Journal of Engineering Science *Vol. XXX, no. 3 (2023), pp. 35 - 59*
Fascicle *Industrial Engineering* *ISSN 2587-3474*
Topic *Applied Engineering Sciences and Management* *eISSN 2587-3482*

https://doi.org/10.52326/jes.utm.2023.30(3).04
UDC 621.311.6:629.113-83

DIRECTING THE UNIFORMITY OF THE LEVEL OF PULSE CHARGING OF LI-ION BATTERIES USED IN AUTOMOTIVE INDUSTRY

Oleg Petrov* ORCID: 0000-0003-4791-2384

Technical University of Moldova, 168, Stefan cel Mare Blvd., Chisinau, Republic of Moldova
*Corresponding author: Oleg Petrov, *oleg.petrov@tran.utm.md*

Received: 07. 14. 2023
Accepted: 08. 26. 2023

Abstract. The lithium-ion (Li-ion) battery is widely used in modern electronics, serves as a power source in electric vehicles and for energy storage in renewable energy systems. The strengths of Li-ion batteries are their high energy density. Modern Li-ion batteries can include arrays of cells, the lifetime of which is determined by factors that depend on charge-discharge characteristics. Li-ion batteries connected in series have different aging rates due to different capacities. The capacity deviation increases as the battery has been used, generating an increase in compensation current, which continues to increase until ignition. To solve this problem, a pulse device and a charging method in a charge equalization battery were proposed in this paper. A numerical simulation of how to charge real Porsche Taycan car batteries was performed. The results obtained confirmed the effectiveness, the energy losses did not exceed 2% of the battery capacity. A bench diagram was developed for studying and programming the operating modes of battery control units for hybrid and electric cars.

Keywords: *lithium-ion battery charging, current pulses, charge equalization, resistive voltage divider, testing charging systems.*

Abstract. Bateria litiu-ion (Li-ion) este utilizată pe larg în electronicele moderne, servește drept sursă de energie în vehiculele electrice și pentru stocarea energiei în sisteme cu surse regenerabile. Punctele forte ale bateriilor Li-ion sunt densitatea lor mare de energie. Bateriile moderne Li-ion pot include rețele de celule, a căror durată de viață este determinată de factori care depind de caracteristicile de încărcare-descărcare. Bateriile conectate în serie au rate diferite de îmbătrânire din cauza capacităților variate. Abaterea capacității crește pe măsură ce bateria a fost utilizată, generând o creștere a curentului de compensare, care continuă să crească până la aprindere. Pentru a rezolva această problemă, în lucrare au fost propuse un dispozitiv de impuls și o metodă de încărcare într-o baterie cu egalizare de încărcare. A fost efectuată o simulare numerică a modului de încărcare a bateriilor auto Porsche Taycan real. Rezultatele obtinute au confirmat eficacitatea, pierderile de energie nu au depasit 2% din capacitatea bateriei. A fost dezvoltată o schemă de banc pentru studiul și programarea modurilor de funcționare a unităților de control a bateriei pentru mașini hibride și electrice.

Cuvinte cheie: *încărcare baterii litiu-ion, impulsuri de curent, egalizarea încărcării, divizor rezistiv de tensiune, testare sisteme de încărcare.*

1. Introduction

Most new electric vehicles are equipped with lithium-ion batteries. Batteries account for about 40% of the cost of electric vehicles and 60% of the cost of high-capacity energy storage [1]. The energy of charged batteries in an electric car is mainly used to power electric drives of cars with a voltage of up to 400 V. A separate battery has a low electromotive force (EMF), therefore, to obtain a high voltage, these batteries are connected in series into a battery.

At the same time, the characteristics of the elements of these batteries must be strictly the same. However, it is known that no two batteries are the same, even if they are made by the same manufacturer and have the same model. Small changes in the characteristics of each cell will still take place, whether it be the state of charge (SoC), equivalent series resistance (ESR), capacity or temperature characteristics. When cells are connected to each other to form a battery, changes in characteristics result in an imbalance in cell voltages. For example, if one cell has a slightly lower capacity, it will continue to discharge, and each time it is charged, it will experience a slight overvoltage. Over time, this will lead to a decrease in its capacity and service life. In a study by Sang-Sun Yun and Seok-Cheol Kee, 2022, [2], it was confirmed that the capacity deviation increased as the battery was used, resulting in an increase in the total amount of compensation current. The total value of the compensating current continues to increase until ignition occurs.

This phenomenon makes equalizing the charge of individual battery cells an indispensable procedure. The process of balancing voltages and SoCs between cells when they are connected and fully charged is called cell balancing.

Bortecene Yildirim et al. 2019 [3] investigated the following types of battery cell balancing:

a. Passive balancing.
b. Active balancing.
c. Runtime balancing.
d. Lossless balancing.

Passive Balancing This is a simple form of balancing by switching a resistor between cells. The energy loss to heat the balancing resistors (typically 30 to 40 Ω) allows overcharged cells to be discharged. This type is acceptable when balancing requirements are low. However, as cells age, the amount of balancing required to optimize energy increases. As a result, the amount of energy lost to heat increases and the charging time increases.

Active Balancing The idea here is to redistribute energy throughout the cells. Power from the cells with the highest SoC is transferred to the cells with the lowest SoC. This is the ideal approach to cell balancing. However, this means that the system must be able to move energy between cells in the battery, so many wires and switches are needed, which means more weight, complexity, and cost.

Runtime Balancing Each cell is connected to a separate low power direct current into direct current (DC-DC) converter, then each converter is connected in series. This then allows full control of the power supplied and received by each cell, depending on their capabilities. This system can provide a much higher level of reliability, but comes at a significant cost increase.

Lossless Balancing This approach turns cells on and off during charging. This means we have a lot of switches and these switches must be rated for full current.

Bortecene Yildirim et al. 2019 [3] showed that the main disadvantage of Active Balancing, by redistributing energy with the help of capacitances, is voltage balancing, which limits the speed and accuracy of balancing.

However, Active Balancing using capacitors can be improved to increase balancing accuracy and reduce time costs by using a pulse charging method.

This article is devoted to the development and research of a new device and method of charging with leveling the charge level of the cells in the battery at the second stage of charging (application for invention No. c20230044 dated 24.05.23, AGEPI R. Moldova) of a high-voltage lithium-ion automotive battery Porsche Taycan and the development of a test bench to investigate the effectiveness of this device.

In the process of research, methods of mathematical, structural and simulation modeling of instantaneous circuits of the charging device and leveling the level of battery charging were used. The calculations were performed using the Microsoft Office Excel 2007 program.

The main elements of the device are:

The list of designations of the main elements presented in figures 1, 2, 13:

B_{11} , B_{12} , ..., B_1n ; B_{21} , B_{22} , ..., B_2n – accumulators of the high-voltage battery;

C_1, C_2, ..., Cn - electrical energy storage devices, in particular capacitors;

R_1, R_2, ..., Rn – voltage divider resistors;

S_1, S_2 - electronic switches for switching on battery cells and energy storage devices;

BS_1, BS_2, ..., BSn - electronic switches for connecting batteries to drives;

RS_1, RS_2, ..., RSn - electronic switches for connecting voltage divider resistors to energy storage devices;

S – voltage sensor;

BSM - battery control unit;

DC-DC - power supply for charging batteries with direct current (DC);

GND - grounding of electrical circuits;

K - the point of connection of the power source to the device for charging and equalizing battery charges.

The main effective electrical quantities in the device are

E_{B11}, E_{B12}, ..., E_{B1n}, E_{B21}, E_{B22}, ..., E_{B2n} - Electromotive force (EMF) of high-voltage batteries;

i_{Bch1}, i_{Bch2} – battery charging current;

i_{Bcv} is the equalizing current of accumulator charging from storage devices;

i_{Cch} – storage current charging;

i_{Scv} - equalizing current of storages and voltage divider for equalization of voltage of storages;

U_{CC} is the voltage of the DC-DC power converter at the stage of charging batteries with constant current (CC);

U_{CV} is the voltage of the DC-DC power converter at the stage of charging batteries at a constant voltage (CV);

U_{R1}, U_{R2}, ..., U_{Rn} – voltage of voltage divider resistors;

U_{C1}, U_{C2}, .., U_{Cn} – energy storage voltage;

E_{B1}, E_{B2}, .., E_{Bn} – EMF of the batteries.

2. Battery leveling device

The proposed Device (1) for equalizing the level of charge of batteries (2) of rechargeable batteries (B_{11}, B_{12}, ..., B_1n; B_{21}, B_{22}, ..., B_2n) Management System (BMS) and consists of: n energy storage devices connected in series in a circuit, which can be capacitors (C_1, C_2, ..., Cn); electronic switches (S_1) and (S_2) for connecting to a direct current source (DC-

DC) circuits: n rechargeable batteries (B_1, B_2, ..., Bn) and n energy storage devices (C_1, C_2, ..., Cn), respectively; n-series connected via electronic switches (RS_1, RS_2, ..., RSn) into a chain of resistors (R_1, R_2, ..., Rn), one output of each of the resistors (R_1, R_2, ..., Rn) is connected by an electrical jumper to the corresponding output of the drive energy (C_1, C_2, ..., Cn), in turn, one output of each of the energy storage devices (C_1, C_2, ..., Cn) is connected by an electrical jumper through electronic switches (BS_1, BS_2, ..., BSn) with the corresponding output connected in series in rechargeable battery circuit (B_{11}, B_{12}, ..., B_1n; B_{21}, B_{22}, ..., B_2n); to the analog input of the control unit (BMS) through a voltage sensor (S) connect the input output of the drive C_{11} to control the voltage of the drives. The connection diagram of the device is shown in fig. 1 where n and i are positive integers, **n** is greater than 1 and $1 \leqslant i \leqslant n$.

3. Battery equalization method

Lithium-ion batteries are known to require 2 stages to properly charge: constant current charging (CC mode) followed by constant voltage charging (CV mode). At the first stage, the current value is 0.2-0.5 C (where C is the battery capacity). For an accelerated charge, it is allowed to increase the current up to 0.5-1.0 C [4]. The high-voltage lithium-ion battery system of the Porsche Taycan consists of 5000 mAh battery cells [5]. The rated charging current at the first stage (CC mode) is 1000 - 2500 mA, and with accelerated charging it can reach 2.5-5 A. In this mode, the battery is charged up to the level of SoC = 80 %. Next, a charge is made with a constant voltage (PV), at which the charging current gradually decreases. When the current drops to a minimum, charging is completed and the current is turned off. When using the proposed technical solution (Figure 1a), the first stage differs in that, together with the battery cells (under the control of the BMS program), up to the cell voltage level. At the second stage of charging the battery in the proposed technical solution, first, a chain of pre-charged capacitors (C_1, C_2, ..., Cn) is connected to the battery charging current source for a time equal to 3τ and charged to a voltage level corresponding to the voltage specified by the manufacturer for A battery is made up of a number of cells connected in series. Such a charging protocol can be referred to as a constant current-pulsed charging current at constant voltage (CC-PCCCV) protocol. Not to be confused with (CC-PCC) [6].

Due to the fact that capacitors manufactured by the industry have a wide range of parameters (up to 20%), the voltages of the capacitors (C_1, C_2, ..., Cn) are equalized using voltage divider resistors (R_1, R_2, ..., Rn).

To this end, at the end of the capacitor charging time for a time of 1τ, a chain of resistors is connected in parallel, each resistor to its own capacitor in the chain of capacitors (C_1, C_2, ..., Cn). Next, the capacitors (C_1, C_2, ..., Cn) are connected in parallel to the battery cells (B_{11}, B_{12}, ..., B_1n; B_{21}, B_{22}, ..., B_2n) and transfer energy to the latter. Resistors (R_1, R_2, ..., Rn) are selected with a parameter spread of no more than 1%. Thus, the cells (B_1, B_2, ..., Bn) are charged with current pulses, the voltage of which corresponds to the level set by the battery manufacturer. The process is repeated until the EMF of each battery is equal to the voltage of the charged storage (Fig. 2). A distinctive feature of the proposed technical solution is that. That the charging current in the second stage does not flow through the rechargeable battery cells (Fig. 2**).**

At the second stage of charging batteries (B_1, B_2, ..., Bn) from a power source (DC-DC) in the constant voltage mode ***Ucv***, in order to prevent the flow of charging current through the series circuit of batteries (B_1, B_2, ..., Bn), they are charged by multiple parallel connection to the appropriate energy storage devices (C_1, C_2, ..., Cn), which, before each connection, are charged to the voltage set by the battery manufacturer:

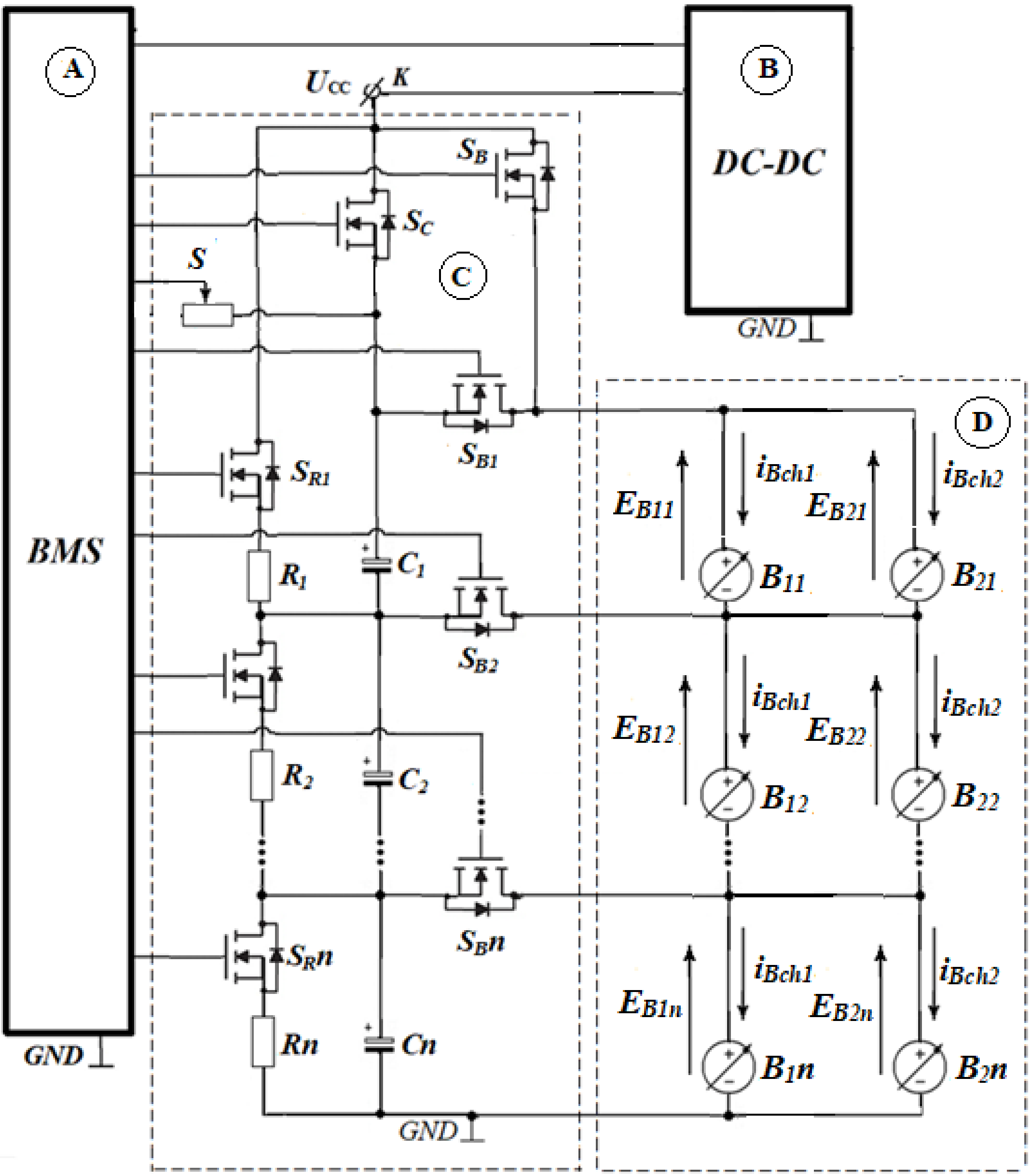

Figure 1. Schematic diagram of the steering device a of the charge level of Lithium-ion batteries at Porsche Taycan model:

A - Porsche Taycan battery management system (BSM);
B - Direct current converter (DC-DC);
C - Battery cell charger and equalizer;
D - Porsche Taycan lithium-ion battery system.

- phase 1.1 of the state of the circuit (see Figure 2 B) of the proposed device, is characterized by the fact that for 2τ (τ is the time constant of the accumulator), the voltage ***Ucv*** is applied to the chain of energy accumulators (C_1, C_2, ..., Cn) for additional charging drive (C_1, C_2, ..., Cn) up to SoC = 99% of drives;

- phase 1.2 of the state of the device circuit (see Fig. 2 C) is characterized by the fact that for a time of 1τ a resistor (R_1, R_2, ..., Cn) is connected in parallel to each storage device (C_1, C_2, ..., Rn) and cause the flow of an equalizing current i_{Scv} to equalize the voltage (U_{C1}, U_{C2}, .., U_{Cn}) on each drive to the voltage specified by the manufacturer, since a chain of series-connected resistors of the same resistance (R_1, R_2, ..., Rn) divides the source voltage (DC-DC) for voltages specified by the battery manufacturer (B_1, B_2, ..., Bn);

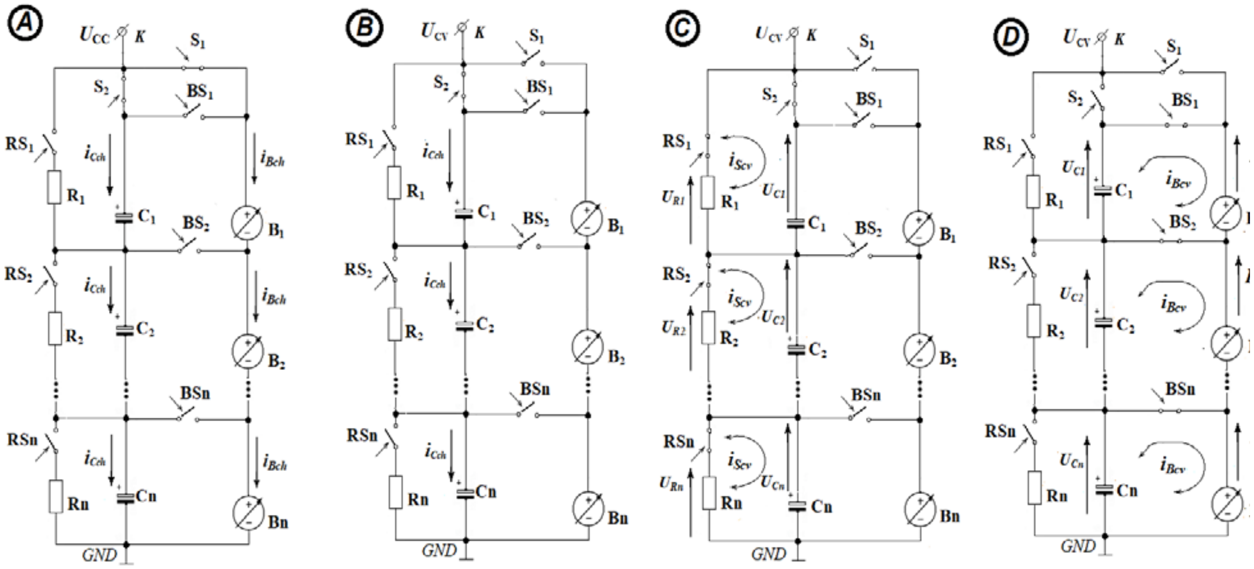

Figure 2. Electrical circuits for switching on the device for charging and equalizing the charge of battery cells for modes:

A - charging of battery cells to the level of SoC = 80% and capacitors to the level of SoC = 91.67% at a constant current value CC;

B - charging capacitors to the level of SoC=99.5%;

C - voltage equalization of capacitors by a voltage divider;

D - transfer of capacitors energy by pulses to battery cells.

- phase 1.3 of the state of the circuit of the proposed device, is designed to measure the total voltage (***U_{C1}, U_{C2}, .., Ucn***) of drives (C_1, C_2, ..., Cn), which is read from the sensor **S** and entered into the memory of the BMS device;

- phase 1.4 of the state of the circuit (see Fig. 2 D) of the proposed device, serves to charge batteries (B_1, B_2, ..., Bn) with an equalizing current ***i_{Bcv}***, which flows when the storage devices (C_1, C_2, ..., Cn) and batteries are connected in parallel (B_1, B_2, ..., Bn). The peculiarity of this charging method is that when the EMF EB of the batteries (B_1, B_2, ..., Bn) is equal to the voltage UC of the storage devices (C_1, C_2, ..., Cn), the equalizing current ***i_{Bcv}*** between these pairs will not flow, and for those batteries , for which the EMF ***E_B*** has not reached the voltage level determined by the manufacturer, the equalizing current ***i_{Bcv}*** from the storage devices will flow and their voltage will decrease, therefore the total voltage (***U_{C1}, U_{C2}, .., Ucn***) of the storage devices (C_1, C_2, ..., Cn) is also at the end charging will go down;

- phase 1.5 of the state of the circuit of the proposed device, is designed to measure the residual voltage UCV’ of storage devices (C_1, C_2, ..., C_1n) which is read from the sensor S and entered into the memory of the BMS device;

- phase 1.6 of the circuit state is designed to compare the residual voltage ***U_{CV}'*** with the value stored in the memory of the BMS device. If the voltage values ***$U_{CV}' = U_{CV}$*** are equal, the second stage of charging the batteries (B_1, B_2, ..., Bn) is stopped, and if the residual voltage ***U_{CV}'*** is less, that is, part of the storage energy is spent on charging the batteries, then go to phase 1.1 and repeat the charging process.

Thus, the charging of each battery separately will be performed by current pulses of the corresponding storage device until the battery EMF is equal to the storage voltage.

The operation algorithm of the device (1) for metered charging of the battery cells by parallel connection of energy storage devices to them in order to equalize the charges, preventing the flow of current through the charged cells, is shown in Figure 3.

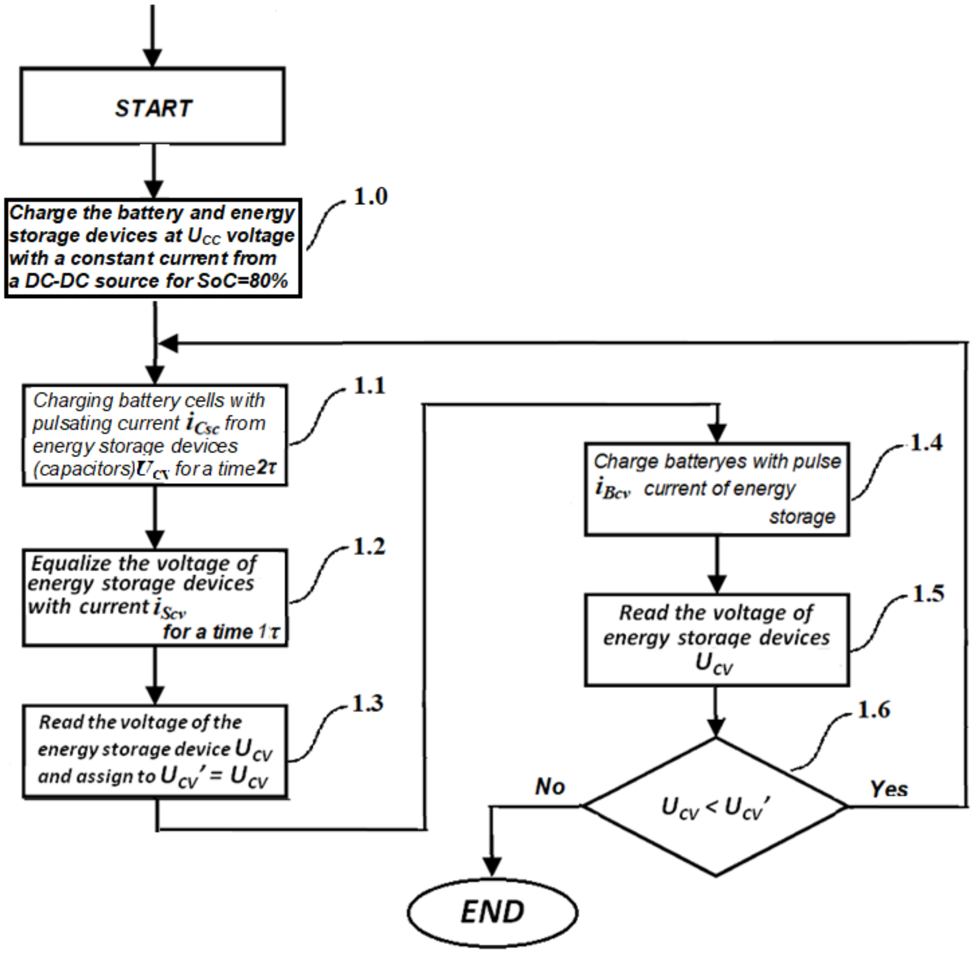

Figure 3. Battery charging algorithm with charge equalization.

3. Porsche Taycan Car Battery Charger Workflow Parameters

To analyze the effectiveness of the proposed device and confirm the possibility of implementing the invention, we will carry out an approximate calculation of the elements of the device and the parameters of the Porsche Taycan battery charging process [5].

Table 2

Parameters High-voltage lithium-ion car battery Porsche Taycan

Specification	Parameter
Nominal voltage	800V
Number of battery cells with nominal voltage	396 cells with U_{BA} = 3.7V
Cell modules	33 modules
Number of elements (in series)	n_A = 198 cells in battery
Battery cell capacity	5.0 Ah = 5000 mA/h
Usable capacity	E_{AB} = 93.4 kWh (336.2 · 10^6 J)
Rated capacity of one cell in a battery	E_A = 18 · 10^3 J
The internal resistance of a cell in a battery	Ra = 20 mΩ

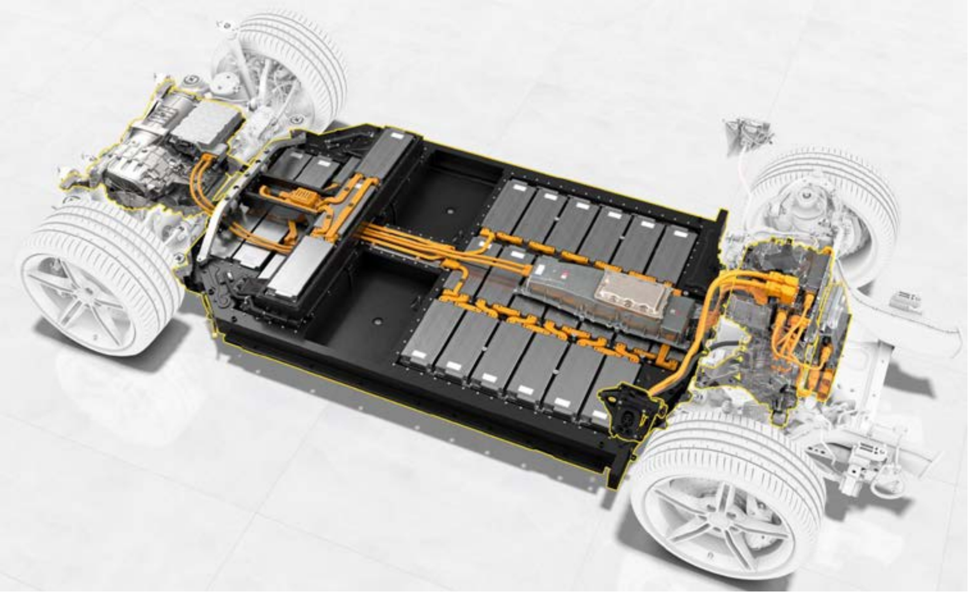

Figure 4. Porsche Taycan high-voltage battery and location of its modules [5].

The Taycan is the first mass-produced vehicle to offer 800 volts instead of the usual 400 volts for electric vehicles. This ensures consistent high performance, reduces charging times and reduces weight and cable management space [5].

The Performance Plus bi-level battery used in the Taycan Turbo S and Taycan Turbo contains 33 cell modules with 12 individual cells each (396 in total). The total power is 93.4 kWh. Each module has an internal control unit for voltage and temperature control and is connected to each other by bus bars [5].

Battery modules consist of battery cells and are connected in series. In each module, two cells are connected in parallel, and then these pairs are connected in series. This solution helps equalize the voltage of two battery cells connected in parallel and reduces the influence of low capacity cells on the resulting battery voltage but does not eliminate the problem of different cell aging rates.

In our case, we will take an electrolytic capacitor manufactured by Jb Capacitors Company (Table 3) with an internal resistance ***Rc*** = 9 mΩ [7]. However, commercially available capacitors have a wide range of parameters: the capacitance of two identical capacitors can differ by +/- 20%.

Table 3

Parameters of electrolytic capacitors

Specification	Parameter
Capacitor type	Aluminum electrolytic JNK
Capacity	Cc = 56 000 uF ± 20%
Working voltage	10 B DC (for 4.2 Reserved 135%)
Working temperature	-40°C ~ +105°C
Resistance Type ESR 20°C, 120Hz	Rc = 9 mΩ = 0.009 Ω

Therefore, in charging mode 1.1 (see Figure 3), the constant voltage from the DC-DC source will be distributed unevenly across the capacitor circuit. To eliminate this disadvantage of capacitors, in the proposed technical solution, after charging the capacitors, they are briefly connected to the voltage divider of the DC-DC source and the voltages are equalized, since the divider is created from the same resistors (RS_1, RS_2, …, RSn), the deviation of the electrical resistance of which is not more than +/-1%. For example, for the High-voltage lithium-ion battery Porsche Taycan, a metal film resistor with a resistance of ***Rr*** = 1 Ω was chosen with a manufacturing accuracy of +/-1% (Table 4).

Table 4

Parameters of voltage divider Metal Film Resistor [8]

Specification	Parameter
Tip:	Wire Wound Resistor
Manufacturer	ABECO ELECTRONIC CO., LTD
Model:	CSR NEW MELF
Putere nominală	5 W
Resistance, Rsh:	1 Ω
High Precision:	0.1%

For electronic switch S_1, S_2, BS_1, BS_2, … , BSn; RS_1, RS_2, … , RSn accept NPN Silicon Epitaxial Transistor Bipolar (see Table 5).

Table 5

Parameters of electronic switch [9]

Specification	Parameter
Marking	FGA25N120
Collector−Emitter Voltage	VCC = 1200 Vdc
Collector Current	IC = 25 A
Maximum power dissipation	125 W

On Fig. 5 shows the degree of completion of the process (as a percentage) of the time of the process (charge or discharge) (see Figure 6) [10]. The first stage of charging ends when the battery charge reaches SoC=80%. At the first stage of charging the battery (2), its batteries (B_1, B_2, ..., Bn), for example, lithium-cobalt oxide batteries ($LiCoO_2$) and storage devices connected to them in parallel, in this case electrolytic capacitors (C_1, C_2, ..., Cn) will be charged to a voltage of U_C = 3.9 V. DoD (Depth of Discharge) is a numerical compliment at DoD =20%, the value of SoC= 80% (see Figure 5) [10].

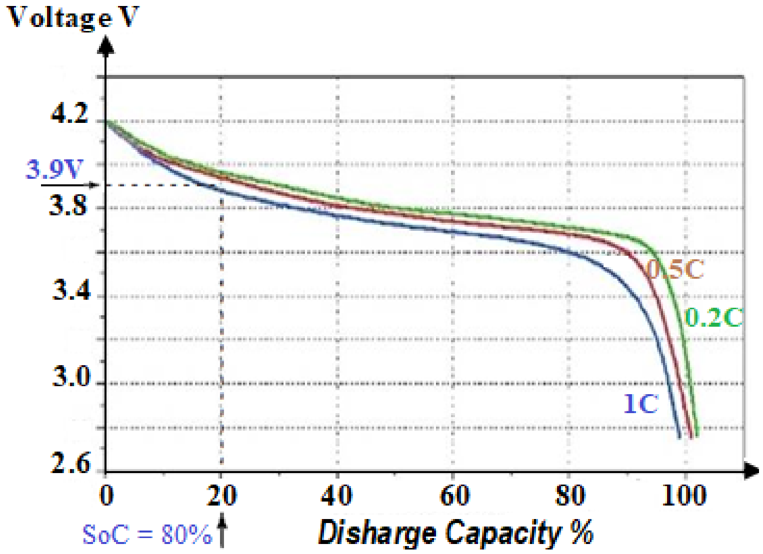

Figure 5. Lithium ion battery voltage and remaining energy [10].

If there is an imbalance of +/-10% battery charge, the individual batteries of the battery will be charged to a voltage of $\boldsymbol{U_C}$ = 3.85 V (Figure 6).

At the second stage of charging, the proposed technical solution is used as follows: in charging mode ***1.1***, turn off the electronic switches (BS_1, BS_2, ..., BSn; RS_1, RS_2, ..., RSn) and to power the capacitor bank (C_1, C_2, ..., Cn) turns on the electronic switch S_2 and supplies a constant voltage $\boldsymbol{U_{CV}}$ from a DC-DC source to a chain of $\boldsymbol{n_C}$ = 99 capacitors.

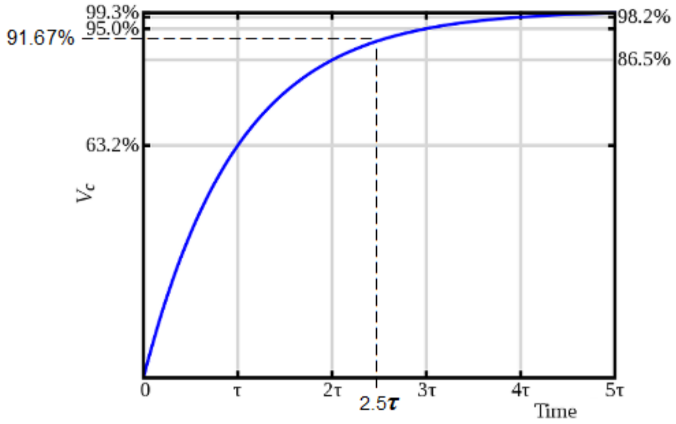

Figure 6. Capacitor charge and discharge [11].

Each capacitor must receive a voltage ***Uash (i)*** = 4.20 V. To charge a chain of $\boldsymbol{n_A}$ = 198 by two parallel-connected cells of the High-voltage lithium-ion battery Porsche Taycan [5], the voltage $\boldsymbol{U_{CV}}$ of the DC-DC source, for charging at a constant voltage, must be equal to:

$$\boldsymbol{U_{CV} = Uash\ (i) \cdot n_A} \tag{1}$$

$$U_{CV} = 4.20 \cdot 198 = 832\ \mathrm{B}$$

The total resistance of internal resistances Rc of series-connected capacitors (C_1, C_2, ..., Cn) with a number $\boldsymbol{n_C}$, equal to the number of batteries $\boldsymbol{n_A}$ and will be:

$$\boldsymbol{R_{CS} = Rc \cdot n_C} / 2 \tag{2}$$

$$R_{CS} = 0.009 \cdot 198 / 2 = 0.891\ \Omega$$

Therefore, when connected to the $\boldsymbol{U_{CV}}$ voltage, the initial charging current of the capacitors can be:

$$\boldsymbol{i_{Sch} = U_{CV} / R_{CS}} \tag{3}$$

$$i_{Sch} = 832 / 0.891 = 933.8\ \mathrm{A}$$

In order to prevent the capacitors from burning out from such a current, in the proposed technical solution, the capacitor banks are charged together with the batteries at the first stage of charging at a constant current value, therefore, at the end of the first stage, the capacitors will also be charged to a voltage of ***U'a(i)*** = 3.9 V , and some, due to imbalance, will be charged up to $\boldsymbol{U_{DC}}$ = 3.85 V. For capacitors, this voltage value is 91.67% (of 4.2V), which for capacitors is equivalent to a charge time of 2.5τ (see Figure 6) [11].

Therefore, at the second stage of charging the batteries, to charge the energy storage (capacitors), there will be enough time 3τ for the capacitor voltage to be slightly more than 4.18 V (99.5% of 4.2 V) (see Figure 6) [11]. The total charge of the capacitor C(i) is calculated by the formula:

$$\boldsymbol{E = U^2 \cdot C / 2} \tag{4}$$

Let's take the EMF level at the beginning of the second stage of battery charging ***Ea'*** and at the end of ***Ea''*** based on the materials of Isabelle Sourmey 2022 [4]. In this case, one storage capacitor C(i) can transfer energy to the accumulator B(i) at the beginning of the second stage with ***Uash (i)*** and:

$$\Delta \boldsymbol{Ecstart} = (\boldsymbol{Uash\ (i)}^2 - \boldsymbol{E_1a}^2) \cdot C/2 \tag{5}$$

$$\Delta \boldsymbol{Ecstart} = (4.2^2 \cdot 3.85^2) \cdot 0.056 / 2 = 0.079\ \mathrm{J}$$

Figure 7 gives reason to take $\boldsymbol{E_2a}$ = 4.1 V. Therefore, at the end of the second stage, this capacitor can transfer energy to the battery cell:

$$\Delta \boldsymbol{Ecend} = (\boldsymbol{Uash\ (i)}^{\ 2} - \boldsymbol{E_2a}^2) \cdot C/2 \tag{6}$$

$$\Delta \boldsymbol{Ecend} = (4.2^2 - 4.1^{\ 2}) \cdot 0.056 / 2 = 0.0232\ \mathrm{J}$$

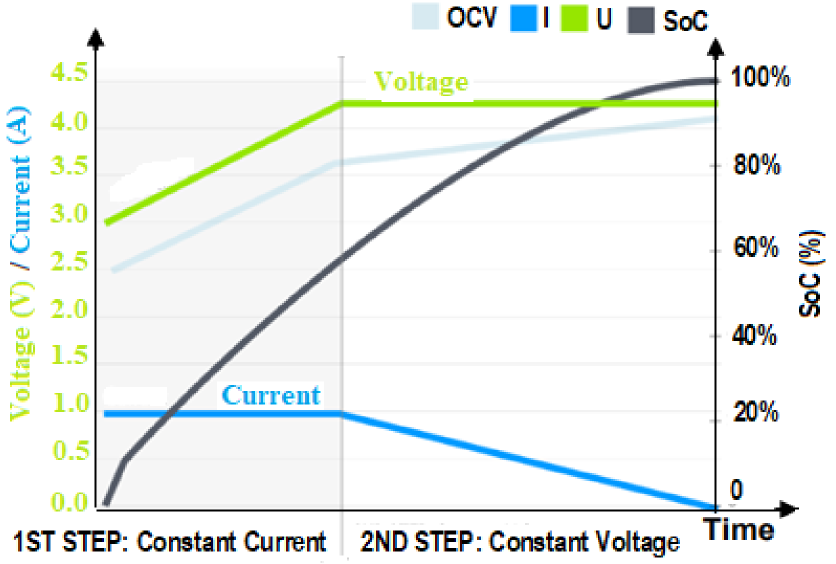

Figure 7. Li-Ion charging progress CC/CV [4].

For one cycle of connecting the capacitor to the battery cell during the second stage, on average, you can transfer:

$$\boldsymbol{\Delta Ec = (\Delta Ecstart + \Delta Ecend) / 2} \tag{7}$$

$$\Delta \boldsymbol{Ec} = (0.079 + 0.0232) / 2 = 0.0511\ \mathrm{J}$$

Charging batteries at the second stage using the proposed technical solution with an imbalance in the charge level of +/-10% means that if the battery cells after the first stage can have a charge of about 80% [4], then individual cells can have 70% or 90%. The calculation of the energy required for charging and equalization, which the capacitor must transfer, is carried out for the case of an incomplete charge of 70%. In this case, it must be taken into account that these cells can be paired. Therefore, the missing energy that must be added with the help of a capacitor at the second stage of charging will be about **Δ*Ep***=60% of the total energy reserve of one cell $\boldsymbol{E_A}$:

$$\boldsymbol{E_A''\ (i)} = \boldsymbol{E_A\ (i)} \cdot \Delta \boldsymbol{Ep} / 100 \tag{8}$$

$$\boldsymbol{E_A''\ (i)} = 18 \cdot 10^3 \cdot 60 / 100 = 10.8 \cdot 10^3\ \mathrm{J}$$

The number of cycles to transfer energy using capacitors to cover the imbalance of a pair of cells in the module **Δ*Ep*** = 60% of the energy of one cell to charge to $\boldsymbol{E_A''(i)}$:

$$\boldsymbol{E_A''\ (i)} = \boldsymbol{E_A\ (i)} \cdot \Delta \boldsymbol{Ep} / 100 \tag{8}$$

$$\boldsymbol{E_A''\ (i)} = 18 \cdot 10^3 \cdot 60 / 100 = 10.8 \cdot 10^3\ \mathrm{J}$$

The maximum number of cycles to transfer with the help of capacitors is still ΔE_p = 60% of the energy to charge up to $E_A''(i)$:

$$N\ cycle = E_A''(i) / \Delta E_c \qquad (9)$$

$$N\ cycle = 10.8 \cdot 10^3 / 0.0511 = 551.9 \cdot 10^3$$

Let us determine the charging time of the capacitors (C_1, C_2, ..., Cn) at the second stage. The duration of the process of charging the capacitor depends on two values: on the electromotive force of the source - U_{CV} and on the time constant - τ.

The time constant of charging / discharging the capacitor τ is determined by the product of the resistance and the capacitance of the capacitor [12], therefore,

$$\tau_C = R_C \cdot C_C\,, \qquad (11)$$

where:

τ_C - time constant, s;
R_C - resistance, Ω;
C_c - capacitance, F.

$\tau_C = 0.009 \cdot 0.056 = 0.504 \cdot 10^{-3}$ s

Charging capacitors (C_1, C_2, ..., Cn) to a value of 99.3% capacity, that is, up to a voltage of 4.2 V, to transfer this charge to the batteries, with an average capacitor voltage of U_C = 3.93 V, will require at least 3τ of time. It will take time to charge the capacitor t_C:

$$t_C = -\ln(1 - UD_C / Uash(i)) \cdot 3\tau'_C \qquad (12)$$

$$t_C = -\ln(1 - 3.85 / 4.20) \cdot 3 \cdot 0.513 \cdot 10^{-3} = 3.75 \cdot 10^{-3}\ \text{s}$$

The total time spent on multiple refueling of the energy storage (capacitor) before transferring energy to the batteries will be:

$$\sum t'_C = t_C \cdot N\ cycle \qquad (13)$$

$$\sum t'_C = 3.75 \cdot 10^{-3} \cdot 551.9 \cdot 10^3 = 2069.6\ \text{s} = 34.5\ \text{min} = 0.57\ \text{hour}$$

In the process of charging the capacitors, in state phase 1.1, the circuits of the device (1) after 2τ pass into the state phase ***1.2*** (capacitor charging with voltage equalization). This phase lasts for another 1τ, that is, one third of t'_C, which is:

$$t'd = 3.75 \cdot 10^{-3} / 2 = 1.875 \cdot 10^{-3}\ \text{s} \qquad (14)$$

The charging time of the capacitors for power transfer in the second stage is much less than the time required to charge the lithium-ion battery. To charge a lithium-ion battery to a level of 99%, on average, it will take t_{2A} = 100 minutes (6000 s). These data are accepted from Rahul Bollini 2022 [13], and from Battery University BU-409 [14].

Therefore, if we neglect the time spent on switch switching, then the total time spent by the device on charging the Porsche Taycan High-voltage lithium-ion battery is from 80% to 99%, with a battery charge imbalance of 20% (see Table 2) will be:

$$\sum t_{CA} = t_C' + t_{2A} \qquad (16)$$

$$\sum t_{CA} = 34.5 + 100 = 134.5\ \text{min} = 2.24\ \text{hour}$$

Let's calculate the frequency of the battery charging current pulses. Assuming that the charge time at the second stage of the battery charge is equal to the sum of the time of all pulses, we determine the duration of one charge pulse - t_p:

$$t_p = t_{2A} / N\ cycle \tag{17}$$

$$t_p = 6000 / 551.9 \cdot 10^3 = 0.0109\ \text{s}$$

If we neglect the time spent on switching switches, then the total time of one cycle ***T***, that is, the period will be equal to (Figure 7):

$$T = t_p + t_C$$

$$T = 0{,}0109 + 3.75 \cdot 10^{-3} = 0{,}01465\ \text{s} \tag{18}$$

Therefore, the pulse frequency will be:

$$f = 1 / T \tag{19}$$

$$f = 1 / 0.01465 = 68\ \text{Hz}$$

Fig. 8 and 9. Schematic representation of a current pulse profile and definition of related parameters. The continuous line represents the current pulse profile and the dotted line represents the associated reference current profile.

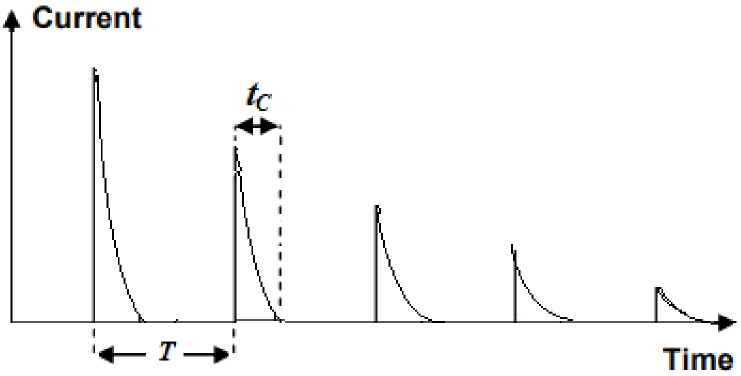

Figure 8. Capacitor current at constant voltage of the voltage divider:
T- Time of one cycle; t_C - the duration of charge of capacitors.

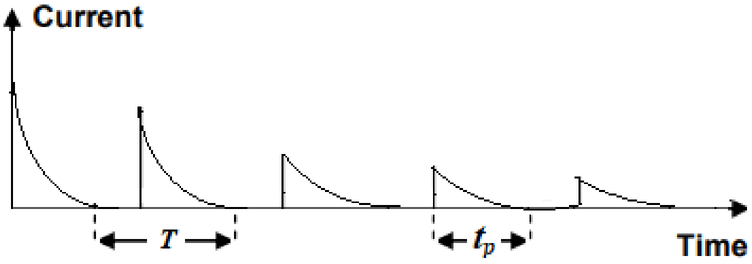

Figure 9. Charging current pulses of battery cells from a capacitor:
T- Time of one cycle t_p - the duration of one pulse.

Makeen P. et al., 2022 [6] concluded that the charging current frequency of less than 6 kHz and more than 50 kHz increases the charging time, and energy losses are minimized. In the considered application of the proposed device, the calculated pulse frequency $f = 68$ Hz, i.e. less than 6 kHz, therefore, the current pulses generated by the proposed device for charging the Porsche Taycan electric vehicle battery should minimize energy losses in the battery.

Additional time costs will be $\sum t'_C = 34.5$ (min) = 0.57 (hour). However, relative to the total charging time of lithium-ion batteries, which is 180 minutes [14], the additional time for charging using the proposed method will increase by no more than 20%.

5. Calculation of the efficiency of the proposed equalization charger

It is of practical interest to determine the resistance value of the voltage divider resistors, the energy loss dissipated by the resistors, the voltage deviation of charged storage devices and the time spent on charging at the second stage with the battery voltage equalization.

Using a voltage divider across resistors to equalize the voltage of the capacitors before charging the batteries will cause energy wastage. To calculate the losses, the operation of the proposed device was simulated in relation to the High-voltage lithium-ion battery of Porsche Taycan (Table 2). The calculation of the instantaneous capacitor charging circuit at the moment of time corresponding to the charge time of the time constant **4τ** at the moment the voltage divider is turned on to equalize the voltages of the storage capacitors is performed. The charge time corresponding to the time constant **4τ** was chosen because the capacitors have already passed the time **2τ** when charging together with the batteries. This circuit will make it possible to select the value of the resistances of the resistors to equalize the voltages of the capacitors.

For a more compact representation of the calculated data, 198 pairs of parallel-connected cells that are connected in series into a battery, for the convenience of calculation and presentation of results, we will divide into groups into groups: ***nga*** = 11 groups, ***nag*** = 18 pairs of cells in each group and, accordingly: ***ngc*** = 11 groups of capacitors from Cg1 to Cg11 and ***ncg*** = 9 capacitors per group. The calculation scheme is shown in figure 12. The rated voltage ***Ua*** = 4.2 V is taken in accordance with the battery charging voltage of the battery Porsche Taycan (Table 2).

The disbalance of storage capacitors capacitances is set by the coefficient of difference between the internal resistances of the group capacitors: ***Disb of Resrg(i).***

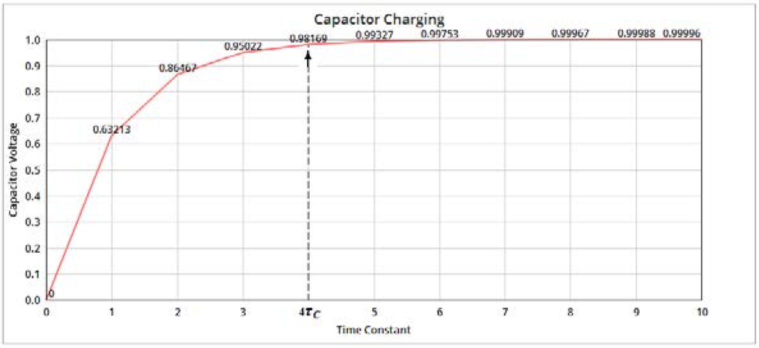

Figure 10. Capacitor charging voltage slope [12].

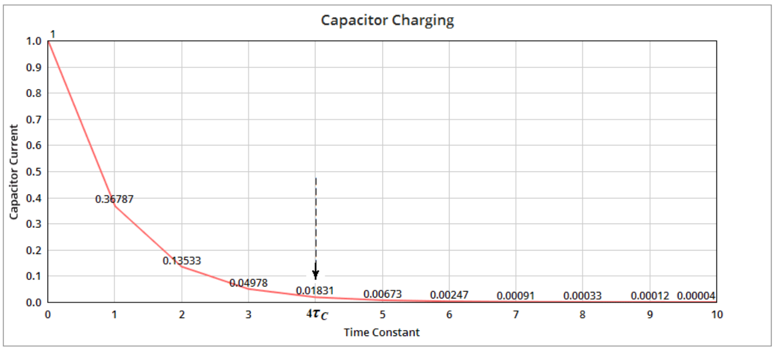

Figure 11. Capacitor charging current slope [12].

To simplify the calculation of the internal resistance of capacitors (energy storage) ***Resr'(i),*** we express in terms of data on the values (expressed as a percentage) of voltage (Voltage) and current (Current), depending on the charge of the capacitor [12]:

$$Resr'(i) = Resr(i) \cdot Voltage/Current \tag{20}$$

The equivalent resistance of the shunt resistor of the voltage divider and the internal resistance of the storage capacitor is determined by the formula:

$$Requiv'(i) = Resr'(i) \cdot Rsh/(Resr'(i)+Rsh) \tag{21}$$

The equivalent resistances of each group of series-connected resistors and capacitors are determined by the formula:

$$Rgequiv'(i) = Re'(i) \cdot nag \tag{22}$$

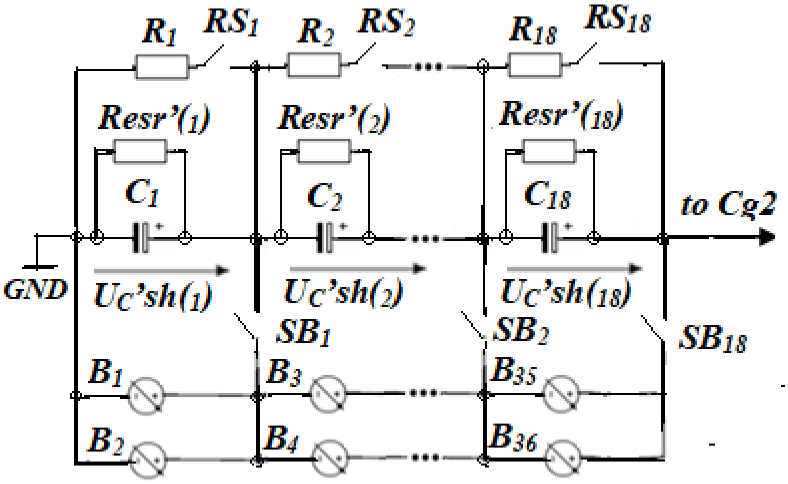

Figure 12. Connection diagram of capacitors and a voltage divider of a group of batteries of the Sg1 battery for calculating the voltage equalization on the capacitors before connecting to the batteries of the group.

The value of the nominal EMF of the capacitor as the product of the battery charging voltage determined by the manufacturer and the correction factor [12] is determined by the formula:

$$EMFc' = Uc \cdot Voltage/100 \tag{23}$$

The value of the rated charging current of the capacitor as the product of the charging current at the battery charging voltage determined by the manufacturer and the correction factor [12] is determined by the formula:

$$Ic' = Idc\text{-}dc \cdot Current/100 \tag{24}$$

The value of the charging current of capacitors with voltage equalization from a DC-DC source is determined by the formula:

$$I_{dc\text{-}dc}' = U_{dc\text{-}dc} / \sum_{i=1}^{i=ngc} Rgequiv'(i) \tag{25}$$

Electromotive force of a group of capacitors:

$$EMFcg' = Ecg \cdot Voltage/100 \tag{26}$$

Power loss to shunt resistors:

$$\Sigma Ploss\ instant' = \sum_{i=1}^{i=ngc} (Ucg'(i) \cdot Ishg'(i)) \tag{27}$$

Energy loss for shunt resistors:

$$\Sigma Eloss\ instant' = \sum Ploss\ instant' \cdot Ncycle \cdot td' / 3600 \tag{28}$$

Equivalent resistance of a group of shunted capacitors:

$$Resrg'(i) = \Sigma Rcesrg \cdot (Voltage / Current) \cdot Disb\ of\ Resrg(i) \tag{29}$$

Equivalent resistance of a group of shunted capacitors:

$$Rgequiv'(i) = Rshg \cdot ncg \cdot R'esrg(i) / (Rshg \cdot ncg + Resrg'(i)) \tag{30}$$

Capacitor group voltage:

$$Ucg'(i) = Rgequiv'(i) \cdot Idc\text{-}dc' \tag{31}$$

Capacitor group charging current:

$Icg'(i) = Ucg'(i) / Resrg'(i)$ (32)

The current of a group of resistors shunting capacitors:

$$Ishg'(i) = Ucg'(i) / (Rshg \cdot ncg) \tag{33}$$

Power loss on groups of shunt resistors:

$$Pc(i) = Ucg'(i) \cdot Icg'(i) \tag{34}$$

Energy loss on groups of shunt resistors:

$$Plossg'(i) = Ucg'(i) \cdot Ishg'(i) \tag{35}$$

Voltage applied to shunted capacitor:

$$Uc'sh(i) = Ucg'(i) / ncg \tag{36}$$

Voltage applied to capacitors:

$$Uc'sh\ less\ (i) = Udc\text{-}dc / \sum_{k=1}^{k=ngc} Resrg'(k) \cdot Resrg'(i) / ncg \tag{37}$$

The calculation was made for the case of using capacitors with a typical capacitance deviation of +/- 20% (parameters in Table 3), used as energy storage devices for pulsed energy transfer to batteries and divider resistors (parameters in Table 4).

The resistors of the charging voltage divider U_{CV} used to equalize the voltage of the capacitors made it possible to equalize the voltage to the limits that allow charging the batteries at the second stage of charging without exceeding the allowable limit of 4.25 V (see Figure 5 and Table 7).

Table 6

Initial parameters of the energy storage voltage equalization mode

Initial data		Data adapted to Time Constant τ=4	
Uc = Ua charging, V	4.2	t'd (c) equalizat. time	0.001875
ncg	18	N cycle	551900
ngc	11	Voltage, %	98.16
Resr nom, Ω	0.009	Current, %	0.02

Continuation Table 6

Σrcesrg, Ω	0.16	EMF' c, V	4.12
Rsh nom, Ω	1.00	I'c, A	0.09
Rshg, Ω	54.00	I'dc-dc, A	4.29
EMFcg, V	75.60	EMF'cg, V	74.21
U dc-dc nom, V,	831.60	ΣP'loss instant, Wt	3492.75
I dc-dc by τ=0, A	466.67	ΣE'loss instant,Wth	1003.99
Usable capacity, kWh	93.4	ΣE'loss in % of usable capacity	1.2%

Table 7

Expected parameters of the energy storage voltage equalization mode

	Cg1	Cg2	Cg3	Cg4	Cg5	Cg6	Cg7	Cg8	Cg9	Cg10	Cg11
Disb of Resrg(i)	1	1.2	1	0.8	1	0.8	1	1.2	1	0.8	1.2
R'esrg(i) (Ω)	868.5	1042.2	868.5	694.8	868.5	694.8	868.5	1042.2	868.5	694.8	1042.2
R'gequiv(i)(Ω)	17.63	17.69	17.63	17.55	17.63	17.55	17.63	17.69	17.63	17.55	17.69
U'cg(i) (V)	75.63	75.89	75.63	75.25	75.63	75.25	75.63	75.89	75.63	75.25	75.89
I'cg (i) (A)	0.09	0.07	0.09	0.11	0.09	0.11	0.09	0.07	0.09	0.11	0.07
I'shg (i) (A)	4.20	4.22	4.20	4.18	4.20	4.18	4.20	4.22	4.20	4.18	4.22
Pc (i) (Wt)	6.59	5.53	6.59	8.15	6.59	8.15	6.59	5.53	6.59	8.15	5.53
P'lossg(i) (Wt)	317.81	319.97	317.81	314.60	317.81	314.60	317.81	319.97	317.81	314.60	319.97
Uc'(i) shunt (V)	4.20	4.22	4.20	4.18	4.20	4.18	4.20	4.22	4.20	4.18	4.22
Uc'(i)without(V)	4.20	5.04	4.20	3.36	4.20	3.36	4.20	5.04	4.20	3.36	5.04

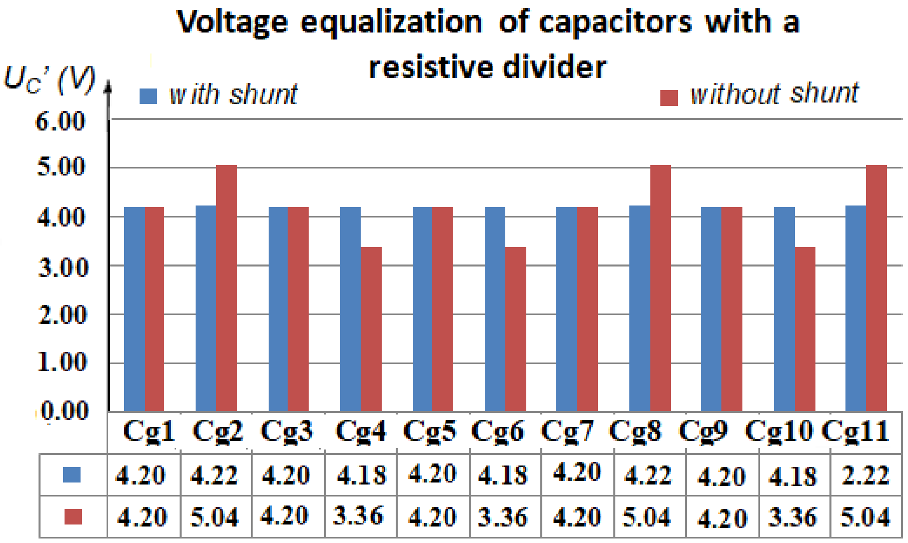

Figure13. Capacitor voltage in storage groups equalized by a resistive divider.

The voltage of capacitors in battery groups (Cg1, ..., Cg11), balanced by a resistive divider, does not exceed the allowable limits for charging cells equal to 4.25 V. At the same time, the diagram in Figure 13 shows how large the voltage spread is when the internal resistances of the capacitors deviate. A similar deviation can also occur in battery cells with a spread in the parameters of the cells, similar to the spread in the parameters of a capacitor.

6. Stand for research and modes of operation of lithium-ion battery cells

Any technical solution must be preliminarily calculated, designed and created in the form of a sample. Before being handed over to the user for use, the sample must be tested and carefully examined.

As for the proposed device (application for invention No. c20230044 dated May 24, 23, AGEPI R. Moldova), calculations were made and the elements of the device for equalizing the charge of the battery cells were selected: for the Audi Q5 hybrid Quattro hybrid car (the report was sent to the ESFA 2023 congress committee); for the e-GOLF electric car (report sent to the IMANEE 2023 international conference committee). Discussions with experts will help improve the proposed technical solution. The next step is to create and test a sample. Due to the technical features of the proposed solution, which consists in the ability to change the battery charging modes, the proposed device can be used to study battery charging modes; it can become the basis of the stand. To do this, a device for charging and equalizing the voltage of lithium-ion batteries must be equipped with measuring instruments: to control the temperature of the battery cells; to measure the internal resistance of battery cells; for measuring voltage, charging current, power consumption and charge time of lithium-ion battery cells.

To control the operation of the stand, a control processor device is required, which will perform the functions of the BMS battery charging management system and collect information about the progress of the charging process. The control device must be programmable for research and laboratory applications.

For this purpose, the Arduino Uno R3 controller is suitable (Fig. 14 (I)) [15,16], which can be used as a control device to control the operating modes of the charger, perform BMS functions, and collect information about the stand. operating modes. The Arduino Uno R3 controller has 14 digital inputs/outputs, 6 of which can be used as PWM outputs (PWM), 6 analog inputs (ADC), a 16 MHz crystal, a USB connector, a power connector, an in-circuit programming connector (ICSP) and a reset button. The Arduino Uno is programmed using the free Arduino software. The ATmega328 microcontroller in the Arduino Uno comes with a firmware uploader that allows you to upload new programs to the microcontroller without the need for an external programmer. In addition, a personal computer can be connected to the USB port (Fig. 14(A)) and perform both experiment management tasks and preparation of programs for testing various battery charging methods.

On fig. 14(B) is a circuit diagram of a battery cell equalization charger (FIG. 14(B)). The charger circuit pins are labeled according to the Arduino Uno R3 PWM outputs (Figure 14(I)): ~3, ~5, ~6, ~9, as well as analog inputs: A1 and A3. Up to 14 pcs. 18650 type batteries (Fig. 14(C)) are connected to the charger to charge and equalize the battery cells based on the proposed technical solution (Fig. 14(B)).

For testing and preparation of batteries, it is advisable to equip the stand with a lithium battery capacity tester 18650, (for four batteries) and a battery charge detector 18650, type C (Fig. 14(D)) [17]. The tester has an operating voltage of 5V DC and is suitable for all batteries that meet the requirements for stopping the discharge at a voltage of 2.5~3.5V and an initial voltage of 2.8V to 4.2V. The tester has the following options:

- Power interface: Two Type-C power interfaces.
- System language: English.
- Number of tests: 4-way measurement of charging and discharging.

- Internal resistance measurement: The two-wire DC method is used to measure internal resistance.
- Charging function: automatic charging shutdown when fully charged.
- Discharging function: automatic stop when conditions are met, discharging current is not adjustable.
- Automatic charging and discharging: supported. The battery is fully charged at the end of automatic mode.

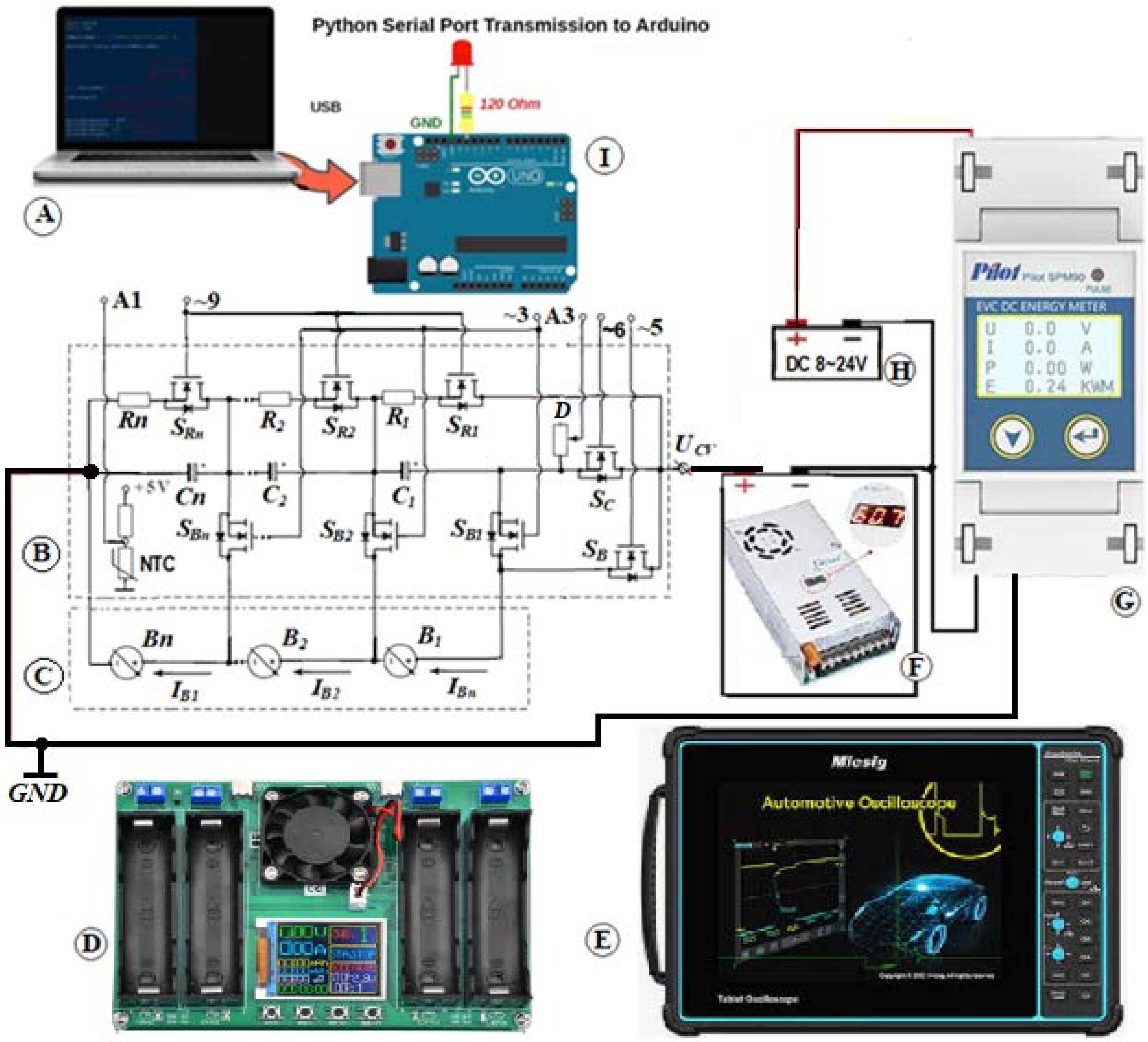

Figure 14. Stand for research and modes of operation of lithium-ion battery cells:
A - Phyton Script Transmits PC [25];
B - Pulsed battery charger with cell equalization;
C -Li-ion batteries type 18650
D -18650 Lithium Battery Capacity Tester [17];
E - Micsig ATO2004 automotive oscilloscope [18].
F - DROK 60V Power Supply [19];
G - Direct current meter SPM90 [20];
H - Energy meter power supply SPM90 [20];
I - Arduino Uno R3 Device to control the stand and perform BMS functions [15].

- Cyclic charge and discharge: supported only in automatic mode, adjustable from 1 to 9 cycles.
- Cooling mode: active fan cooling.
- Discharge stop voltage: 2.5V, 2.6V, 2.7V, 2.8V, 2.9V, 3.0V, 3.1V, 3.2V, 3.3V, 3.4 V, 3.5 V. Total 11 adjustable gears.
- Discharge current: the maximum current is about 1A.
- Charging voltage: controlled by a special battery charging chip, with a maximum charge of about 1A and a full charge voltage of 4.2V [17].

Table 8

Stand for research of batteries of electric vehicles

Nr	Name of elements	Brand	Quantity	Unit price	Price
1	Arduino controller	Arduino Uno R3	1	€29.99 + €6.70	€36.69
2	4-channel oscilloscope from Micsig specially made for the automotive industry	Micsig ATO2004 automotive oscilloscope	1	€950.41+ €50	€1000.41
3	18650 Lithium Battery Capacity Tester Module MAh Digital Type-C Four Batteries 18650 Battery Power Detector Capacity Tester, Mainland China	Battery Capacity Tester	1	€11,33 + €10	€21.33
4	n - channel MOSFET or IGBT transistors	FGA25N120	26	€1,26	€32.76
5	Resistor R1 = 100 Ω	C5-35B-50 100	26	$3.59	€93.34
6	Resistor R2 = 10 kΩ		29	€19.03 (for 100 units)	€19.03
7	Voltage divider resistors Rd = 1, 3, 5 Ω ± 1% , 5 W		36	€5.30	€190.80
8	Aluminum Electrolytic Capacitor JNK	56 000 μF ± 20% 10 B DC	12	€4,80	€57.60
9	830 dot solderless breadboard	MB-102	3	€3,28	€9.84
10	DC voltage source DROK 60V Power Supply, AC 220V to DC 0-60V 0-8A 480W	DROK 60V Power Supply	1	€36.89+ €25	€ 61,89
11	Film temperature sensor	Selco TF-F010K-1-2	3	€1.44	€4, 32
12	SPM90 - DIN rail DC meter and current shunt		1	€103	€103.00
13	Battery Samsung 18650 20A INR18650-25R	INR18650-25R	12	€7,75	€ 93.00
	Total				**€1724.01**

An oscilloscope must be included in the stand to observe and record the forms of capacitor current pulses for charging batteries. An automotive digital oscilloscope Micsig ATO2004, 200 MHz, 220 Mbps is suitable for this purpose [18]. This portable oscilloscope has a touch screen and can be used to diagnose the electrical and electronic equipment of vehicles (Fig. 14(E)). The choice of this oscilloscope model is due to the characteristics of this model, which allow it to be used not only to study electrical processes in the model of the proposed technical solution, but also to conduct laboratory work on diagnosing a Skoda Fabia car in the Laboratory of the Department of Transport. The ATO2004 model has: 200 MHz bandwidth; analog channels - 4; sample rate (max.) 2 GS/s; memory depth 220Mpts; acquisition rate (max.) 300 000 wfms/s; segmented storage for recording up to 10 000 events.

The oscilloscope Micsig ATO2004 model supports testing procedures for charging/starting circuits, sensors, actuators, ignition, network (CAN L/H, CAN FD, LIN, Flexray, K line) of vehicles. Model ATO2004 allows you to perform combined tests of vehicle electrical equipment and is equipped with an Industrial 10.1" TFT-LCD (1280x800) display [18].

The proposed device is powered by 600W digital display switching power supply Adjustable voltage 0-12V 24V 36V 48V 60v 80V AC 110/220V to DC SMPS LED POWER SUPPLY.

Single Display 60V Power Supply, AC 220V to DC 0-60V 8A 480W Buck Converter (Fig. 14(F)), Voltage Adjustable: 5V 12V 24V 30V 36V 48V 60Volt Transformer 3A 5A 8Amp Charger for Lab CCTV [19]. This device allows you to adjust the voltage up to 60 V when charging battery cells with direct current. This is enough to power up to 14 cells, in particular the 18650 size, connected in series by a chain into a battery. The Single Display 60V Power Supply, with an input voltage of 220V, allows you to adjust the output voltage in a wide range: 0-60V DC. The device is easy to operate and can be used to adjust the output voltage directly with a potentiometer. The voltage adjustment accuracy is 0.1V. The maximum current is 8A. This buck converter is equipped with an LED screen and a cooling fan. When the working power is high, the cooling fan will activate automatically.

The converter has overload protection, overvoltage protection, short circuit protection, which can protect your device from damage. The input voltage is 220V.

The SPM90 DC meter is designed to measure DC electricity consumption and to be installed in electric vehicle charging equipment on a 35mm DIN rail.

SPM90 is equipped with RS-485 interface with ModBus RTU protocol, pulse output and accuracy class 0.5.

The SPM90 DC electricity meter measures voltage, current and power in the DC circuit with high accuracy in real time.

The SPM90 meter belongs to the accuracy class of 0.5 electricity meters for all technical parameters. A current measuring shunt is included with the SPM90 DC electricity meter to measure the total amount of electricity kWh used to charge the battery.

The selected equipment and other necessary details for the creation of the stand are shown in Table 8. It is planned to assemble the stand by the staff and graduate students of the Department of Transport. The stand will allow you to check the effectiveness of the proposed device for charging and equalizing the voltage of battery cells at the second stage of charging these cells. The design of the device uses capacitors to charge the cells, so using capacitors of different capacities; you can change the frequency and power of the current pulses that charge the battery cells. Due to the presence of the Arduino control controller, it is possible to programmatically control the battery cell power switch and charge the battery cells with PWM current pulses at the first stage of their charging. Only a smoothing filter is required so that the supply voltage does not exceed the allowable limit. The measuring equipment of the stand allows monitoring the charging processes and investigating the effect of various mode parameters on the efficiency of the battery cell charging process. These studies are currently of interest to improve methods for charging lithium-ion batteries, the use of which is growing rapidly. Regarding the use of the stand for laboratory work, the topic of work related to the study of lithium-ion batteries is relevant for the Department of Transport due to the enormous increase in the number of electric and hybrid vehicles in Moldova.

6. Results

A new technical solution to the problem of charging a battery of batteries with the equalization of battery charges using energy storage devices is proposed. A device and a method for charging batteries connected in series are described, which excludes the flow of current through batteries that have reached the level of full charge, when charging batteries that have not reached this level.

By calculating the instantaneous circuit at the second stage of voltage equalization and charging of storage devices with the expected spread of storage parameters, it is shown that charging lithium-ion batteries using the proposed device and the proposed method using the High-voltage lithium-ion battery of Porsche Taycan as an example, allows charge lithium-ion batteries with current pulses generated by capacitive storage devices at the second stage, at a constant charging voltage close to the nominal value, preventing current from flowing through charged batteries and without exceeding the permissible level of battery charging voltage.

The charging time of the considered high-voltage battery with the elimination of 15% of the imbalance of the batteries will last up to 139 minutes (2.31 hours).

To equalize the charges of the High-voltage lithium-ion battery Porsche Taycan using capacitive storage devices in this example, additional energy costs $\Sigma E'_{loss}$ = 334.7 Wh will be required, which is 1.2% of the usable capacity of the battery (93.4 Wh).

The cost of creating a stand will require costs up to €2000, since not all companies have presented the cost of delivery to the Republic of Moldova and the cost of customs costs should be taken into account.

7. Discussion

The article discusses the operating modes and selects the parameters of a device that provides capacitor voltage equalization by resistive dividers for pulsed, individual charging of lithium-ion batteries at the final stage of charging (in constant voltage mode). An original method for calculating instantaneous voltage equalization circuits by resistive dividers is applied. However, the effect of pulse charging on Li-ion batteries, charging time and service life of Li-ion batteries has always been a bottleneck in the application of electric vehicles [21]. The discussion about the efficiency of charging batteries with current pulses continues, some authors believe this mode is effective and develop power supplies for pulsed charging [22]. Others report positive effects in terms of charging efficiency, charge time, and battery degradation, but feel the results are mixed [23]. To analyze the behavior of lithium-ion batteries, models based on linear regressions, manufacturer characteristics and integration of equations into an electrical model of electrochemical phenomena are proposed [24]. The Department of Transport of the Technical University of Moldova lacks scientific personnel and funding to conduct research of this level, therefore, the creation of a stand for studying the charging modes of real batteries using modern measuring equipment will contribute to obtaining new scientific results. With the help of the stand it will be possible to bring the proposed technical solution to implementation. The expected type of change in the voltage and current of the battery charging using the proposed device for charging and equalizing the voltage of the battery cells is shown in Figure 8 and 9. The author wants to present this graph to students using an oscilloscope on the stand.

A good indication of the cost savings of setting up a stand in the Department of Transportation is that researchers Xinrong Huang and others 2021 [22] to study various modes of charging with a pulsed current of lithium-ion batteries, the frequency and shape of the current pulses were reproduced using an expensive KEPCO BOP 100-10 device MG bidirectional programmable power supply worth $10 614.10. In our case, the principle of the proposed device is to generate charging current pulses for charging lithium-ion batteries, and the presence of a controller as part of the designed stand will allow: to change the frequency of the pulses. The selection of capacitors will allow you to change the duration of the pulses and conduct similar studies at a lower cost.

The possibility of using the selected brand of oscilloscope not only for research and laboratory work, but also for diagnosing automotive sensors and devices is also a good argument in favor of creating a stand with the costs shown in Table 8.

The stand will make it possible to study the effect of charging modes with pulsed current at different frequencies, amplitudes, and duty cycles on the battery life but will also allow using the stand for laboratory work in such disciplines as "Electrical and electronic equipment of cars", "Electric and hybrid cars".

8. Conclusions

The proposed device for equalizing the level of charge of batteries when charging batteries can be created on the basis of commercially available electronic components and can be used to equalize the charges of high-voltage batteries used in the automotive industry, as well as to charge batteries from renewable energy sources.

The proposed method of levelling the charge level of the batteries in the battery allows you to:

- increase the service life of batteries by eliminating the flow of current through fully charged batteries, that is, preventing them from overcharging and overheating;
- reduce energy losses for heating balancing resistors, as they turn on for a short time in the voltage equalization phase on the capacitors;
- get rid of the need to control the voltage of each battery cell separately.
- to provide improved performance and longer service life of lithium-ion batteries by pulse charging of the proposed device.

Numerical simulation of the preparation mode of the proposed device for charging a real car battery of the Porsche Taycan electric car was carried out, which made it possible to determine the technical parameters of the proposed device.

Obtained results confirmed the effectiveness of the technical proposal, energy losses do not exceed 2% of the useful battery capacity of the Porsche Taycan electric vehicle, and the time spent on charging using the proposed device and charging method will increase by no more than 20% relative to the average charging time of lithium-ion batteries. batteries, which is 180 minutes.

To continue the study, a bench scheme was developed to study the effect of the operating modes of the proposed device and the charging method on the charging efficiency of lithium-ion batteries, and the equipment necessary for research was selected. This stand can be used not only for scientific research, but also for laboratory work on car mechatronics and programming control units for charging batteries of hybrid and electric vehicles.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Ryan, A. Tackling the rising cost of electric vehicle batteries. Available online: https://www.fleetnews.co.uk/electric-fleet/costs-and-incentives/tackling-the-rising-cost-of-electric-vehicle-batteries (accessed on 20.07.2022).
2. Yun, S.-S.; Kee, S.-C. Effect of Capacity Variation in Series-Connected Batteries on Aging. *Batteries* 2023, *9*, 22.
3. Yildirim, B.; Elgendy, M.; Smith, A.; Pickert, V. Evaluation and Comparison of Battery Cell Balancing Methods IEEE. Available online: https://eprints.ncl.ac.uk/file_store/production/261931/F4ADEC30-2EDD-4881-A81A-AC0BFDE3D9EB.pdf, (accessed on 12.02.2023).
4. Sourmey, I. Charging your lithium-ion batteries: 5 expert tips for a longer lifespan. Saft Connected Energy Division. Available online: https://www.saft.com/energizing-iot/charging-your-lithium-ion-batteries-5-expert-tips-longer-lifespan (accessed on 13.01.22).
5. Gudkov, N. We disassemble the 800-volt Porsche Taycan sedan by electron. Available online: https://www.drive.ru/kunst/porsche/5d6fc320ec05c48e5300013c.html (accessed on 04.09.2019).
6. Makeen, P.; Ghali, H.A.; Memon, S. A Review of Various Fast Charging Power and Thermal Protocols for Electric Vehicles Represented by Lithium-Ion Battery Systems. *Future Transp.* 2022, 2, pp. 281–299.
7. Jb Capacitors Company. Available online: https://www.jbcapacitors.com/pdf/JNK-5000H-at-105-Snap-in-Aluminum-Electrolytic-Capacitor.pdf (accessed on 4.07.2023).
8. Rf parts company. Available online: https://www. rfparts.com/rs5-1-dale-wirewound-resistor-1-ohm-5-watt-1-tolerance.htm (accessed on 04.07.2023).
9. NdFT Company. Available online: https://ndft.com.ua/product-category/semiconductor-devices/tranzistory-i-drugie-aktivnye-komponenty/silovye-tranzistory-bipolyarnye/ (accessed on 4.07.2023).
10. McEwen, R. Voltage Vs remaining energy of Lithium Ion batteries. Available online: https://meloyelo.nz/knowledge-base/voltage-vs-remaining-energy-of-lithium-ion-batteries/ (accessed on 14.07.2020).
11. Zaread i razread condensatora. Ingenernye sistemy cvartiry i doma. Available online: http://ingsvd.ru/main/polza/1147-zaryad-i-razryad-kondensatora.html (accessed on 4.07.2023).
12. Simple Equation for Capacitor Charging with RC Circuits. Wira Electrical. Available online: https://wiraelectrical.com/equation-for-capacitor-charging/ (accessed on 04.07.2023).
13. Bollini, R. Understanding Charge Discharge Curves of Li-ion Cells. EVreporter Magazines. Available online: https://evreporter.com/understanding-charge-discharge-curves-of-li-ion-cells/, (accessed on 04.01.2022).
14. BU-409: Charging Lithium-ion. Available online: https://batteryuniversity.com/article/bu-409-charging-lithium-ion (accessed on 25.10.2021).
15. Arduino Uno R3 Specifications/Functions, 2022-12-11. Available online: https://spiceman.net/arduino-uno/ (accessed on 11.12.2022).
16. Arduino Uno Rev3 Entwicklungsboard Development Board, ATmega328, UNO R3, A000066, 2023. Available online: https://www.ebay.de/p/2254348831?iid=252313246890 (accessed on 7.07.2023).
17. Aliexpress 18650 Lithium Battery Capacity Tester, 2023, Available online: https://aliexpress.ru/item/1005004862750518.html?gatewayAdapt=glo2rus&sku_id=12000031144439656 (accessed on 7.07.2023).
18. Micsig ATO2004 automotive oscilloscope. Available online: https://eleshop.eu/micsig-ato2004-oscilloscope.html, (accessed on 7.07.2023).
19. Signle Display 60V Power Supply, AC 110V 220V to DC 0-60V 8A 480W Buck Converter. Available online: https://www.droking.com/DROK-60V-Power-Supply-AC-110V-220V-to-DC-0-60V-8A-480W-Buck-Converter-Adjustable_1 (accessed on 20.07.2023).
20. Energometrika. Available online: https://www.energometrika.ru/catalog/spm90-schetchik-postoyannogo-toka-na-din-reyku.html (accessed on 20.07.2023).

21. What Is Pulse Charging For Lithium-Ion Batteries? What Is The Impact Of Pulse Charging On Lithium-Ion Batteries? Available online: https://www.linkedin.com/pulse/what-pulse-charging-lithium-ion-batteries-impact-bruce-feng (accessed on 27.02.2023).
22. Huang, X.; Liu, W.; Acharya, A. B.; Meng, J.; Teodorescu, R.; Stroe, D-I. Effect of Pulsed Current on Charging Performance of Lithium-ion Batteries. *IEEE Transactions on Industrial Electronics* 2022, 69(10), pp. 10144-10153.
23. Vermeer, W.; Stecca, M.; Mouli, G. R.C.; Bauer, P. A Critical Review on The Effects of Pulse Charging of Li-ion Batteries. In: *19th International Power Electronics and Motion Control Conference (PEMC),* Gliwice, Poland, 2021, pp. 217-224.
24. Camas-Náfate, M.; Coronado-Mendoza, A.; Vega-Gómez, C.J.; Espinosa-Moreno, F. Modeling and Simulation of a Commercial Lithium-Ion Battery with Charge Cycle Predictions. *Sustainability* 2022, 14, 14035.
25. Sreedharan, R. Cross Platform serial communication using Python (PySerial) and Arduino. Available online: https://www.xanthium.in/Cross-Platform-serial-communication-using-Python-and-PySerial (accessed on 24.06.2022).

Citation: Petrov, O. Directing the uniformity of the level of pulse charging of Li-ion batteries used in automotive industry. *Journal of Engineering Science* 2023, 30 (3), pp. 35-59. https://doi.org/10.52326/jes.utm.2023.30(3).04

Submission of manuscripts: jes@meridian.utm.md