Charging balance management for automotive battery in low-voltage power network under low temperature conditions and at deep discharge of the automotive battery in the car

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Abstract. The paper presents the results of theoretical analysis and mathematical modeling and implementation of algorithms for controlling the charging balance of battery in a low-voltage power network at low temperatures and at deep discharge of the battery as part of an intelligent vehicle control system with a combined power unit. The target of the research is to develop methods to prevent the critical discharge of the battery, methods of charging the battery and methods for control of the current state of the automotive battery. Experiments were performed, experimental data and graphs were obtained. The results of the research allow performing adjustment of the rechargeable battery charge balance management model and contribute to improving the energy balance of the grid, increasing the efficiency and service life of batteries.

1. Introduction
The comfortable and safe operation of vehicles depends on the performance and reliability of the vehicle electronic control systems. An important criterion for their reliability is the failure-free operation of the on-board low-voltage power supply network, to which electronic devices and actuators are connected [3]. The on-board power supply network consists of sources, converters and batteries, which ensure the operation of systems and devices in various modes. The most important components are batteries, since they are most sensitive to operating conditions and work at low temperatures [11].

Rechargeable battery characteristics are dependent on operating conditions, temperature conditions, and battery charging and discharging. In this case, the critical modes are when the battery is in a highly discharged state, as well as at low temperatures, when the density of the electrolyte changes and the electrochemical processes in the battery slow down. This leads to the appearance of negative effects that introduce a destabilizing effect on the operation of the battery itself and the on-board power supply network [6], [7]:

- Decrease in the density of the electrolyte and sulfation of the battery plates.
- Increasing the resistance of the battery, and current limitation.
- With a low charge, the battery becomes a powerful consumer of electrical energy with more voltage dropping on it, which leads to destabilization of voltage level of vehicle's power network.
- Self-discharge of the rechargeable battery in conditions of negative temperatures, which is proceeded with the physical properties change of the battery and the loss of its electrical capacity, and decrease of the charge-discharge working cycles.
- The charging time of the rechargeable battery and the current flowing increases from tens to hundreds amperes, which requires the use of more powerful sources and converters capable of providing target power to the battery and consumers.
- An increase in the charging current at low temperatures and with a considerable discharge leads to the fact that because of electrolysis, a large amount of heat released, which affects heating the battery. An elevated battery temperature degrades the electrochemical characteristics of the battery.
- Battery charge refiling over a long period to charge the battery at low temperatures and low charge. Density changes of the electrolyte leads to the subsequent degradation of the battery.

The abovementioned and other factors lead to decrease the operational efficiency of the vehicle battery. As a result, some systems operate for a short time and not at full power in order to maintain operation of the battery, generator or DCDC converter at maximum power to ensure the battery charge. The power supply loses stability and charging balance tends to the negative digits. The functions of damping current oscillation, which are normally performed by the battery, are not performed, and when powerful consumers are turned on, the function of systems and devices is interrupted due to the voltage drop. It becomes necessary to replace such expensive battery with a new one.

Requirements for batteries and operating conditions under Russian domestic standards and International standards, including GOST R 53165-2008, GOST R 58092.1-2018, GOST 15596-82, GOST R ISO 6469-1-2016, GOST R IEC 62485-3-2013.

It is necessary to use improved power management algorithms to avoid the negative effect of low temperatures of the automotive battery, as well as to exclude its sulfation, critical discharge, voltage drop at the battery terminals, short circuit of one of the modules, decrease in maximum power and efficiency, as well as to prevent other changes, to control the battery’s discharge, as well as to carry out timely and quick battery charging in negative temperatures.

2. Internal resistance influence of the battery on the charge and discharge current

The internal resistance of the battery is the ability of the battery to deliver current to the active load, the value of which depends on the value of this resistance. When the value of internal resistance is low, the battery is capable to deliver a higher current to the load (without significant voltage decrease at terminals), and therefore more power, while a high value of internal resistance leads to immediate decrease in the voltage at the battery terminals with an immediate increase load current. This leads to the fact that an outwardly good battery is unable to fully transfer the energy stored in it to the load.

The internal resistance includes the resistance of the plate material, the active surface layer of the plates, separators, and the resistance of the electrolyte, which is highly dependent on temperature, a decrease in ion mobility and an increase in the viscosity of the electrolyte increase the internal resistance.

Equation for different values of the load current is to be solved to determine the internal resistance. When the load is connected, it is necessary to determine open circuit voltage of the source and the voltage at the terminals of the power source. Internal resistance can be found from the following equations:

\[ U_{\text{out1}} = U - rI_1 \]  \hspace{1cm} (1)
\[ U_{\text{out2}} = U - rI_2 \]  \hspace{1cm} (2)
in which $U$ is the open circuit voltage, $U_{\text{out1}}$ is the output voltage at the current $I_1$, $U_{\text{out2}}$ is the output voltage at the current $I_2$. When the system of equations is solved, a formula for the internal resistance and voltage at the source output is obtained:

$$r = \frac{U_{\text{out1}} - U_{\text{out2}}}{I_2 - I_1}$$  \hspace{1cm} (3)

$$U = U_{\text{out1}} + I_1 \frac{U_{\text{out1}} - U_{\text{out2}}}{I_2 - I_1} = U_{\text{out1}} + I_1 r$$  \hspace{1cm} (4)

To calculate the internal resistance, it is necessary to find the voltage in open circuit mode and the current in the short circuit mode. In this case, the system of equations is as follows:

$$U_{\text{OC}} = U - 0$$  \hspace{1cm} (5)

$$0 = U - r I_{\text{SC}}$$  \hspace{1cm} (6)

in which $U_{\text{OC}}$ - output voltage with no consuming at zero load current; $I_{\text{SC}}$ - load current in short circuit mode with a load with zero resistance. The no consuming output current and the short-circuit output voltage are zero. get equation:

$$r = \frac{U_{\text{OC}}}{I_{\text{SC}}}$$  \hspace{1cm} (7)

$$U = U_{\text{OC}}$$  \hspace{1cm} (8)

To calculate the internal resistance and EMF of an equivalent generator, which electrical circuit is already known it is indispensable to:

- Calculate the output voltage in no consuming mode.
- Calculate the output current in short-circuit mode.
- To find $r$ and $U$ by the formula based on the obtained values.

The process of changing the value of the rechargeable battery internal resistance when changing the load current should be examined in more detail. The internal resistance increase during high current discharge as a result of electrolyte density decrease in the pores of the active mass and near the Pb electrodes. When the battery temperature drops, the maximum battery current decreases.

The voltage drop of a lead-acid battery is not linear and depends on the discharge current. When the discharge current is over 30A-50A, then diffusion of electrolyte ions and current varies in a wide range occurs, as well as the internal resistance of the battery does not change linearly. At low discharge current of 1-5A of the battery, internal resistance changes limited by the physical and chemical characteristics of the lead plates. Therefore, the internal resistance of the battery at high discharge or charge currents is several times less than the internal resistance of the same battery at low currents.

Lead-acid batteries with a capacity of 100-200A have larger mass and the amount of lead, which is used than batteries of small capacity 45-65A. More powerful batteries have a larger working surface of the lead plates and more volume for electrolyte diffusion inside the battery. As a result, batteries with large mass and capacity have less internal resistance than batteries of small capacity.

The diffusion rate of electrolyte ions increases at high temperatures. This dependence is linear and determines the dependence of the internal resistance of the battery on temperature. At high temperatures, the internal resistance of the battery is much lower.

The amount of active mass on battery plates decreases, which leads to a decrease in the active surface of the plates during the battery discharge. Therefore, the internal resistance of a charged battery is lower than a discharged battery’s internal resistance.

Figure 1 and 2 shows discharging process of a lead-acid battery with a nominal capacity of 100A*h at low temperatures to an active load. The discharge current varies from -35A to -20A at -40˚C. So the discharge of the battery decreases in proportion to the value of this resistance, as well as a change in the internal resistance, which increases during the discharge of the battery and indicates that the maximum output current a charged battery can deliver. [12]

For the load current (Fig. 1), the internal resistance curve of the battery is obtained (Fig. 2). Measurements of currents, voltages, low temperature and internal resistance made by means of values of the intelligent battery sensor. The block diagram for measuring the operating parameters of the battery is...
shown in Fig. 3. The error of measurement of operating parameters is less than 10% according to the specification.

**Figure 1.** Graphics of battery charge and current with a varying load, where 1 – SOC battery charge curve, 2 - battery current curve with a changing active load.

**Figure 2.** Graphics of charge and internal resistance with a varying load, where 1 – SOC battery charge curve, 2 – change of internal resistance \( R_{ip} \).
The block diagram explains a method of battery voltage measuring considering the current going through the battery, battery temperature, which is necessary in order to calculate the internal resistance of the battery. Internal resistance used to predict battery life and battery replacement. It is believed that after 1 year of operation, the internal resistance of the battery, with proper operation, is to increase by no more than 5-8%. If the rate of cells resistance increase exceeds the expected rate, the operating conditions of the battery, its load, charging process and other processes. Battery cells with the internal resistance, which differs from the average calculated for all cells by more than 10%, are considered defective, so the battery needs to be replaced.

3. Battery capacity changes under the influence of external factors

The capacity of a battery is the amount of stored electrical energy that a fully charged battery can provide electric energy at certain discharge mode, ambient temperature and final voltage. The capacity is measured in ampere-hours and determined by the formula [8], [9], [11]:

\[
Q = \frac{I_p}{t_p} \int_0^t \frac{dE}{dt} \, dt
\]  

in which \( Q \) - the battery capacity [Ah], \( I_p \) - discharge current [A], \( t_p \) - discharge time [h].

If the battery connected to a constant load, then the capacity calculated by multiplying the time required to discharge the battery by the constant discharge current.

The nominal capacity of the battery is determined by the manufacturers and introduced in the product specification.

\[
SOC_t = \frac{Q_t}{Q_r}
\]  

(10)

The battery capacity is determined at the end of the charge cycle at time \( t \), and \( Q_r \) - the nominal battery capacity specified by the manufacturers.

\[
SOC_0 = \frac{Q_0}{Q_r} = 100\%
\]  

(11)
Battery current capacity can be expressed in terms of released capacity, as in the equation:

$$Q_t = Q_0 - Q_{rl}$$

in which $Q_0$ - the initial capacity of fully charged battery and $Q_{rl}$ - battery load released capacity. Therefore, battery SOC at any time can be expressed as in the equation:

$$SOC_t = \frac{Q_0 - Q_{rl}}{Q_r}$$

Equation for battery SOC:

$$SOC_t = \left(1 - \frac{Q_{rl}}{Q_r}\right) \cdot 100\%$$

The equation shows that the battery charge is estimated by the amount of released capacity in relation to the nominal capacity battery storage per unit of time $t$. Considering the term of capacity, it is worth mentioning the battery life as a characteristic of residual capacity. SOH is a measure of the aging of the battery in relation to its original condition, which decreases with time of use. It shows how much of the battery life has been used up and how much it is left before it is replaced. Battery SOH is the criterion that indicates battery state between the start and end of life as a percentage. The end of battery life is reached when the battery cannot operate at the minimum requirements. A fully charged battery has the maximum charge that can be transferred to the load. Battery charge changes depending on the charging and discharging current, aging and external factors, therefore, the characteristics of the battery differ from the nominal. Therefore, battery SOH is defined as the ratio of the maximum charge capacity to the nominal battery capacity:

$$SOH = \frac{Q_m}{Q_r}$$

in which $Q_m$ is the maximum possible battery capacity during its operation, and $Q_r$ - the nominal battery capacity according to the product specification.

Battery capacity simple formula for any type of battery:

$$Q = \frac{P \cdot t}{V} \cdot k$$

in which $P$ is the load power; $t$ - reservation time; $V$ - the voltage at the battery terminals; $k$ - the utilization factor of the battery capacity.

Energy capacity measured in units such as W/cell characterizes the capacity of the battery for a certain short period of time (no more than 15 minutes, in constant power mode). For a raw calculation of the battery storage capacity, measured in Ah by the value of its energy capacity in W/cell for a period of 15 minutes, the following formula is to be used:

$$Q = \frac{W}{4}$$

in which $Q$ is the battery capacity (Ah), $W$ - the energy capacity of the battery (W/cell).

The reserve capacity indicates the ability of the battery to power the electrical equipment of moving car when the standard vehicle generator not work, it is measured in minutes of battery discharge with a current of approximately 25 A. To count a rough estimated value of nominal battery capacity by its reserve capacity, indicated in minutes, with the following formula is to be used:

$$Q = \frac{T}{2}$$

in which $Q$ is battery capacity (Ah), $T$ - battery reserved capacity (min).

Battery state of charge is assessed with a normally open circuit, after the minimum of 6 hours of rest, and at a temperature from +18°C to +22°C. In case of temperature variation, a temperature correction is made. It is believed that lowering the temperature by 1°C reduces the capacity by about 1%, so at -30°C the capacity of the battery will be approximately half of that at +20°C.

Nominal capacity storage decrease of a battery at low temperature is caused by viscosity increase of the electrolyte and a slowdown in the electrolyte diffusion into the pores of the active mass, the inner layers of which do not participate in the electrolysis reaction and battery discharge.[13]

With an increased discharge current, the time it takes for the battery to discharge reduces. This dependence is non-linear and described by the Peukert formula:

$$C_p = t^k \cdot t$$
in which $C_p$ - the battery capacity, and $k$ - the Peukert number is an exponent constant for a given battery or battery type. For lead acid batteries, the Peukert number usually ranges from 1.15 to 1.35.

The formula for the real battery capacity ($E$), which is composed of the Peukert formula, for random discharge current $I$:

$$E = E_n \left( \frac{I_n}{I} \right)^{p-1}$$  \hspace{1cm} (20)

in which $E_n$ - battery nominal capacity and $I_n$ - battery’s nominal discharge current.

An important factor, such as the ambient temperature, where the battery is used, greatly affects the battery capacity. If the temperature rises from 20°C to 40°C, the battery capacity indicator increases by 5%, and if the temperature drops to 0°C, it decreases on average by 15%. A further decrease in air temperature to -20°C leads to the specified parameter’s drop by another 25% relative to the nominal value.

4. Leakage current and discharge monitoring

Leakage current control is an important scientific and technical problem, which allows deviations identifying from the high power consumption mode, battery discharge in conditions of long-term parking of the vehicle without charging from a generator or a DC voltage converter. Leakage current monitoring also allows to identify the remaining battery charge and prevent its further decrease by controlling the power supply modes of consumers.

Batteries used to provide power to the automobile, when the current source is disconnected are very sensitive to loss of charge. This leads to poorer performance, so the most common states of battery charge are identified. These are shown in the table (for lead-acid battery 12V, 100Ah).

| Battery charge state            | Voltage at COV | Density of electrolyte g/cm$^3$ | Battery internal resistance mOhm | Battery charge SOC % | Battery charge time with current 0.1C to 100% SOC |
|---------------------------------|----------------|---------------------------------|---------------------------------|----------------------|-----------------------------------------------|
| Full charge of battery         | U>12.7         | 1.265                           | 3-7                             | 100                  | 0-3 hours                                     |
| Normal charge of battery       | 12.35+\-0.1    | 1.225                           | 18-45                           | 75                   | 3-8 hours                                     |
| Low charge of battery (sulfation risk) | 11.95-12.10   | 1.155-1.190                     | 65-230                          | 25-50                | 8-12 hours                                    |
| Discharged destroyed battery (irreversible sulfation) | or U<11.7 | 1.120                           | R>230                           | 0                    | 12-24 hours                                    |

Figure 4 and 5 show the process of 100Ah battery discharge and changes in its internal resistance under negative temperatures at -30°C, as well as the voltages at the terminals, which are equivalent to the discharge characteristic, which is shown in Figure 6. The presented graphs show increasing in internal resistance, which limits the current that the battery can deliver. It can also be concluded that the capacity has decreased. At low temperatures, the battery discharge occurs 1.15-1.35 times faster than when the battery is discharged in room conditions for a constant load. If we integrate the current for the specified time, we will get a battery discharge of 14.5 A*h in 30 minutes, which exceeds the calculated discharge for normal conditions (12Ah) without taking into account the correction factors by 14%. The illustration of the charge cycle shows that after a short discharge of 12.5% from the fully charged state, the charging current increases significantly to 0.5C, and decreases according to the hyperbolic dependence. Battery charge increases much more slowly, and to refill the nominal battery capacity it will take time, which correlates with Table 1.
**Figure 4.** Dependence of current and voltage on the load at negative temperatures on a fully charged battery during the discharge process and at the beginning of the battery charge cycle, where 1 - the graph of the voltage on the battery, 2 - the graph of the load current.

**Figure 5.** Dependence of the internal resistance and charge on the load at negative temperatures on a fully charged battery during the discharge process and at the beginning of the battery charge cycle, in which 1 - the internal resistance, 2 - the battery charge.
Figure 6. Discharge characteristics of automobile batteries with the capacity of 55Ah to 65Ah at room temperature from 100% SOC when connected to a fixed load.

In order to ensure that the battery capacity does not decrease during usage as well as the discharge rate of the battery does not increase, it is indispensable to control the discharge current in time and limit operation of powerful consumers. High discharge currents and an increase in internal resistance will require a higher current from the power source, which the battery will consume as a load. When comparing the charge and discharge, it should be taken into account that when the battery is discharged at low temperatures, the discharge rate increases from 1.15 to 1.35 times, and when charging at low temperatures, the charge rate decreases by 1.5-2 times, which can be seen from Figure 4.

5. Battery state of charge and incoming current monitoring methods
The chemical process of rechargeable battery charging and discharging is to be regarded [1], [2]. One electrode of the battery is a lead plate coated with PbO$_2$, the other is a lead plate made of spongy lead Pb. The electrolyte is a sulfuric acid H$_2$SO$_4$. During the discharge, PbO$_2$ is renewed and due to the reaction with sulfuric acid, PbSO$_4$ is formed. Lead is oxidized at the other electrode and forms Pb(SO)$_4$. At the end of the discharge, both plates are filled with lead sulfate. When the battery is charged, electrolysis takes place and dioxide and metallic lead are formed from sulfate [4], [5]. When the battery is discharged, the electrolyte solution is diluted with water. The main current-forming process in accordance with the theory of double sulfation in a lead battery is described by the following reaction:

$$Pb + PbO_2 + 2H_2SO_4 \rightleftharpoons 2PbSO_4 + 2H_2O$$ \hspace{1cm} (21)

EMF calculation performed by the formula:

$$E = E^0 + \frac{2.303RT}{F} \log \frac{a_{H_2SO_4}}{a_{H_2O}}$$ \hspace{1cm} (22)
in which $E^0$ is the EMF value of the battery cell ($E^0 = 2.041$ V), $a_{H_2SO_4}$ is the activity of sulfuric acid; $a_{H_2O}$ - water activity.

In practice there are several varieties of battery charging methods to launch an electrolysis reaction in a battery are used. Charging methods used in control systems to charge battery in a car should now be examined.

Battery charging with constant current.

To use this method, the current value is maintained constant throughout the charging cycle. The voltage on the battery increases, reaching 2.5-2.7 V by the end of the charge of each cell, the constant current changes by using rheostats, thyristors or current regulators. Charging at constant current is accompanied with gas extraction, which leads to decrease of the current. Reducing the current increases the charging time.

Two-stage and multi-stage charging.

For the first stage, the charging current is equal to 0.5C-1C of the nominal battery capacity. When the voltage on one battery cell reaches 2.4 V (when water electrolysis process starts), the charge current decreases by 2 times, battery charge continues in stages with a predetermined time interval until a predetermined voltage is reached. Voltage reaches 2.5-2.7 V at the last stage of charging. Condition of end cycle with a stepwise constant current charge for each stage is reaching of constant battery voltage and electrolyte density.

Charge at constant voltage with a decreasing current.

The constant voltage charging method is the main method for charging batteries in cyclic mode. With this method, a constant voltage is applied to the battery poles at the rate of 2.35-2.65V per cell. First, the charge current is set at 0.2-0.4C, and then the voltage value is stabilized by the end of the charge. The charging time is 6-12 hours, depending on the charge of each battery cells.

Two-stage combined charge method.

The two-stage charge is performed in two stages at a constant voltage: first at a higher voltage and then at a lower voltage. The initial current at the first stage is about 0.4C, and the current at the second stage is 0.15C. This method is not suitable for charging the battery if the battery is in buffer mode with a load.

Compensation charging method.

The compensation charge method is used at the end of the charge and is as well used as an independent charging method when charging lead-acid batteries operating in standby vigil mode. Charge voltage value setting is 13.6-13.8V for 12V batteries. The initial charge current is about 0.15C, and at the end of the charge, charge current is about 0.05C.

Battery recovery charging method.

When the battery is deeply discharged, a recovery charge is performed to avoid sulfation of the lead plates. The recovery charge is carried out at a constant charge voltage and an initial charge current of 0.1–0.25C for 18–24 hours. If the battery is slightly sulfated, then the method of charging with an asymmetric current is applied: when the load is connected in parallel to the battery, and the charge occurs in current pulses. During charging by the current pulsed rechargeable battery is charged, and at the pause moment battery discharges to the active load.

Recharging.

With all methods of charging, the consumption of electricity for electrolysis of water is taken into account, the battery supplied with an additional amount of electricity, which exceeds the nominal value of 10-15% at the beginning of operation and of 25% or more at the end of the service life. For some types of lead-acid battery boost charging are used.

Boost battery charging method.

Boost charge is used when the battery needs to be charged quickly in a limited period of time, for instance, after an emergency or a deep discharge. So it is advisable to charge the battery by a combined two-stage method. The end of the charge is determined by the overcharge coefficient of 0.95-1.05 achievement. It is allowed to perform several forced charges. After the boost charge, a charge with a overcharge coefficient of 1.15-1.20 is performed.
Additional recharging.
To keep a battery with low self-discharge in a full charged state, it is necessary to perform periodic recharging. Control-training cycle is carried out in accordance with the following procedure: the battery is discharged to a capacity of at least 10%, and then recharged. Complete battery discharge is not permissible, since deep discharge leads to a decrease of battery capacity. Depending on the design of the batteries, the charging current should not exceed 0.1–0.3C.

6. Power management during battery discharge
The described methods of discharge and charge, taking into account the influence of external factors affecting the change in internal resistance and capacity value of the battery, allow coming to choice of the most optimal concept for using battery as a buffer and main source of power. Due to the fact that the battery is operated in a combined mode the task of achieving the greatest efficiency is to reduce control its discharge current and refill the charge applying the most suitable method for each case. In comparison to lithium-ion battery, it takes much longer time to recharge the lead-acid batteries, so it requires minimizing the discharge current in order to ensure a positive charge balance and extend the battery life.

There are several the most common controlled discharge modes of battery, as well as methods for reducing discharge currents during operation:
1) Low power consumption mode – power mode, when consumers are disconnected, but individual consumers get connected to the battery for a short period of time and consume low power. For example, a perimeter security system and keyless entry system.
2) Preheating mode - consumption mode when the battery provides power to the load for a long time and the process accompanied by a deep battery discharge at low temperatures.
3) Mode of starting engine by starter - power mode, when the starter is temporary powered by the battery, and the charge refilled in a cycle of one trip.
4) Load damping mode – power mode, when power and operation speed of alternator or DCDC converter are not enough to decrease short current peak that occurs when the load is turning on.
5) Consumer power mode after turning off the ignition - a mode in which the battery is maximally charged and often warmed up, and powerful consumers are turned off in stages, which contributes to the correct completion of their work.
6) The mode of increasing the ICE torque by reducing the load on the generator - a mode in which, in order to unload the engine, the generator operate into idle mode. This is often necessary when moving the beginning or when overtaking, when it is required to transmit the maximum torque to the transmission shaft, then the entire load is connected to the battery.
7) Short-term increase load mode (for example, when ESP in regulation) - a mode in which a powerful consumer is turned on for a short time, and then consumed battery charge that refilled during the trip. The operating mode is limited to 15 seconds at up to 50A current, this process consumes less than 5-10% of the nominal capacity charge, and battery operates in a buffer mode.
8) The mode of short-term power consumption of the low-voltage power network when the units in waking up mode - power mode in which short-term power consuming occurs to power the load with a current of less than 25% of the calculated power of the consumers, after turning on the ignition or vehicle unlocking, and they remain at the energy-saving mode until the engine starts and the generator is turned on.
9) Emergency power supply mode in case of a generator or DCDC converter in malfunction. This is operation mode when the current source fails and the battery is able to power consumers for a short time. Typically, battery power is selected to keep vehicle control systems running for 15-30 minutes after generator or DCDC converter fails.[14]
10) Power limitation mode, when the generator power is much lower than the consumed and it is required to turn off powerful consumers that do not affect the safety of the vehicle - such a mode when, in order to ensure the required level of supply voltage, it is required to switch off powerful consumers step-by-step.
In order to keep the battery in working condition and extend its service life, when choosing power management methods, it is necessary to preserve 70-80% of the battery charge and prevent deep discharge. Deep discharge accompanied by sulfation, which can be irreversible, the charge cycle may be sufficient to desulfate the battery plates.

The discharge process accompanied by an increase in the battery charge current, which requires an increase in the converter current setting, as well as a correction of the power network voltage, which the converter supports. At different temperatures and battery charge, the voltage regulation map is shown in Fig. 7, and graphically in Fig. 8. The formula that describes correction of charge current with an increase in the battery current flowing performed for the modes of boost charge and multistage charge:

$$I_{req} = \sum I_{DCDC} + I(t^0, SOC)_{BAT,LIM} - I_{BAT} - I_{rap,crg},$$

in which $I_{BAT}$ - the current flowing into or from the battery, $\sum I_{DCDC}$ - the total current of DCDC converters, $I(t^0, SOC)_{BAT,LIM}$ - the current limit according to the battery charging characteristic model, $I_{rap,crg}$ - the current providing the fast charge mode.
7. Conclusions
Reducing the negative impact on the battery at low temperatures and with increased discharge current is possible through the use of a complex of actions related to reducing the current consumption when the generator is off or DCDC converter is not operating, as well as control of the current and voltage settings of DCDC converters or generator to ensure one of the selected battery charging processes.

Methods for disconnecting powerful consumers and reducing power consumption, which are most effective for equalizing the rechargeable battery charging balance:
1) Disconnection of powerful consumers - allows to completely switch off the consumer, which helps to reduce the power consumption from the power network depending on time.
2) Reducing the brightness of internal lights, that do not affect safety of the vehicle.
3) Reducing the duty cycle of PWM signals for controlling electric drives and mechanisms, which allows you to maintain the operation of systems such as windshield blowing, interior ventilation, trunk and steering column positioning control systems, heaters and other system components, but at the same time maintain their functionality.
4) Current limitation of such systems as electric power steering, hydraulic unit of the ABS / ESP system, engine-cooling fan reduces the current consumption.

When analyzing the existing charging methods, it can be concluded that the battery charging methods described above are best suited for operating battery in a vehicle and when using it as a damper at constant voltage:
1) Two-stage and multi-stage method - allows you to provide the battery with the initial energy to prevent the process of sulfation of lead plates.
2) Charging at constant voltage – process that is performed during operation with a sufficiently charged battery, which dampens the load current pulses.
3) Compensating charge method – it is performed to prepare the battery for connection to the load for a short time.
4) Forced charge – it used to refill the expended energy when powering consumers with high current for a long time and at low temperatures.

The change in internal resistance is an indicator of the battery life, and also allows you to evaluate the battery charging efficiency after a prolonged operation under load and at low temperatures, and allows you to select the most optimal battery-charging mode.

Capacity change is accompanied by temperature decrease and can cause irreversible discharge and sulfation of the battery. To extend the battery life, it is necessary to minimize operation time of consumers at low temperatures, and to replenish the battery charge as soon as possible.

Monitoring leakage currents allows to conclude that the charging and discharging rates of the battery are not equal, therefore, the greatest attention should be paid to avoiding discharge, since refilling takes a long period of time and then warming up the battery to transfer electrolyte to a liquid aggregate state is also required.

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