resistance correspond to an open and short circuit of the armature winding of the starter electric motor, and, consequently, to starter failure. The results obtained are instrumental to the development of a diagnostics method for automotive starters without removing them from the motor.

1 Introduction

Despite the high reliability, the technical condition of units, systems, components and parts of vehicles under operating conditions is changing and failures occur from time to time.

Electrical equipment failures are mostly explained by an ever-expanding range of products, an increase in their technical complexity which is consistent with data from other studies. The electrical equipment in vehicles accounts for from 25% to 34% of all failures, and their elimination accounts for up to 30% of the repair time [1], [2].

A vehicle starter, which serves to impose the initial speed to the internal combustion engine, is a reliable device, the service life of which is comparable to the service life of a vehicle itself. However, during the operation of the starters, sooner or later, malfunctions occur, often leading to their failures. Failure of automotive starters automatically leads to the inability to pull away, which in case of adverse circumstances (for example, an unexpected stop of the automobile at a busy intersection or railway crossing) can create a risk of a road traffic accident. Therefore, there is a need for timely determination of the technical condition of automotive starters without removal from the automobile [3], [4], [5], [6], [7], [8], [10], [11], [12].

Traditionally, the composition of car starters includes: an electric motor serving to impose the running torque to the internal combustion engine (ICE) flywheel; a drive mechanism gearing the flywheel and the hauling relay which, first of all, imposes force to the starter drive mechanism and, second of all, connects the electric motor to the battery.

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The distribution of automotive starter failures is shown in Figure 1.

The aforementioned failures can cause the inability to start the ICE (17%), failure to turn on the starter electric motor (40%) or the hauling relay (20%), failure to turn off the starter after starting (11%), as well as increased heating and noise during operation (12%) [13], [14], [15].

The reasons for automotive starter failures are oxidation of the terminals and wire ends (9%), discharged batteries (25%), damage to the flywheel teeth (8%), loosening and fastening of the starter (9%), malfunction of the ignition switch (11%), as well as low quality of components (15%), violation of operating rules (11%), ingress of water, dirt, etc [16], [17], [18].

2 Mathematical model development

Figure 2 represents the electrical diagram of an automotive starter showing that electric motor elements, connected by an electric (electromagnetic) energy stream, form a closed loop. Therefore, deviations in operating parameters of any of these elements (the extreme case is a failure) will lead to a decrease in the probability of a reliable ICE start. It can be stated that the starter electric motor has a series-parallel reliability circuit [19].

The voltage supplied to the starter electric motor through the hauling relay contact elements can be written as follows
\[ \begin{align*}
U_S &= U_B - \Delta U_{TR} \\
\Delta U_{TR} &= f(F_K, R_{CTR})
\end{align*} \]

where \( U_S \) is the voltage at the starter, V; 
\( U_B \) is the battery voltage, V; 
\( \Delta U_{TR} \) - voltage drop on the hauling relay contact elements, V; 
\( R_{CTR} \) - resistance of the hauling relay contact elements, Ohm; 
\( F_K \) - contact spring forcing, N.

In general, the voltage drops of \( \Delta U_{BR} \) in the brush holder can be expressed as follows:

\[ \Delta U_{BR} = f(R_{BR}); R_{BR} = f(g_{BR}, R_C) \Rightarrow \Delta U_{BR} = f(g_{BR}, R_C) \]

where \( R_{BR} \) is the resistance of the circuit "brush holder-armature winding", Ohm; 
\( g_{BR} \) - brush pressing force, N; 
\( R_C \) - collector resistance, Ohm.

In this case, the voltage at the armature winding of the starter electric motor will be described as follows

\[ U_A = U_B - \Delta U_{TR} - \Delta U_{BR} \]
The following factors will influence the running torque of the starter electric motor: armature winding resistance $r_a$ and magnetic flux value $\Phi$.

$$M_A = C_M \cdot \frac{U_s}{r_a} \cdot \Phi, \ \Phi \approx F_B$$ (4)

where $C_M$ is the constant factor defined by parameters of the armature winding; $\Phi$ – magnetic flux, Wb; $F_B$ - magnetomotive force, A; $r_a$ - armature winding resistance, Ohm; $M_A$ - running torque of the starter electric motor, Nm.

A change in the armature and field winding resistance (in case of electromagnetic excitation) is caused by a change in the insulation resistance: interturn and frame insulation. In good condition, the resistance of the interturn and frame insulation (tens of MOhm) is much higher than the resistance of the windings and does not affect them. In the case of a significant decrease in insulation resistance under the influence of destabilizing factors (moisture ingress, high temperature, corrosive substances), an interturn short circuit or short circuit to the frame occurs leading to a decrease in the resistance of the windings.

Based on the above, the mathematical model of the armature winding performance will be as follows:

$$r_a \sim \omega_a \rightarrow r_a^{\text{nominal}} \text{ если } R_{ci} \rightarrow \max, R_{ti} \rightarrow \max$$ (5)

where $r_a^{\text{nominal}}$ is the nominal value of the armature winding resistance, Ohm; $\omega_a$ - the number of turns of the armature winding; $R_{ci}$ - resistance of frame insulation, MOhm; $R_{ti}$ - resistance to interturn isolation, MOhm.

In turn, the mathematical model of the inductor will be as follows

$$\begin{cases} r_{fw} \sim \omega_{fw} \rightarrow r_{fw}^{\text{nominal}} \text{ если } R_{ci} \rightarrow \max, R_{ti} \rightarrow \max \\ F_B^1 = \frac{U_s}{r_{fw}} \cdot \omega_{fw}, F_B^2 = \text{const} \end{cases}$$ (6)

where $F_B^1$ is the magnetomotive force of the poles, A; $F_B^2$ - magnetomotive force of permanent magnets, A; $r_{fw}$ - field winding resistance, Ohm; $\omega_{fw}$ - the number of turns of the field winding; $r_{fw}^{\text{nominal}}$ - nominal value of the field winding resistance, Ohm.

Since the running torque at the starter output is formed by an increase in the built-in planetary reduction gear, the running torque of the starter can finally be expressed as follows

$$M_S = M_A \cdot i_r \cdot \eta_r$$ (7)

where $M_S$ is the starter running torque, Nm; $i_r$ - reduction gear ratio; $\eta_r$ - reduction gear efficiency.

Based on the above, the condition for starter performance can be expressed as follows:
The voltage of the starter electric motor, according to the theory of electrical machines, is determined as follows

\[ U_A = U_B - I_A \cdot r_a - \Delta U_{BR} \]  \hspace{1cm} (9)

where \( I_A \) is the current in the armature winding, A.

\[ I_A = \frac{U_B - E}{r_a} \]  \hspace{1cm} (10)

where \( E \) - back-electromotive force, V.

\[ E = c_e \cdot n \cdot \Phi = c_e \cdot n \cdot k_{\Phi} \cdot I_A \]  \hspace{1cm} (11)

where \( n \) is the rotation frequency, 1/min;
\( k_{\Phi} \) - proportion factor.

After all the transformations we get

\[ U_A = U_B \cdot (1 - \frac{r_a}{r_a + c_e \cdot n \cdot k_{\Phi}}) - \Delta U_{BR} \]  \hspace{1cm} (12)

Thus, the starter voltage, which is a diagnostic parameter, is determined by the value of the armature winding resistance \( r_a \), that is, the structural parameter.

The voltage of the battery is subject to significant fluctuation during the vehicle operation leading to a corresponding change in voltage and amperage of the starter. Therefore, the armature winding electrical resistance, which is determined on the basis of the measured amperage and voltage values, was chosen as a generalized diagnostic parameter.

In the event of electrical malfunctions associated with the armature winding, its resistance will change affecting in its turn the voltage of the starter.

Therefore, the voltage of the starter can be expressed in the form of the following mathematical model

\[ U_A = a_0 \cdot U_B \cdot (1 - \frac{r_a}{r_a + b_0}) \]  \hspace{1cm} (13)

where \( a_0, b_0 \) are the factors determining the relationship between structural and diagnostic parameters.

3 Experimental findings

To establish a clear difference between the operable and inoperable state of the armature winding of the starter electric motor, there was an experiment carried out involving physical modeling of winding faults using adjustable active resistance.

To determine the factors of the mathematical model, an experiment was carried out aimed at establishing the influence of the armature winding resistance on one of the diagnostic parameters - starter voltage. For this purpose, the increase and decrease of the armature...
winding resistance was simulated on a specially designed stand [20]. Among the advantages of this method are a significant acceleration of the experiment, the ability to simulate a set of several failures, as well as establishment of a clear difference between the operable and inoperable state of the starter.

The electrical circuit of the experiment is shown in Figure 3.

Fig. 3. Electrical circuit of the experiment

To simulate the discontinuity of the armature winding, an adjustable active resistance (rheostat) is connected in series with it. By adjusting the resistance of the rheostat, it is possible to simulate the oxidation of the collector surface and loosening of the brush springs (in the intermediate position) or the discontinuity of the armature winding in the extreme position of the rheostat [22].

Results of simulating the discontinuity of the armature winding (Figure 4) showed that with an increase in the resistance of the rheostat, the starter voltage drops and when the critical value $R_{critical} = 0.319 \, \text{Ohm}$ is reached, the starter stops rotating, which means that the armature winding is broken.

To simulate a short circuit of the armature winding, the rheostat must be connected in parallel with it, while there is a decrease in the current flowing through the armature winding, and, consequently, the magnetic field created by it. With a decrease in the rheostat resistance, the starter voltage drops and when the critical value $R_{critical} = 0.0085 \, \text{Ohm}$ is reached, the armature winding is completely shunted and the current flows through the rheostat (Figure 5).

Thus, the electrical resistance of the armature winding is both a structural and diagnostic parameter, the determination of which makes it possible, without removing the starter from the engine, to evaluate the technical condition of the electric part of the starter.
Fig. 4. Results of simulating the discontinuity of the armature winding of the starter electric motor

\[ U_a = U_s \cdot \frac{\alpha_2}{r_a} \]
\[ R^2 = 0.964 \]

\[ R_{critical} = 0.319 \text{ Ohm} \]

Fig. 5. The results of simulating the short circuit of the armature winding in starter electric motor

\[ U_a = U_s \cdot \left(1 - \frac{\alpha_1}{r_a}\right) \]
\[ R^2 = 0.9513 \]

\[ R_{critical} = 0.0085 \text{ Ohm} \]

As a result, the solution to the problem of predicting the performance of an automotive starter becomes possible, when the dependence of the change in the quantitative values of the electrical resistance of the armature winding on the mileage of the automobile (starter) is established.
4 Conclusions

Failures of automotive starters (approximately 12% of all electric equipment failures) make it impossible to reliably start internal combustion engines, which, under adverse circumstances, may cause a risk of road traffic accidents. A significant part of starter failures is associated with electrical faults in electric motors.

Electric motor elements, connected by an electric (electromagnetic) energy stream, form a closed loop. Therefore, deviations in operating parameters of any of these elements (the extreme case is a failure) will lead to a decrease in the probability of a reliable ICE start.

The developed mathematical model establishes the dependence of the starter’s performance from the magnitude of the electrical resistance of its windings. Since modern starters, as a rule, do not have a field winding, the role of which is played by permanent magnets, the main structural parameter of the starter electric motor is considered to be the armature winding resistance.

Physical modeling of failures was carried out using an adjustable active resistance connected in series and parallel to the armature winding. Critical values of electrical resistance correspond to an open and short circuit of the armature winding of the starter electric motor, and, consequently, to starter failure.

Further studies will be aimed at obtaining a generalized mathematical model of the automotive starter performance including both electrical and mechanical elements. The results obtained are instrumental to the development of a diagnostics method for automotive starters without removing them from the motor.

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