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DEFINITION OF RESIDUAL OPERATION RESOURCE OF STARTER BATTERIES BY WAY OF IMPEDANCE RESEARCH AT DIFFERENT SERVICE TERMS

Abstract. The **subject matter** of the article is the physicochemical processes occurring in a battery under different conditions and operating times. The **goal** of the study is to develop, a methodology for estimating the residual life-span of the batteries to make recommendations on the extension of their service life on the basis of an analysis of the conditions of use of the batteries. The **tasks** to be solved are: to analyze the influence of starter battery conditions on their performance and service life; to analyze the existing methods of determining the residual life of the batteries; to study the dependences of the deviation of the impedance from the standard value for the batteries at different moments of their normal life and to develop a method for predicting the residual life of the rechargeable batteries (RB). General scientific and special methods of scientific knowledge are used. The following **results** are obtained. On the basis of the readings of the ammeter and voltmeter when switching on the battaries in the circuit at different load values and according to the data obtained during the control-training cycle (CTC), the dependence of the impedance deviation from the base value at different regular battery life was investigated. According to the proposed method, it is easy to determine in which batteries the degradation has just begun and in which they have reached the level when they need to be replaced without waiting for a fatal failure, by obtaining a minimum number of values of the electric parameters of the battery and comparing the data obtained at different times. Proper selection of chargers, skilled operation and timely monitoring of battary's residual life are the most important requirements for their operation. In full-time batteries, the internal resistance begins to increase over time due to natural wear and tear. Significant deviation from the norm in the smaller side indicates a clear malfunction such a battery must be replaced regardless of its useful life. When the deviation from the baseline exceeds 25%, it is time to replace the battery. The conducted studies revealed nonlinear relationships between the battery life and its predicted residual life. **Conclusions.** Ensuring that the equipment is ready for use depends largely on the state of the RB. The greatest impact on the performance and life of the batteries is due to the temperature conditions, the degree of sparseness of the batteries on the machine and the level of charging voltages on the network. In the actual operating conditions of the RB, there is a need to assess their technical condition, disassemble them for troubleshooting, maintain their availability and extend their service life. RB degradation is reflected in the internal support of the battery cells. Determining the internal resistance of the RB is based on the Ohm dependencies of the complete circle and reduces to a system of two equations. RB life can be considered one of its most important performance characteristics. The relationship between battery life and its estimated residual service life is nonlinear. Proper selection of chargers, skilled operation and timely monitoring of RB's residual life are the most important requirements for their operation.

Keywords: starter batteries; residual life; impedance; internal current source resistance.

Formulation of the problem and research tasks

Ensuring that the equipment is ready for use depends largely on the state of the rechargeable batteries. Typical service life standards for lead-acid starter RB write-offs are set in accordance with industry regulations, but the determination of residual operating life is usually difficult because it is probabilistic.

Based on the need to maintain a high level of combat readiness of troops at the lowest cost, given the shortage of time, it is necessary to justify the minimum diagnosis of RB, which can be carried out in the course of their storage, when charging or discharging or by organizing special test effects.

From now on, the relevance of robots to think over is that, simply, the method of identifying the excess operating resource of RB is not informative, costly and time-consuming.

The methodological basis of the prejudice has become the igneous sciences and the special methods of the science of knowledge. They are the following:

– theoretical foundations of electrical engineering and electrodynamics have been used to obtain mathematical relationships to determine the internal resistance of a starter battery;

– comparative analysis of existing methods for determining the residual operational life of the starter battery;

– mathematical methods for statistical processing of measurement data to obtain graphical dependencies of the impedance deviation of the current source from the standard value at different service life.

Analysis of recent research and publications

The causes of degradation and failure of the RB have been thoroughly researched by specialists to date, and the basic rules of operation and maintenance have been defined. lead starter battery life [1, 2].

Extension of battery life is possible both when choosing a rational amount of work and their periodicity during maintenance and by introducing new equipment for their diagnosis [3-9].

Manufacturers and users of rechargeable batteries are paying great attention to the creation and implementation of fundamentally new diagnostic methods and devices. This is due to the fact that the existing, including the standard devices used in the diagnosis of armored weapons and military equipment batteries, and the diagnostic tools that have become widespread use in civilian enterprises, are imperfect and do not provide the necessary accuracy of measurements.

For example, while measuring the density of an electrolyte, the hydrometer gives an error of up to 10%.

In addition, battery diagnostics can also be performed when disassembled. The purpose of diagnosis in this case is to determine the processes that take place in a lead battery, primarily on its electrodes, and which lead to battery failure. That is, to find the causes of defects that reduce the area of the active surface of the electrodes, increase the leakage current, which increase the internal resistance of the battery.

To determine the phase composition of the active mass of the battery electrodes, a multi-stage process is used, consisting of a given sequence of chemical reactions with special reagents (selective solvents).

During these chemical reactions, the analyte also undergoes a number of physical effects, such as heating. The residue is then weighed (its chemical composition is known) and the analytical content of the industry standard determines the percentage of the desired substance in the sample to be analyzed. In this regard, this method of diagnosis allows to determine the composition of the active mass only indirectly, since there are no direct measurements of the elemental composition, and the error in determining the chemical composition of the electrode substance can be quite large.

Existing modern methods of spectral analysis of the elemental composition and surface structure of various materials to determine the composition of the active mass of the electrodes, the processes that occur on the lead electrodes of the battery and lead to its failure, have not been used and have not been considered in the literature.

Experience in the operation of starter batteries shows that the dependence of their service life on the quality of diagnosis and maintenance is very large and according to experts, will remain for a long time.

Therefore, the reasons discussed above for batteries are currently being used forcible maintenance. In maintenance troops, stored batteries are filled with electrolyte, and their periodicity is directly determined by the management. Other sources only provide specific recommendations for the amount and frequency of battery maintenance work.

The battery life of armored weapons and military equipment under the existing system for diagnosing and maintaining stored batteries is limiting and achievable only with strict observance of the periodicity and complete performance of the set work.

The **goal** of this work is to develop, on the basis of an analysis of the operating conditions of the AB, a methodology for estimating the residual life of the batteries and make recommendations on the extension of their service life. To achieve this goal the following research objectives are proposed: o analyze the influence of operating conditions of starter batteries on their performance and service life; to analyze the existing methods of determining the residual life of the batteries; to study the dependences of the deviation of the impedance from the standard value for the batteries at different moments of their normal life and to develop a method for predicting the residual life of the RB.

Main material

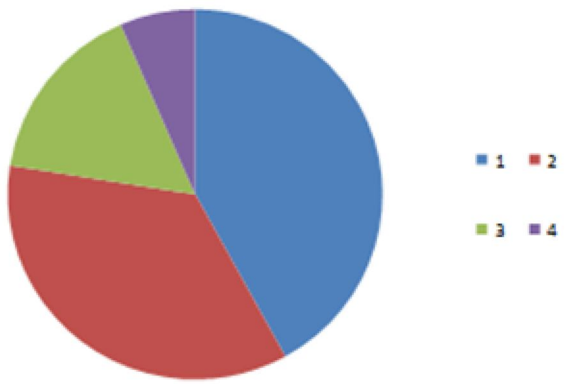
1. Effect of operating conditions on the performance and battery life. Rechargeable batteries are capable of operating within the specified service life, subject to the rules of operation and storage.

As noted, the greatest impact on the performance and life of rechargeable batteries has: temperature conditions; the degree of battery discharge in the car; the level of charging voltages in the board. For the batteries used on existing armored weapons and military equipment units, the ratio of the number of different malfunctions according to fig. 1.

In this case, the formation and development of individual malfunctions of lead batteries occurs in their close relationship. The service life and storage of batteries filled with electrolyte, defined during the conduct now is 4 - 5 years [10].

The following processes and factors have a decisive influence on the battery life:

– corrosion of positive electrode current collectors;
– spitting of the active mass of positive electrodes;
– quality of separators;
– design features of the electrode block.



1 – corrosion of positive electrode current collectors; 2 – spitting of the active mass; 3 – destruction of separators; 4 – other faults

Fig. 1. Main causes of failure of domestic lead starter batteries installed in armored weapons and military equipment

2. Residual operational resource as a condition of their readiness for use on machinery. The main failures of lead-acid batteries are in one way or another related to the processes occurring at their electrodes, that is, to the processes of changing the mechanical, physical and chemical properties of metals and alloys due to the thermodynamic nonequilibrium of their initial state with a gradual approach to equilibrium.

The RB's residual resource will be considered as the average total battery life under certain operating conditions in the period from the moment of control of the technical condition to its transition to the limit state.

As the statistical sample is usually insufficient for this purpose, the RB life expectancy methodology needs further refinement**.** Degradation is susceptible to any battery, and in any case this is reflected in the internal resistance of the battery cells. In full-time batteries, the internal resistance begins to increase over time due to natural wear and tear.

Strictly speaking, full impedance includes internal impedance, inductive and reactive component [11].

3. Methodology for determining residual operational life of starter RB by measuring internal resistance. The method of determination of residual operational life of starter ABs by measuring internal resistance is considered in the article. Determining the internal resistance of the RB is based on the Ohm dependencies of the complete circle and reduces to a system of two equations.

According to Ohm's law in the full circle of EMF is equal to the sum of all voltage drops on the inner and outer sections of the circle

$$\varepsilon = U_{ex} + U_{in}. \tag{1}$$

Considering Ohm's law for a circle section,

$$U_{ex.} = I \cdot R_{ex}, \tag{2}$$

$$U_{ex} = I \cdot r, \tag{3}$$

here r – internal resistance of the current source. So,

$$\varepsilon = I R_{ex} + Ir. \tag{4}$$

There are two unknowns in this equation, so finding them by algebra rules requires at least two equations that include these unknowns.

To obtain these two equations, we will study the experimental circle in two stages. An electrical circuit is proposed for the study, which includes the following elements: battery; ammeter; switch; resistance shop, with known the values of all resistances that are it includes (Fig. 2).

When choosing some average resistance value R_1 i the closing circuit of the ammeter arrow will show some value of the amperage I_1.

Then the following will be true:

$$\varepsilon_1 = I_1 R_1 + I_1 r. \tag{5}$$

It is suggested that the experiment be repeated, replacing the resistor in the resistance store by some value R_2.

The ratio is true for this case

$$\varepsilon_2 = I_2 R_2 + I_2 r. \tag{6}$$

Since the experiments were conducted with the same current source, it is natural to assume that

$$\varepsilon_1 = \varepsilon_2. \tag{7}$$

Solving equations (5) and (6) together, we have:

$$r = \frac{I_1 R_1 - I_2 R_2}{I_2 - I_1}. \tag{8}$$

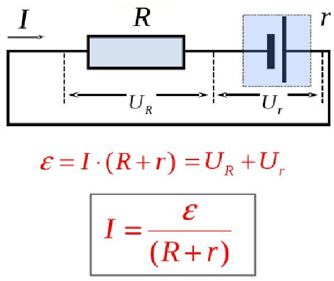


Fig. 2. Scheme of measurement of the internal resistance of the Ohm current source for the complete circuit

To control the quality of the experimental data, follow these steps:

We calculate the EMF value by substituting r into one of the equations. We will have the value of EMF:

$$\varepsilon_1 = I_1 R_1 + I_1 \frac{I_1 R_1 - I_2 R_2}{I_2 - I_1} \tag{9}$$

or

$$\varepsilon_2 = I_2 R_2 + I_2 \frac{I_1 R_1 - I_2 R_2}{I_2 - I_1} \tag{10}$$

We measure the voltage U at the terminals of the source with the key open. It is equal to the EMF of the current source.

To offset the statistical and instrumental errors, a series of experiments were conducted, the results of which were subject to statistical processing.

The average results of measurements and calculations of the internal resistance RB are shown in Table 2.

Table 2 – **Results of measurements and calculations of the EMF of the current source**

№	Amperage *I*, A	External circuit resistance *R*, Ohm	Internal Resistance *r*, *Ohm*	EMF $_1$ of source ε_1, *V*	EMF $_2$ of source, ε_2, *V*	The voltage at the terminals of the source when the key is open *U*, *V*
1	0,97	2	0,02	1,98	2,0	2,0
2	0,39	5	0,02	1,997	2,0	2,0

4 Determination of internal resistance of the battery during the CTC. The control and training cycle (CTC) is carried out to monitor the technical condition of the batteries, check the capacity given to them, and recharge the lagging batteries.

During the control-training cycle, a control (training) discharge of 10-hour current is performed.

The discharge current must be carefully maintained throughout the discharge, which should end when the voltage on one of the batteries drops to $U = 1.7$ *V*.

The value of the discharge current for the batteries during the training cycle is determined by the technological documentation and is known for calculations [12]. The values of temperature, electrolyte density, etc. should also be considered as unchanged when conducting one series of experiments.

According to the data obtained during the CTC, were calculated values of the internal struts of the batteries. Since the measurements of the discharge current were carried out at intervals of 2 hours to 15 minutes, it can be considered that a statistical sample of the results is sufficient for ignition. Examples of the results of the measurement of discharge noise for batteries when conducting a training cycle are shown in Table 3.

Table 3 – **The value of the discharge current for the batteries during the training cycle**

Battery type	Discharge current, A	Battery type	Discharge current, A
6STEN-140M	12,6	6ST-75	6,8
6ST-140P	12,6	6ST-82	7,5
12ST-85P	8,0	6ST-90	3,1
12ST-70M	7,0	6ST-105	9,5
I2ST-70	7,0	6ST-132	12,0
ZST-150	13,5	6ST-182	16,5
ZST-215	19,5	6ST-190	17,0
6ST-45	4,2	ZMT-12	1,2
6ST-50	4,5	ZMT-8	0,7
6ST-55	5,0	6MTS-9	0,8
6ST-60	5,4	6MTS-22	2,0

As noted for the current source, the ratio is:

$$\varepsilon = U_p + I_p r\,, \qquad (11)$$

Here U_p, I_p – corresponding values of load voltage and discharge current at discharge; ε – electromotive force RB; r – internal resistance RB.

That is,
$$r = \frac{\varepsilon - U_p}{I_p} \qquad (12)$$

Since, ε = 2 *V*, and the values of I_p and U_r are measured when conducting CTC, ie they are known, the solution of equation (11) makes it possible to determine the internal resistance of the battery after carrying out only two measurements of current and voltage at different values of load resistance in the circuit.

Examples of the results of calculations of the internal resistance of the RB during the CTC are given in table 4. Let's note that the study was subject to RB with different life spans and for the period of one-time CTC, that is, it is impossible to say that these AB belong to one statistical sample. But the results in Table 4 (similar to the statistically averaged data) indicate deviations of the internal resistance of the RB from the base at different operating times.

Table 4 – **Deviation of the internal resistance of the RB from the base under different operating conditions**

№	I_p, *A*	ε, *V*	U_p, *V*	*r*, Ohm	Operating time RB, year
1.	8	2	1,7	0,0375	0,1
2.	8	2	1,8	0,038	0,5

5. Results of studies of internal resistance of rechargeable batteries with different service life. According to the method discussed above, the dependence of the impedance deviation from the base value at different standard battery life was investigated.

The batteries were subjected to different investigations.

Significant deviation from the norm in the smaller side indicates a clear malfunction, such a battery must be replaced regardless of its useful life.

It has been found that the internal resistance begins to increase with the use of full-time batteries due to natural wear and tear. When the deviation from the baseline exceeds 25%, it is time to replace the battery. For some batteries, the deviation threshold is about 50% (but it's best to check the battery manufacturer's specifications).

The time spent on measuring procedures did not go beyond reasonable. According to the results of graphical dependencies presented in Fig. 3. These dependencies will allow the user to better understand the process of operation of the RB, to identify possible problems and problems.

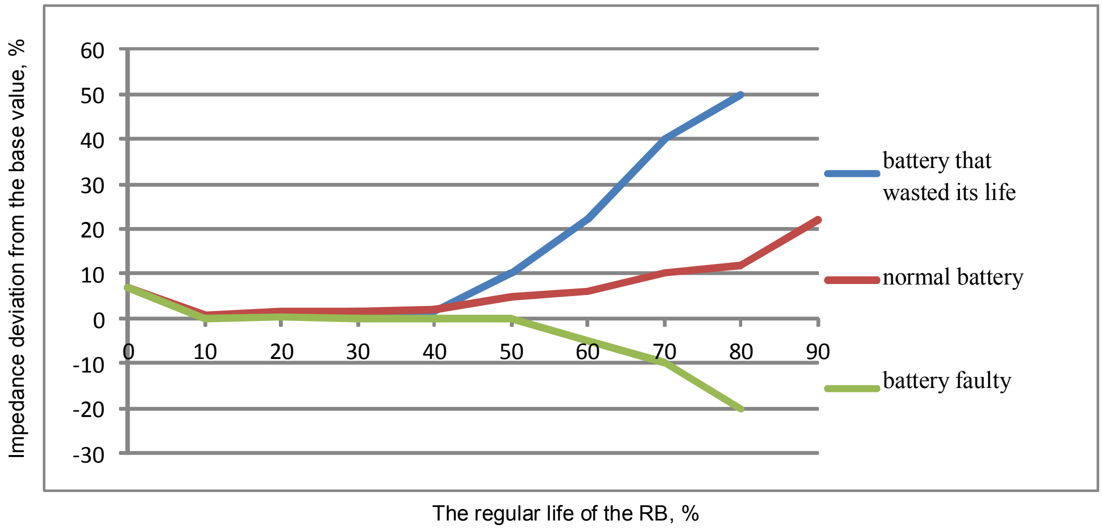


Fig. 3. Results of the study of the dependence of the impedance deviation from the base value at different standard battery life

According to the proposed method, by comparing the data obtained at different times it is easy to determine in which batteries the degradation has just begun and in which they reached the level when they need to be replaced without waiting for a fatal failure [13-15].

6. Forecasting the residual operational life of RB. Studies conducted on rechargeable batteries with different service life revealed nonlinear relationships between the battery life and its predicted residual service life (Fig. 4).

Table 5 – **Forecasted residual service life RB**

№	Battery life, year	Forecasted residual service life of the rechargeable battery, year
1.	0	5
2.	1	3,1
3.	2	1,9
4.	3	1,5
5.	4	1
6.	5	0,1

These data indicate the need to strictly adhere to the rules of operation, the amount and frequency of their maintenance to ensure the reliability, efficiency and maximum life of batteries when operating on machines.

Proper selection of battery chargers and chargers, skilled operation and timely control of residual life are the most important requirements for their operation. Only in this case, it is possible to achieve the greatest economic efficiency of the use of AB and the extension of their operational life.

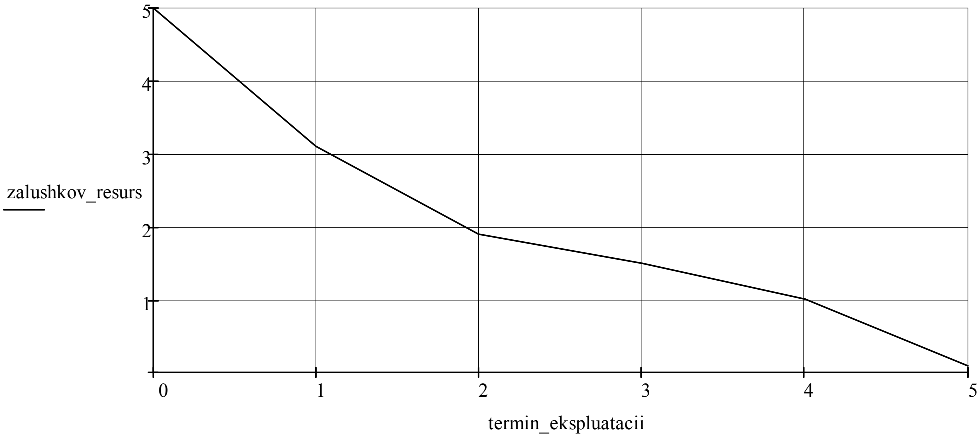


Fig. 4. Dependence of projected residual service life on battery life

Conclusions

1. Ensuring that the equipment is ready for use depends largely on the state of the RB. The greatest impact on the performance and life of the batteries is due to the temperature conditions, the degree of sparseness of the batteries on the machine and the level of charging voltages on the network.

2. In the actual operating conditions of the RB, there is a need to assess their technical condition, disassemble them for troubleshooting, maintain their availability and extend their service life.

RB degradation is reflected in the internal support of the battery cells. Determining the internal resistance of the RB is based on the Ohm dependencies of the complete circle and reduces to a system of two equations.

3. RB life can be considered one of its most important performance characteristics. The relationship between battery life and its estimated residual service life is nonlinear.

4. Proper selection of chargers, skilled operation and timely monitoring of RB's residual life are the most important requirements for their operation.

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Визначення залишкового експлуатаційного ресурсу стартерних акумуляторних батарей шляхом дослідження імпедансу при різних термінах служби

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Анотація. Предметом вивчення в статті є фізико-хімічні процеси, що протікають у акумуляторній батареї при різних умовах і термінах експлуатації. **Метою дослідження** є на основі аналізу умов експлуатації АБ розробити методику оцінки залишкового експлуатаційного ресурсу акумуляторних батарей дати рекомендації по подовженню термінів їх служби. **Задачі:** проаналізувати вплив умов експлуатації стартерних акумуляторних батарей на їх працездатність та терміни служби; зробити аналіз існуючих методів визначення залишкового експлуатаційного ресурсу акумуляторних батарей; дослідити залежності відхилення імпедансу від штатного значення для акумуляторних батарей у різні моменти їх штатного терміну експлуатації та розробити методику прогнозування залишкового експлуатаційного ресурсу АБ. Отримані такі **результати.** На основі знятих показань амперметра та вольтметра при вмиканні АБ у коло при різних значеннях навантаження та за даними, отриманими при проведенні КТЦ, було досліджено залежність відхилення імпедансу від базового значення при різних штатних термінах служби батарей. За методикою, що пропонується, шляхом отримання мінімальної кількості значень електричних параметрів акумуляторної батареї та зіставлення отриманих в різний час даних нескладно визначити, в яких батареях деградація тільки почалася, а в яких досягла рівня, коли їх необхідно замінити, не чекаючи фатального збою. Правильний підбір зарядних пристроїв, кваліфікована експлуатація та своєчасний контроль залишкового ресурсу АБ є найголовнішою вимогою їх експлуатації. У штатно працюючих батарей з часом з-за природного зносу внутрішній опір починає зростати. Істотне відхилення від норми в меншу сторону свідчить про явні несправності, таку батарею необхідно замінити незалежно від терміну її використання. Коли відхилення від базового рівня перевищує 25 %, батарею пора замінити. Проведені дослідження виявили нелінійні залежності між терміном експлуатації акумуляторної батареї та її прогнозованим залишковим експлуатаційним ресурсом. **Висновки.** Забезпечення належного рівня готовність техніки до використання у значній мірі залежить від стану АБ. Найбільший вплив на працездатність і термін служби акумуляторних батарей здійснюють температурні умови, ступінь розрідженості акумуляторних батарей на машинш та рівень зарядних напруг в бортовій мережі. В реальних умовах експлуатації АБ виникає необхідність оцінки їх технічного стану, розбиранню для усунення несправностей, підтримки у встановленому ступеню готовності та подовжуванню терміну служби. Деградація АБ відбивається на внутрішньому опорі елементів батареї. Визначення внутрішнього опору АБ грунтується на залежностях закону Ома для повного кола та зводиться до розв'язання системи двох рівнянь. Термін служби АБ можна вважати однією з її найважливіших експлуатаційних характеристик. Залежності між терміном експлуатації акумуляторної батареї та її прогнозованим залишковим експлуатаційним ресурсом носять нелінійний характер. Правильний підбір зарядних пристроїв, кваліфікована експлуатація та своєчасній контроль залишкового ресурсу АБ є найголовнішою вимогою їх експлуатації.

Ключові слова: стартерні акумуляторні батареї; залишковий експлуатаційний ресурс; імпеданс; внутрішній опір джерела струму.

Определение остаточного эксплуатационного ресурса стартерных аккумуляторных батарей путем исследования импеданса при разных сроках службы

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Аннотация. Предметом изучения в статье являются физико-химические процессы, протекающие в аккумуляторной батарее при различных условиях и сроках эксплуатации. **Целью исследования** является на основе анализа условий эксплуатации АБ разработать методику оценки остаточного эксплуатационного ресурса аккумуляторных батарей дать рекомендации по продлению сроков их службы. **Задачи:** проанализировать влияние условий эксплуатации стартерных аккумуляторных батарей на их работоспособность и сроки службы; провести анализ существующих методов определения остаточного эксплуатационного ресурса аккумуляторных батарей; исследовать зависимости отклонения импеданса от штатного значения для аккумуляторных батарей в разные моменты их штатного срока эксплуатации и разработать методику прогнозирования остаточного эксплуатационного ресурса АБ. Получены следующие **результаты.** На основе снятых показаний амперметра и вольтметра при включении АБ в круг при различных значениях нагрузки и по данным, полученным при проведении КТЦ, была исследована зависимость отклонения импеданса от базового значения при различных штатных сроках службы батарей. По предлагаемой методике путем получения минимального количества значений электрических параметров аккумуляторной батареи и сопоставления данных, полученных в разное время, несложно определить, в каких батареях деградация только началась, а в каких достигла уровня, когда их необходимо заменить, не дожидаясь рокового сбоя. Правильный подбор зарядных устройств, квалифицированная эксплуатация и своевременный контроль остаточного ресурса АБ является главным требованием их эксплуатации. В штатно работающих батареях со временем из-за естественного износа внутреннее сопротивление начинает расти. Существенное отклонение от нормы в меньшую сторону свидетельствует о явных неисправностях, такую батарею необходимо заменить независимо от срока ее использования. Когда отклонение от базового уровня превышает 25%, батарею пора заменить. Проведенные исследования выявили нелинейные зависимости между сроком эксплуатации аккумуляторной батареи и ее прогнозируемым остаточным эксплуатационным ресурсом. **Выводы.** Обеспечение надлежащего уровня готовности техники к использованию в значительной степени зависит от состояния АБ. Наибольшее влияние на работоспособность и срок службы аккумуляторных батарей осуществляют температурные условия, степень разреженности аккумуляторных батарей на машине и уровень зарядных напряжений в бортовой сети. В реальных условиях эксплуатации АБ возникает необходимость оценки их технического состояния, разборке для устранения неисправностей, поддержки в установленной степени готовности и продолжения срока службы. Деградация АБ отражается на внутреннем сопротивлении элементов батареи. Определение внутреннего сопротивления АБ основывается на зависимостях закона Ома для полной цепи и сводится к решению системы двух уравнений. Срок службы АБ можно считать одной из ее важнейших эксплуатационных характеристик. Зависимости между сроком эксплуатации аккумуляторной батареи и ее прогнозируемым остаточным эксплуатационным ресурсом носят нелинейный характер. Правильный подбор зарядных устройств, квалифицированная эксплуатация и своевременный контроль остаточного ресурса АБ является главным требованием их эксплуатации.

Ключевые слова: стартерные аккумуляторные батареи; залишковиць эксплуатационный ресурс; импеданс; внутреннее сопротивление источника тока.