Physical simulation of the faults of starter batteries

A V Puzakov and D A Smirnov
Orenburg State University, Pobedy avenue, 13, Orenburg, Russian Federation
andREW78@yandex.ru

Abstract. The parameters of the starter battery may degrade during its operation in the vehicle resulting in failures of the consumer units, for example, starter. It is necessary to know the principle of the battery parameters changes during its operation for the purpose of prevention of the battery fault incidence and simplification of the process of their correction. The purpose of the article is the development of the ways of simulation of various faults. This will enable to perform the extensive testing of the battery under laboratory conditions because testing on board would complicate the experiments significantly. The article proposes the ways of simulation of seven the most typical faults of the starter battery. The proposed experiments will make it possible to regulate the battery fault scale manually. This will enable to identify the output parameters of the battery under various conditions, as well as to find the critical points. Discharge of the battery up to 70, 55 and 40% of charge was simulated in the context of the article. Moreover, the results of testing of this battery with the use of discharge tester were presented. Further researches will be devoted to the identification of the battery parameters during simulation of its faults.

1. Introduction
The number of electric accessories increases consistently in modern motor transport vehicles. More and more motor transport vehicles using only electricity as the energy source appear. Moreover, the motor transport vehicles being able to generate electric power individually appear, for example, fuel cell electric vehicles. The number of plug-in hybrid vehicles also increases. The electric equipment of such motor transport vehicles may be easily called as the most important from all in-vehicle systems.

The electric equipment on board of the motor transport vehicles with the internal combustion engine (ICE) is no less important since it provides both engine starting and stable operation of all other system of the motor transport vehicle. Strengthening of the environmental requirements, necessity of improvement of the comfort and fuel efficiency results in the development of corresponding electrical and electronic systems.

General operational performance of the motor transport vehicle depends on the electric equipment integrity. The engine starting becomes impossible in the event of the battery breakdown. Currently the vehicle design does not provide for the devices enabling to prevent such situations. The possibility of the evaluation of the battery technical condition on board of the motor transport vehicle will significantly improve the general reliability of the motor transport vehicle.

About 30% of all faults of the motor transport vehicle account for the electrical equipment on the average. Moreover, every second equipment failure is related to the battery.
The main faults of the starter batteries include: lowering of the battery charge level (34% of all faults), oxidation of the pole terminals (18%), paste shedding (14%), short-circuit fault (12%), plates sulfation (10%), local action (8%), breaking of circuit inside of the battery (4%) [1, 2, 3, 4].

Lowering of the battery charge level is the most common fault; it is caused usually either by long isolated operation of the battery or by the event that the capacity of the utilized consumer units exceeds the capabilities of the automotive alternator. Simply said, in most cases the battery is not broken; it is uncharged. Charge lowering is characterized primarily by voltage reduction on the terminals resulting in possible malfunctions of the consumer units. This also includes the lagging battery when the loss of charge occurs in one of the battery cells.

Sulfation of the battery plates is another common fault. This defect appears due to improper battery operation and result in formation of poorly soluble crystals of lead sulfates on the plates. The crystals diminish the working surface of the plates decreasing the battery capacity hereby. The battery may be recovered by special cycle, by means of its low current charging in the event of poor sulfation. However, strong sulfation is beyond recovery [5, 6].

Short-circuit fault of the electrodes of opposite charge; it may be identified due to gassing during charging. This defect is usually related to the damages of separators during assembly, separator damage in the group of plates, deviation from the separator dimensions predetermined by the draft, low quality of the separators materials and tilting of certain plates in the group. The battery with such defect may remain functional under certain conditions, for example, during constant operation in summer season. However, its cranking capability reduces significantly due to the fact the considerable part of energy in one of the battery cells is spent for short-circuit operation during standstill (nightstand). Short-circuit fault in any battery cell may be easily established by means of measurement of electrolyte density in the event of standstill of such battery within one or two weeks. The electrolyte density in the faulty battery reduces more actively as compared to the other batteries [7, 8].

Pole terminals oxidation. This fault usually has this name in the papers. Specifically, this is the oxidation of the point of contact of pole terminals and posts. This defect may occur due to absence of proper battery care cleaning of pole terminals and posts. This fault may be characterized by the accelerated lowering of discharge capacity because the resistance increased due to corrosion, and this is the equivalent of the increase in load on the battery [9, 10].

Paste destruction or shedding. It may occur due to long-term use of the battery with high degree of discharge or with high degree of charge but low electrolyte level or by the vibrations caused by imperfect battery fixation, as well as after freezing of the discharged battery in winter. The symptom of the fault includes rapid voltage reduction after discharge to starter.

Battery local action. The normal self-discharge is characterized by the fact that the charged battery losses no more than 10% of its capacity within 14 days and under the electrolyte temperature equal to 20 degrees Celsius. This fault occurs due to closing of terminals by dirt, electrolyte on the cover surface, shorting of electrodes of opposite charge by shedding paste and metallic impurities in the electrolyte.

Breaking of circuit between the battery cells may occur either due to manufacturing defect or because of long-term use under heavy vibration loads. Breaking of inner circuit occurs usually in places of details welding, due to deviation from the design welding conditions or upon availability of crater pipes and cavities appearing in the weldments in the event of violation of the modes of their casting. The conclusion on the reason of circuit breaking may be made based on the battery opening and exploration of the destructed connection. In some cases, the breaking of circuit in the high-quality batteries may be caused by long-term (problematic) engine starting. In any case such fault results in complete battery failure. The symptom of this fault includes the absence of discharge to starter upon availability of the potential between the battery terminals.

Complete corrosion of the grids of the positive electrodes may be also caused by the operating conditions violation. Overcharging due to high voltage on the alternator, as well as the motor transport vehicle operation in taxi mode. As practice and the academic papers show, such fault occurs usually during battery operation under hot climate conditions.
2. Simulation of the starter batteries faults
The necessity of examination of the great number of the batteries with various technical specifications is challenging for the investigation of the faults of the starter batteries. Moreover, determination of the fault nature and extent is also problematic. So, the faults simulation under laboratory conditions is preferable option [11, 12, 13, 14, 15].

Let us consider the ways of simulation of certain faults of the starter batteries below (Table 1).

| Fault                  | Way of simulation                                           |
|-----------------------|-------------------------------------------------------------|
| Lagging battery cell  | Forcible discharge of one of the battery cells, by means of parallel connection of additional resistance to it |
| Plates sulfation      | Decrease of the plates active area, by means of draining of some portion of electrolyte |
| Short-circuit fault   | Connection of additional resistance to one of the battery cells |
| Pole terminals oxidation | Connection of additional resistance subsequently with the battery |
| Paste destruction     | The simulation method was not established                   |
| Deep discharge        | Forcible battery discharge to various voltage at a standstill |
| Residual capacity lowering | Decrease of the electrolyte level in the entire battery    |
| Breaking of circuit   | Connection of additional resistance between the cells       |

Let us consider the ways of simulation of each fault in detail below.

The lagging battery cell: to discharge forcibly one of the battery cells at a standstill, having connected it simultaneously with the variable resistor R2 (as illustrated in the fig. 1) [16]. The key S2 of the variable resistor shall be opened during measurements.

Short-circuit fault. The way of simulation is like the way for the lagging battery and shall be carried out according to the same manner (Fig. 1). The difference resides in the fact that the measurements shall be taken under closed key S2 of the variable resistor R2.

Plates sulfation. The plate active area decreases due to formation of lead sulphate crystals on the electrode surface. This process may be simulated by draining of some portion of electrolyte, stripping the part of the plate. It is demonstrated in the fig. 2.

\[
S = h \cdot b
\]

where: \(S\) – electrode surface, \(h\) – electrode height, \(mm\); \(b\) – electrode width, \(mm\).

The electrode active area shall be defined by the equation

\[
S' = S - \sum_{i=1}^{n} S_i
\]

where: \(S'\) – electrode active area, \(mm^2\); \(n\) – number of sites of sulfation; \(S_i\) – area of all sites of sulfation, \(mm^2\).
Figure 2. Model of the battery plates sulfation.

The simulated electrode active area shall be defined by the equation

$$S_1 = h_1 \cdot b$$  \hspace{2cm} (3)

where: $S_1$ – simulated electrode active area, mm$^2$; $h_1$ – battery electrolyte level, mm.

By simulation condition

$$S_1 = S'$$  \hspace{2cm} (4)

Pole terminals oxidation. The current passage through the battery terminals is made difficult under this fault. So, it is necessary to connect the variable resistor R1 subsequently with the battery (as shown in the fig. 1) for the purpose of simulation of this fault.

Deep discharge. It may be simulated by means of utilization of load on the battery and its forcible discharge to certain values.

We should keep in mind during measurements that the battery recovers the voltage partially over time after load removal in the event of the battery discharging.

Residual capacity lowering. The simulation may be carried out in a similar manner to the experiment with sulfation, except perhaps the electrolyte shall be drained from all cells of the battery.

Breaking of circuit. The simulation is carried out according to the chart of the fig. 1, with the use of the variable resistor R3. For this purpose, five cells of the battery GB1 and one cell of the battery GB2 are used; the variable resistor R3 is turned on between them. This will enable to improve the resistance between the cells like in the event of real fault.

3. Experimental part

The discharge tester providing connection of the low-value resistor to the battery was used as a load device during the experiment. The strength of the current drawing now of loading is within the range (180-260 A) for the properly functioning battery. Due to the fact that the discharge tester notes the indications of the voltage and strength of the current on a single occasion, the digital multimeter Testo 760-2 and the current clamp Testo 770-2 (fig. 3) was used for the identification of nature of change of these parameters in the course of loading.

The nature of change of the discharge current and battery voltage for deep discharge, terminals oxidation and short-circuit fault in one of the cells was established experimentally. The battery was fully charged again before each new stage [17].
A – discharge tester H-2005; GB – starter battery 6CT60VL; PV – multimeter Testo 760-2; T – current clamp Testo 770-2

Figure 3. Design of experiments.

Change of the battery voltage and the discharge current of the properly functioning fully charged battery were determined at the first stage. Afterwards the battery was discharged to the final voltage 12.0, 11.5 and 11.0 V (deep discharge simulation) and the nature of the battery parameters change was also determined for each case. The results are presented in the fig. 4. It follows from the charts of the fig. 4 that the deep discharge results in larger change of voltage rather than discharge current.

Figure 4. Results of discharged battery testing.

The resistor with a resistance of 0.025, 0.05 and 0.1 Ohm (simulation of oxidation of terminals and posts) was connected subsequently with the battery at the second stage. The experiment results are presented in the fig. 5. The initial phase of the characteristics (fig. 5) does not have a dramatic drop in parameters.

The resistor with a resistance of 0.025, 0.05 and 0.1 Ohm (simulation of short-circuit fault in one of the cells) was connected simultaneously with one of the cells of the battery being last in a row at the third stage. The experiment results are presented in the fig. 6. It can be observed that the short-circuit fault resulted in the battery parameters increment.
4. Conclusions
General operational performance of the motor transport vehicle depends on the battery operable condition. According to statistic data, about 15% of all breakdowns of the motor transport vehicles with the internal combustion engine (ICE) accounts for the battery. The engine starting becomes impossible in the event of the battery breakdown. Currently the vehicle design does not provide for the devices enabling to prevent such situations. The possibility of the evaluation of the battery technical condition on board of the motor transport vehicle will significantly improve the general reliability of the motor transport vehicle.

It is necessary to know the principle of the starter battery parameters changes under certain fault for the purpose of troubleshooting on board of the vehicle. Physical simulation of the starter batteries faults enables to accelerate the process of obtainment of such information. Most of the faults may be
simulated with the use of connection of the adjustable effective resistance simultaneously or subsequently with the battery. The nature of change of discharge current and voltage of the battery for deep discharge, terminals oxidation and short-circuit fault in one of the cells was established experimentally.

Further researches will be oriented to the physical simulation of other faults and compilation of data array for the system of automatic diagnostics of starter batteries.

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