Charging balance management technology for low-voltage battery in the car control unit with combined power system

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Abstract. The article presents the results of mathematical models and algorithms development complex, which is aimed at ensuring a positive charge balance of an automobile low-voltage rechargeable battery in car control systems with a hybrid power system. The aim of the work is to create and implement a set of software and mathematical models on one of the existing passenger car model, using the default components and systems of the car, to achieve a positive energy balance of the automotive low-voltage power network, and also to solve the problem of battery discharge by normalizing the turn-on time of powerful consumers leading to fast battery discharge. As criteria for the optimal performance of the proposed models and algorithms, the SOC parameters are considered - state of charge (%), battery charge (A * h), charge and discharge current of a battery (A), voltage on a battery during its charge when a charging current is absent or in a quiescent state (V), ambient temperature (°C). Authors defined: composition of a control system, the necessary logic and a set of mathematical models implemented by electronic systems to control the charging balance of the automotive low-voltage power supply network, connections and functions of systems and components. As a result of a full-scale experiment, charge and discharge graphs, experimental data, current characteristics and dynamics of their changes during operation, experimental time-current dependencies during the operation of each component of a low-voltage power grid were obtained. The results of the work support to improve energy balance of an electrical power network, increase the efficiency and service life cycle of batteries, formulate system and technical requirements for control systems and their subsequent implementation. Versatility solutions are provided for improving management of charge balance car battery.

1. Introduction

A modern car is full of electronic systems that allow solving a number of different tasks: to control the power unit, adjust the gears, ensure stability and safety on the road, make a comfortable climate in the vehicle, control interior and exterior lighting, play media files, control various drives and mechanisms. All this is made possible by equipping the car with electronic systems that provide power to the on-board network and maintain the positive energy balance of the electrical network to which consumers are connected.

On a modern automobile, it is customary to locate several sources of electrical energy [7], which provide the on-board network with consumers and ensure the charge of car batteries [8]. Thus, one of the devices produces electrical energy by converting the mechanical rotation of electric machines or generators shaft to electrical energy, other devices convert it to the required power level of the on-board
network, and the third perform the function of accumulating electrical energy for subsequent start and powering the on-board network [3, 4].

Despite the fact that it seemed that all existing automobile systems for generating, converting and storing energy are capable of providing the necessary current and voltage to power consumers, in real-life conditions this does not always become possible. To provide the required level of output current for all systems, we would have to increase the characteristics, and as a result, the dimensions of electric machines and generators. This would result in a higher torque requirement for the powertrain, and as a result, higher power and fuel consumption, which would also complicate the implementation of current standards for toxicity and harmful emissions. Increasing the capacity of the same type would increase their size and weight, which would require large fuel resources when the vehicle is moving.

To solve the problem of improving the efficiency of vehicle operation and reducing fuel costs, reducing harmful emissions and other tasks aimed at ensuring the overall energy efficiency [1] of a vehicle, it is necessary to create intelligent electronic power management systems. These systems must ensure the optimal energy balance of the car when using energy sources with lower mass and dimensions, and often contribute to a decrease in the energy capacity of the accumulator storage cells while maintaining the functionality of all connected control systems. This is achieved, first of all, due to the efficient distribution of energy between sources and consumers, monitoring the state of the battery and its timely charging, reducing the work duration of powerful consumers, distributed control of energy converters.

2. The task of developing methods and algorithms for ensuring the charging balance of an automotive low-voltage rechargeable battery

Annual tightening of the requirements for harmful emissions cannot be achieved without reducing the operating time of the power unit and proper distribution of electrical energy between sources and consumers. In this connection, cars with combined power system have been widely developed [12]. Cars are equipped with an internal combustion engine that connected with an electric machine. It operates in both engine and generator mode. In the generator mode, the electric machine provides the high-voltage on-board network and contributes to the charging of the high-voltage battery [5]. The low-voltage network is powered by a high-voltage network through DCDC converters. To the low-voltage on-board network, consumers of electrical energy and a rechargeable battery are connected in parallel scheme, which serves as a storage buffer and dampens a unusual changes in the network.

Damping function becomes impossible without the use of batteries with improved charging and time-current characteristics. AGM or helium batteries are often used. These types of batteries can accumulate charge faster due to faster chemical processes. But at the same time, as with lead-acid batteries, they have a feature, that at higher temperatures, above +20 degrees Celsius, it is necessary to reduce the charging current and voltage to prevent boiling of the electrolyte. At low temperatures, it is required to increase the output voltage and charging current to help the battery warm up and increase its charge rate.

Due to the fact that the battery during the operation of the vehicle assumes the functions of a damper when electric power generator or DCDC converter fails to provide the necessary current to power the consumers, it is constantly required to monitor and charge the battery, disabling powerful consumers to prevent its discharge and subsequent degradation. There is a range of charge for batteries where the most efficient use is from 65% to 95% for most modern helium batteries and AGM battery.

During the charging of the battery, the operating voltage is no less important, since at values of charging voltage less than 12.5-13.5 volts, the battery stops charging and becomes a source, transferring the accumulated energy to the on-board network. In order to ensure the required voltage level of the on-board network at which the battery is charged, it is necessary to regulate the output voltage of the generator or DCDC converter which provide the on-board network.

When solving the problem of ensuring the charging balance of an automobile low-voltage battery, it is necessary to solve several key problems connected with its operation:
• It is necessary to monitor and diagnose the state of the battery in order to monitor and detect deviations of its operating parameters from normal values;
• It is necessary to create an optimal control method for the generator set or the power converter in order to adjust the charging current and battery voltage for its effective charge in different temperature conditions and at different values of the load current;
• It is necessary to develop a method that allows disconnecting high-power consumers in case of a negative charge balance of a low-voltage rechargeable battery in order to equalise the currents produced and given to consumers;
• It is necessary to develop a model [11] that monitors the state of the battery at rest in order to detect timely leakage currents and disconnect devices that lead to the consumption of electrical energy when the ignition is off, for example, keyless vehicle access systems.

Solution of the tasks should be a set of mathematical functions, combined into a single model that ensures the implementation of the tasks and implemented as a program code in the automotive electronic unit that acts as a power controller and a car battery charge.

As part of the tasks solution, it is necessary to create a block diagram of the modern power vehicle system structure, including the main sources and converters of electrical energy, as well as sensors that allow measuring the operating parameters of a low-voltage rechargeable battery during its operation. It is necessary to present the allowable intervals for changing the operating parameters of the battery during its operation.

It is necessary to present a generalized concept of mathematical model implementation for controlling the charge balance of a car battery and describe the main connections of its individual elements.

It is necessary to assess the possibility of applying the technology in harsh climatic conditions and to assess the boundary modes of application.

It is required to test the method as part of the existing vehicle sample, to investigate the effectiveness of the proposed charge method and to obtain experimental dependencies of the car battery charge processes when regulating the currents and voltages in the vehicle’s on-board network during its operation. When high-powered consumers are turned on, it is necessary to estimate the speed of the battery charge system’s response to an instantaneous change in load. To assess the possibility of applying the proposed method on other vehicles is required.

3. Modern power system structure of a passenger car equipped with a combined power system
Modern power system of cars with combined plants is often presented in the following form.

![Diagram of modern power system structure](image-url)

**Figure 1.** Modern energy system of cars with HES.
The power unit has a direct rigid connection with the electric machine through a shaft or gearbox. Then the electric machine with its shaft is connected to a manual gearbox or an automatic gearbox (automatic transmission). The electric machine is connected to the inverter through a high-voltage cable that powers the electric machine at the time of start-up, and when the power unit is up and running, it supplies the power inverter, which, using the BMS charge control system, charges the high-voltage traction battery (HI voltage battery) to the required level [9]. The DCDC DC-DC converter is powered by a high-voltage network, performing the functions of converting electrical energy from a higher voltage to a lower voltage and vice versa (reversible energy converters). DCDC converter performs two functions. The first function is power supply of the on-board low-voltage network 12V-14V which charges the low-voltage rechargeable battery, all consumers are connected to it. The second function is to help the high-voltage battery to start at low temperatures, when the converter operates in a reverse mode [10]. When the ignition is on, but the power unit isn’t working, the power supply of the on-board electronics is combined. Part of the energy is converted by DCDC from a high-voltage battery to low voltage, and another part comes from a low-voltage battery. When the ignition is off, while DCDC is inactive, the entire on-board electronics are powered by a low-voltage rechargeable battery. The battery is used to power the BMS system [6] and control units, including the electronic control unit (ECU) of the traction inverter, until the DCDC converter turns on or the power unit is started up.

4. Block diagram of the main elements involved in managing the charge balance of a low-voltage battery

In order to ensure the most stable balance of electrical energy within the framework of the existing vehicle architecture, it is necessary to choose the concept of ensuring the charge balance of an automotive low-voltage battery. To do this, initially it is necessary to develop a structural diagram (Figure 2) of the main elements involved in managing the charge balance of the battery.

In the presented scheme, the high-voltage battery is connected to the DCDC converter, which is controlled by the charge balance control unit by generating current and voltage requests at the low-voltage output of the converter. The low-voltage battery is connected with the DCDC converter in parallel to the on-board power supply through an intelligent battery sensor (IBS). The battery sensor allows you to monitor the degree of battery charge (SOC,%), battery life level (SOH,%), battery voltage (U, V), battery pole temperature (T, ºC), as well as inflowing and flowing current (I, A). A complete list of parameters, ranges of change and accuracy of measured values for the most common types of sensors for rechargeable batteries with wake-up function are presented in Table 1.

According to the known parameters of the battery, the electronic control unit calculates the values of the setpoint of currents and voltages for the DCDC converter, and also determines operation duration of powerful consumers and, if it's necessary it increases the current in the high-voltage network during start-up by charging the low-voltage battery.
Table 1. The most common measured parameters for an intelligent current sensor of battery.

| Parameter name                                      | Measurement range          |
|-----------------------------------------------------|----------------------------|
| Duration of sleep mode until the next wake up       | 30 .. 7620 s               |
| Discharge current when it wake up                   | -250 .. 0 mA               |
| Charge current when it wake up                      | 0 .. 2500 mA               |
| Charge when the sensor wake up                      | 0 .. 125 Ah                |
| Battery current range                               | -2000000 .. 2000000 mA    |
| Battery voltage                                     | 0 .. 50 V                  |
| Battery model temperature                           | -40 .. 125 °C              |
| Error of current                                    | 0 .. 1 (logic)             |
| Error of voltage                                    | 0 .. 1 (logic)             |
| Error of temperature                                | 0 .. 1 (logic)             |
| Wake up by current                                  | 0 .. 1 (logic)             |
| Wake up by charging                                 | 0 .. 1 (logic)             |
| Wake up by charge level                             | 0 .. 1 (logic)             |
| Wake up by timeout                                  | 0 .. 1 (logic)             |
| Wake up by voltage                                  | 0 .. 1 (logic)             |
| Sensor Sleep Time                                   | 0 .. 65534 min             |
| Min Battery Quiescent Current                       | -65000 .. 0 mA             |
| Battery charge                                      | 0 .. 100%                  |
| Battery helth                                       | 0 .. 100%                  |
| Internal resistance of battery                      | 0 .. 200 mOhm              |
| Available capacity                                  | 0 .. 249 Ah                |
| Effective capacity                                  | 0 .. 249 Ah                |
| Nominal capacity                                    | 0 .. 249 Ah                |
| Charge current                                      | 0 .. 65535 Ah              |
| Discharge current                                   | 0 .. 65535 Ah              |
| Voltage open circuit                                | 0 .. 65.535 V              |
| Charge at open circuit                              | 0 .. 127.5 %               |

5. The structure of the mathematical model of the charging balance

The structure of developed mathematical model is created and the main connections between the developed program modules are described (Figure 3). The structure of the model consists of the following main elements:

- Charge Balance Manager (MS)
- Condition diagnostics model of the low-voltage power supply network (MD)
- Model of energy control converters DCDC (MC)
- Power Disconnect Management Model (MR)
- Model of the residual battery charge control (MQ)

![Figure 3. Structure of mathematical model of charging balance.](image-url)
Mode manager determines which of the models will be active in various modes of vehicle operation. There is following division according to the modes of modules operations is presented in Table 2.

| Mode            | MS | MD | MC | MR | MQ |
|-----------------|----|----|----|----|----|
| Sleep           | On | On | Off| Off| On |
| Preheat         | On | On | Off| On | On |
| Standby         | On | On | On | On | On |
| Radio           | On | On | Off| On | On |
| Climatic        | On | On | Off| On | On |
| Ignition        | On | On | On | On | Off|
| Drive           | On | On | On | On | Off|
| PowerOff        | On | On | Off| Off| On |
| Transportation  | On | On | Off| On | Off|

The mode manager and the diagnostic model must always be active when the electronic power management unit wakes up by timer, external or internal interruption, then errors that occur during vehicle operation are stored in non-volatile memory (NVRAM) and become available for reading through the tester.

The energy converter control model is active when the high-voltage system is in operation and it is used to select the most optimal converter operation modes according to the current state of the battery for supplying the on-board network and charging the battery with currents that depend on the current charge and battery temperature and also an operating mode.

The model of disconnecting high-powered consumers is turned on at the moment when the DCDC converter is working at the limit of its capabilities, and the calculated current balance in the power grid is shifted to the negative side. Then it is decided to disconnect consumers, which do not affect the safety of the vehicle, but contribute to the unloading of the low-voltage power supply network. In the case when the power supply balance is not reached, then an error flag is set that informs the driver by means of a message on a special display that a problem has occurred and you should immediately contact the service center to fix the problem.

The model of the control of the residual battery charge is used to track the leakage currents in the car after turning off the ignition and powering the electronic components. This is due to the fact that some of the electronic modules are able to turn on after the main ignition is turned off. In the case of an uncontrolled leakage current, there is a risk of discharging the battery to a state when further engine start is not possible or the battery is completely degraded. The model contributes to the formation of a request for de-energizing consumers which wake up in a sleep mode in order to exclude full discharge of battery.

6. Battery monitoring and diagnostics

Monitoring and diagnostics [2] of a battery state are performed in several stages for which the critical parameters of the battery and the state of its charge are determined [XX].

The first stage of diagnostics is that the absence of software error flags is checked by the measured parameters of the intelligent sensor, which are represented by the self-diagnostic functions of the sensor element.

The second stage includes checking the boundary modes of the battery, as well as determining its actual aging and battery life.

The aging and unsuitable battery check is performed by comparing the SOH (state of health) parameter of the battery with the set thresholds.

Old battery is determined based on the following conditions:
$MD_{Aged\ Bat} = Bat_{Pct\ SOH} < Bat_{Pct\ Aged\ Thr}$, \hspace{1cm} (1)

where $MD_{Aged\ Bat}$ is a sign of battery aging, $Bat_{Pct\ SOH}$ is the age or battery life, in percentages, $Bat_{Pct\ Aged\ Thr}$ is a threshold at which it is determined that the battery has aged and does not correspond to the stated specifications.

An unsuitable battery is determined on the basis of the following conditions:

$MD_{NotSuffBatt\ Bat} = Bat_{Pct\ SOH} < Bat_{Pct\ Aged\ Thr}$, \hspace{1cm} (2)

where $MD_{NotSuffBatt\ Bat}$ is a sign of battery unsuitability, $Bat_{Pct\ SOH}$ is the age or battery life expressed in percentages, $Bat_{Pct\ NotSuffBatt\ Thr}$ is the threshold at which it is determined that the battery is not suitable for further use as a part of the car.

The battery voltage check is performed by estimating the voltage value in the measured time interval. Low voltage on the battery is determined from the conditions:

$MD_{UnderVoltage} (10s) = (U_{IBS\ Voltage} < Bat_{U\ UnderVolt\ Thr})$, \hspace{1cm} (3)

where $MD_{UnderVoltage}$ is the logical function of the output signal versus time when the logical condition is met, $U_{IBS\ Voltage}$ is a battery voltage, $Bat_{U\ UnderVolt\ Thr}$ is the voltage threshold at which the error is determined in a given time interval.

High voltage on the battery is determined from the conditions:

$MD_{OverVoltage} (10s) = (U_{IBS\ Voltage} < Bat_{U\ OverVolt\ Thr})$, \hspace{1cm} (4)

where $MD_{OverVoltage}$ is the logical function of the output signal versus time when the logical condition is met, $U_{IBS\ Voltage}$ is a battery voltage, $Bat_{U\ OverVolt\ Thr}$ is the voltage threshold at which an error is determined in a given time interval.

The voltage of a discharged battery is determined from the conditions:

$MD_{DeepDschrg} (60s) = (U_{IBS\ Voltage} < Bat_{U\ DeepDschrg\ Thr})$, \hspace{1cm} (5)

where $MD_{DeepDschrg}$ is the logical function of the output signal versus time when the logical condition is met, $U_{IBS\ Voltage}$ is a battery voltage, $Bat_{U\ DeepDschrg\ Thr}$ is the voltage threshold at which the error is determined at a given time interval.

High and low voltage, which is determined in conditions when all consumers are disconnected from the battery.

$MD_{DisconectUppThr} (10s) = (U_{IBS\ Voltage} < Bat_{U\ DisconectUppThr\ Thr})$, \hspace{1cm} (6)

$MD_{DisconectLowThr} (10s) = (U_{IBS\ Voltage} < Bat_{U\ DisconectLowThr\ Thr})$, \hspace{1cm} (7)

where $MD_{DisconectUppThr}$ and $MD_{DisconectLowThr}$ are logical functions of the output signal versus time when the logical condition is met, $U_{IBS\ Voltage}$ is a battery voltage, $Bat_{U\ DisconectUppThr\ Thr}$ and $Bat_{U\ DisconectLowThr\ Thr}$ are the voltage thresholds at which errors are determined in a given time interval.

The determination of a battery charge state is performed in the third stage of checks (Figure 4) and is performed by comparing the current charge level with permissible thresholds. It is customary to single out several basic battery charge modes, for example:

- A fully discharged battery ($SOC < MD_{Stt1UppLim}$);
- Fast battery charge ($MD_{SOC\ UppLim2} > SOC > MD_{SOC\ UppLim1}$);
- Normal battery charge ($MD_{SOC\ UppLim3} > SOC > MD_{SOC\ UppLim2}$);
- Full battery charge ($MD_{SOC\ UppLim3} < SOC$)

An error state is detected in the case of a long state, when $SOC = 100\%$ or $SOC = 0\%$. 


A feature of the presented state diagram of the control algorithm is that in the event of a change in any of the modes, an instantaneous response of the control system occurs, allowing to compensate the destabilized state.

Figure 4. State diagram of determining the state of a battery charge.

7. Control method of the DCDC converter to charge the battery and achieve a positive charge balance

The method consists in calculating the current balance of the power supply, followed by the determination of the required current limit and voltage set point, which vary depending on what changes in temperature and battery charge, how many consumers are turned on and what is the actual load of DCDC converters.

Current calculation is performed based on what current is required from DCDC converters to ensure battery charge, which maximum battery charge current is permissible at current values of charge and temperature, and which current flows in or out of the battery itself. This method of forming the current setting for a system of DCDC converters can be described by the formula:

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

(8)

where  \( I_{BAT} \) - is the current flowing in or flowing out of the battery, \( \sum I_{DCDC} \) - is the total current of the DCDC converters, \( I(t^0, SOC)_{BAT,LIM} \) - is the current limit, according to the battery charging characteristic model for which the example of implementation is presented in Figure 5.

Figure 5. The model implementation example of battery charging characteristics.
The figure shows that as the charge increases, the inverter's current setting decreases. This is due to the fact that as the charge increases, the internal resistance of the battery changes, which leads to a decrease in the input current. Therefore, to charge the battery in this case a large current does not require. With a low charge, the current is artificially limited to prevent battery degradation. At the same time, it should be a little bit higher than the rated charging current in order to dampen the switching on of consumers and not interrupt the process of battery charging. If the battery is damaged or completely discharged, the current has a maximum value and compensates the defect of the battery. As the battery temperature rises, the charging current decreases to prevent boiling of the electrolyte.

The voltage setting for the DCDC converter is selected depending on the mode of the car battery operation. For the following modes, the principle of setting the voltage of the converters is used, which is described further in the text.

The condition in which an error is detected requires a permanently high voltage value of 14.6 V if the error occurred due to a low charge and a constant low voltage of 13.5 V if the error occurred due to a constant high charge.

In the case of low charge, you need to charge the battery quickly. For this purpose, the voltage setpoint is higher than usual, 15.6V for a fully discharged battery.

As the battery starts charging, the voltage setting changes to a lower value of 14.8 V in order to charge the battery and then go back to normal operation.

In the normal operation mode of the car battery, the battery charging model is used, for which the voltage setting depends on temperature and battery charge as shown in Figure 6. As the temperature rises, the voltage requested from the DCDC converters also decreases as the battery charges and also voltage reduces. At the highest possible temperature and with a fully charged battery, the voltage setting is approximately equal to the open circuit voltage of the battery in steady state at 13.2 V at room temperature in order to protect the battery from destruction.

![Figure 6. Voltage setting for battery charging depending on the electrolyte temperature and low voltage battery charge.](image)

In normal mode, in case of rapid changes in charge, for example, as a result of switching on powerful consumers, when the DCDC converter transmits the maximum current for a given control mode. Further adjustment of the maximum output power is achieved by not significantly adjusting the voltage setting. The total power will be represented by a formula where the output value of the mode is about 2-5% more, which allows to provide additional current in the power supply system and additional power to consumers.

\[
P_{\text{total, max}} = P_{\text{requested, max}} + P_{\text{extra, power}} = U_{\text{req}} \cdot I_{\text{req}} + U_{\text{extra, power}}(SOC) \cdot I_{\text{req}}
\]

The additive voltage, additionally requested in the counting function (Figure 7) of the maximum power, is represented by the function of the dependence of the output voltage on the battery charge. The additive voltage decreases as the battery charges.
After the selection of the current and voltage setting of the DSDS of the converter is made, it is necessary to calculate the current and voltage setting individually for each converter, if there are several such converters. If the converter is used alone, the current and voltage setpoints are calculated based on the maximum power of the device and its load factor. The setpoint calculation function also takes into account that if the converter is overloaded or there is an error, then the current and voltage setpoint are calculated for the second converter, taking into account its mode of operation.

Figure 7. Additive voltage setting function for the converter.

For greater clarity, Figure 8 shows the state diagram where the current and voltage settings are calculated for two DCDC converters that supply the on-board network from the high-voltage network. In the first relation, the total current of the converters is checked and if the requested current is bigger than the total, then the current setting is equal to the maximum current of the converter. In the second condition, the request current and the load of the first converter are checked. If the converter current is less than the total, but more than one of the two converters, then the current setting for the first converter is equal to the maximum current based on the load, and at the second converter the setting is the remainder of the current difference between the requested and the first converter.
Figure 8. Calculation of the setpoint currents and voltages for two DCDC converters.

The third mode provides for the case when the requested current is less than that any of the converters can give, then the current setting of the second converter takes a zero value, and the first is loaded with a current corresponding to the calculated setpoint. In case of a converter error or its 100 percent load, with a zero current request, which means overheating, only one converter is operated, which is limited by the maximum output current based on the converter power.

8. Battery status monitoring in waiting mode
In order to monitor the state of battery charge, a model is needed that monitors leakage currents. To do this, it is necessary to wake up the electronic unit containing the model of ensuring the energy balance of the car in order to check the leakage current with the nominal rest mode and then again set the time for the current sensor until a request is made to wake up the electronic control unit. As the transition to the low-power mode occurs, the electronic modules included in the on-board power supply network disconnect powerful loads and later other loads, up to the transition to the hibernation mode with waking up on an event or a timer.
Figure 9. Model for calculating the controller waking time and leakage current threshold.

Figure 9 shows a model that tracks the duration of the time during which the controller was in power saving mode. After that, a current setpoint is formed, which is set as a threshold for the battery sensor comparator, and the time until the next waking up is set. The time until the next waking up is regulated by the step size and is necessary to compare periodically the current value with the allowable one, check the residual charge, and in case of a critical battery discharge, de-energize devices that periodically wake up and consume electrical energy while the rest remain off.

The charge monitoring function is represented by a model for calculating waking time and a set of comparators that turn off other consumers to prevent critical discharge of the battery in power saving mode. In normal mode, when the DCDC converters are active, the function is disabled.

9. A method that allows disconnecting powerful consumers when charge balance of a low-voltage battery is negative

In the course of operation, when the current of all consumers exceeds the sum of maximum converters current and charging battery current, then in order to bring the consumption of the entire system to the optimum mode, high-power consumers are disconnected in series. They are determined based on the priority of their use in the car. So, for example, heating nozzles or hoses of headlight washer has the lowest priority, and the ABS / ESP hydraulic unit or electric power steering has the highest priority and are disconnected in the most recent case when the battery charge is not sufficient to carry out a response to the disturbance and there is a risk of loss board voltage, leading to a sudden shutdown of all on-board electronics.

To avoid sharp disturbances or premature reactions, a moving average type filter is used. Filtration is performed for charging and flowing current through a low-voltage battery. Next, the following parameters are calculated:

1) The sign of the process, where charge is positive, and discharge is negative.
2) It is determined how long it takes to charge the battery to the set value.
3) It is determined how much charge in amperes / hours flows in and out of the battery.
4) The actual battery charge is calculated taking into account how old the battery is.
5) For a known current, the maximum charge time is limited.

Next, using the obtained values, a comparison is made with the permissible limits of the residual charges of the battery for the low-voltage power supply network, and on this basis, a group of consumers is selected that needs to be turned off in order to achieve a positive charge balance of the car battery (Figure 10).
When selecting a group of disconnected consumers, a flag is formed depending on whether this mode is critical or not, which is used by the system (Figure 11) to inform the driver about an abnormal situation in the power supply.

10. Experimental studies
Testing the proposed method of controlling the charge battery balance was carried out using a sample of a battery, a DCDC converter, an intelligent current sensor, different power loads, and a control unit
into which the proposed control model was integrated. The characteristics of the test battery and DCDC converter are presented in Table 3 and 4.

Table 3. Technical characteristics of the battery EFB 6CT-100.

| Parameter                        | Value     |
|----------------------------------|-----------|
| Maximum current                  | 930A      |
| Rated voltage                    | 12.5V     |
| Open circuit voltage (NRC)       | 11.7…13.2V|
| Battery Capacity                 | 100Ач     |
| Operating temperature range      | -25…+50 °C|
| Leakage current                  | 50 mA     |

Table 4. The dependence of the OCV on SOC and density of electrolyte for EFB 6CT-100.

| The state of battery charge, % | Discharge ratio Kr | OCV, V (2 hours after charging) | Electrolyte density, reduced to 25 °C, g / cm³ |
|--------------------------------|--------------------|---------------------------------|-----------------------------------------------|
| 100                            | 0                  | 12.7 or higher                  | 1.28                                          |
| 75                             | 0.25               | 12.5                            | 1.25                                          |
| 50                             | 0.5                | 12.3                            | 1.22                                          |
| 25                             | 0.75               | 12.1                            | 1.18                                          |
| 0                              | 1                  | 11.8                            | 1.12                                          |

Table 5. Technical characteristics of the DCDC converter BSC624.

| Parameter                                  | Value     |
|--------------------------------------------|-----------|
| The range of high rated voltage            | 220-450 V |
| Low Voltage                                | 14.0 V    |
| Low Voltage Range                          | 8-16 V    |
| Continuous current at rated for example    | 200 А     |
| Maximum allowable current                  | 250 А     |
| Long conversion mode                       | 2.8 kW    |
| Maximum possible power conversion          | 3.5 kW    |
| Converter efficiency                       | 94.4 %    |
| Ambient temperature                        | -40 to +85 °C |

Figure 12 shows a plot of an experiment in which a battery is charged with low currents about 3-5% of the nominal value in accordance with the calculated setting, which limits the value of the current flowing into the battery in this experiment. The graph shows that with an increase in the actual current, the current demand for the DCDC converter changes, which allows for a positive battery charge balance in the process of load control. At the moment of connecting the load, the system destabilizes, which leads to a short-term current increase in the power supply system with subsequent return to a stable value. The response time of the control system, taking into account software delays, is about 100 ms, and the error in controlling the value of the output current and voltage is no more than 5%, which is sufficient to confirm the correctness of the proposed model. The presence of current peaks is due to the fact that the nature of switching on loads isn’t linear and repeatedly leads to destabilization of the current in the low-voltage power supply network.
11. Results and conclusions

As a result of the work, you can come to the following conclusions:

- Monitoring and diagnostics of the battery state allows you to detect deviations from the nominal modes in time and inform you that intervention of technical services in the analysis of faults causes is necessary.
- The proposed method of controlling a power DCDC converter promotes efficient charging in different temperature conditions and under different loads.
- The method, which allows disconnecting of powerful consumers, contributes to the alignment of current converters and load currents.
- A model that monitors the battery state at rest contributes to the long-term preservation of the battery charge and the prevention of critical discharge below the set value.

The solution of the set tasks was accomplished due to the implementation of mathematical functions combined into a single model and implemented as a program code as part of an automotive electronic control unit.

The presented generalized concept of the implementation of a mathematical model for controlling the charge balance of a car battery can be implemented both for vehicles with ICE and for traditional vehicles with ICE.

It is necessary to assess the possibility of applying the technology in harsh climatic conditions, and to assess the boundary modes of application.

Testing the method as part of the control unit on an existing vehicle sample confirms that a positive battery charge balance is achieved for standard electronic control systems.

12. References

[1] Yakunov D M, Debelov V V and Endachev D V Energy efficiency of electric and hybrid vehicles in conditions of low negative temperatures In the collection: Intellectual transport systems Collection of works of the International Automotive Scientific Forum IASF-2017 pp 270-78

[2] Kozlovsky V N, Debelov V V, Deev O I, Kolbasov A F, Petrovsky S V and Novikova A P 2017 Perspective diagnostic systems for managing an autonomous transport object Truck 6 pp 21-28

[3] Debelov V V, Kozlovsky V N, Stroganov V I and Pyanov M A 2014 The complex of electronic control systems for the movement of a passenger car with a combined power plant Part 1 Electrotechnical and Informational Complexes and Systems 1 pp 40–48

Figure 12. Graph of the experiment with the load change in the power supply system.
[4] Kozlovsky V N, Stroganov V I, Debelov V V and Pyanov M A 2014 The complex of electronic control systems for the movement of a passenger car with a combined power plant Part 2 Electrical and information systems and systems 2 pp 19-28

[5] Endachev D V and Skripko L A 2017 Calculation of the degree of charge of lithium-ion batteries used in battery systems of electric vehicles and hybrid cars Electronics and electrical equipment of transport 4 pp 8-11

[6] Varlamov D O, Eremenko V G and Yakunov D M 2016 Simulation of a balancing device on boosting DC / DC converters for a LIFEP04 battery Practical power electronics 3 pp 16-20

[7] Barzukov S N, Guskov A V, Zinoviev E V, Shiganov D A, Shorin A A and Eidinov A A 2013 Electric energy storages for motor vehicles with combined power plants Works NAMI 252 pp 62-80

[8] Yutt V E, Morozov V V, Sokolov L A, Reznik A M and Ospanbekov B K 2017 Modern current sources and charging stations for electric vehicles Tutorial. Moscow State Automobile and Road Technical University (Moscow)

[9] Bakhmutov S V, Sizov Yu A and Kim ME 2015 Development of a mathematical model and the study of a traction battery of a hybrid power plant Works NAMI 262 pp 105-112

[10] Kurmaev R Kh, Struchkov V S and Tsimbalyuk M A 2015 The issue of ensuring the specified temperature regimes of KEU elements when using them on the PBX Works NAMI 260 pp 69-80

[11] Stroganov V I, Kozlovsky V N, Shakursky M V and Zayatrov A V 2018 Modeling the basic processes of electric vehicles and cars with a combined power plant Electronics and electrical equipment of transport 2 pp 8-13

[12] Kozlovsky V N, Aydarov D V, Vasilyev M M and Debelov V V 2018 Development of electric cars and cars with hybrid energy unit Gruzovik 6 pp 18-21