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METHOD OF CREATION OF POWER SOURCES FOR HOME APPLIANCES UNDER CONSTRAINTS OF LIMITED RESOURCES

The subject *of study in this article is the voltage ranges, methods, and tools for prototyping independent sources of power supply and artificial lighting for home appliances with reuse of only widespread components. The* ***goal*** *is to improve the efficiency of the creation and use of independent power supply sources for home appliances.* ***Task****: to analyze the history of the development of voltage standards for households; analyze existing autonomous power sources and types of batteries; analyze different loads; find rational voltage ranges based on fundamental values; analyze charge control and balancing circuits for lithium-based batteries; propose the technique of prototyping independent sources of power supply based on reused lithium-ion (Li-ion) accumulators; provide an example of the practical application of the results of research. According to the tasks, the following* ***results*** *were obtained. The evolution of voltage standards of electrical supply networks is analyzed. Types of autonomous power supplies, including pure sine versions, are discussed. The analysis of batteries for autonomous power sources of different chemical compositions is performed. It is proposed to use the water analogy of current and area as an analogy of battery capacity for visual representation of electrical processes. Models of constant current consumption and constant power consumption are considered. It is proposed to reduce the internal resistance of the battery assembly by parallel connection of the reused lithium-ion accumulators. Correspondence of voltage ranges of sequential connection of lithium-ion cells to ensure compatibility with existing devices is investigated. Rational parameters of voltage ranges to ensure compatibility of lithium-ion and acid accumulators with the ability to charge directly from solar panels without a charge controller are found. Charge controllers, battery management systems (BMS), and battery balancing circuits are analyzed. A set of steps for reuse of lithium-ion accumulators for the creation of autonomous power sources is proposed.* ***Conclusions.*** *The main contribution of this research is the proposed method of creation of power supply and interior lighting based on the reuse of accumulators without additional components. The discovered and proposed magic numbers of 3, 5, 7, 9, 11 and 13 for series connection of lithium-ion cells allows to obtain the equivalent of standard voltage ranges of 12 V, 19 V, 27 V, 36 V, 42 V and 48 V. The proposed technique of adjusting the voltage of the passive balancer allows adding 4.5 % to the capacity of the battery assembly. The described solutions allow to build the completely scalable autonomous low-voltage electrical supply network with the ability to charge directly from solar panels without expensive charge controllers.*

Keywords: *voltage ranges; accumulator; charge controller; solar panels; power supply; passive balancing; Li-ion; BMS; secondary good market; reuse of electronics.*

Introduction

An autonomous power and lighting sources are very important devices during a period of power outages. For areas without a centralized power supply, such power supplies are an integral part of the improvement. At the same time, such solutions can be useful in much wider applications.

Existing solutions of high quality are also associated with high price. Such solutions may not be available on the market during periods of crisis and periods of high demand. However, even if such power sources are available on the market, their cost increases many times.

At the same time, ready-made solutions allow to simplify the use and reduce the requirements for required skills for installation and operation. But in conditions of limited supply or when there is no way to buy, it is possible to build solutions for autonomous power supply, lighting, and connection of household devices. This becomes especially relevant during periods of crises associated with disruption of the delivery of goods and centralized energy supply.

Enough people have the skills and qualification, materials and experience needed to build solutions of energy supply for home appliances from available resources. Therefore, finding universal ideas and methods for constructing such autonomous direct current (DC) power supply systems is a topical task.

The high change rate of battery-powered portable electronic solutions accumulates a huge number of Li-ion accumulators for recycling [1]. At the same time, some of them retain their capacity, and the life cycle duration planned by the manufacturer allows to continue operation of such power cells [2].

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Even used original accumulators are of interest. Their residual capacity is higher and the price is much less than even the inexpensive non-original Li-ion counterpart accumulators. The original product is original because it was made without material saving. This opens up the possibility of using materials from the secondary goods market [3] with the priority of using only original products.

Laptop battery manufacturers often do not provide technical documentation on the details of the construction of their accumulators. Therefore, to implement the tasks of reusing the components of their batteries it is important to find the general concepts of the reuse process. Reverse engineering is one of the possible ways to obtain information about the cells and charge controller.

Batteries, especially those based on lithium compounds, may cause a fire if not handled carefully [4]. Therefore, research on the possibility of reuse and rules of their use is relevant for finding the technique for secondary use of accumulators for building autonomous power systems in conditions of limited resources.

Such conditions restrict the possibility of using generally accepted DC-to-DC converters and control elements. At the same time, among the available materials, there are all solutions for controlling the current and regulating the process. Finding steps to use these solutions makes the process of building such custom and artisanal solutions predictable and reproducible. The main advantage of such solutions is the minimum number of components and their extremely high availability.

The construction of efficient household electrical networks of autonomous power supply requires finding the most reasonable operating voltage range. The values of the voltage ranges are different for different devices for generation, accumulation and consumption of electricity. It makes more important the task of finding voltage ranges for building a household autonomous electrical network or an autonomous power source.

The purpose of this study is to improve the efficiency of the creation and use of independent power supply sources for home appliances. To achieve this goal, the following **tasks** will be performed:

1) to analyze the history of the development of voltage standards for household networks;

2) to analyze existing autonomous power sources and types of batteries;

3) to analyze different load models for batteries;

4) to find rational voltage ranges based on fundamental values;

5) analyze charge control and balancing circuits for lithium-based batteries;

6) propose a technique for creation independent sources of power supply based on reused accumulators;

7) provide an example of the practical application of the results of research.

1. Analysis of evolution of voltage standards of electrical supply networks

The issue of choosing a nominal voltage or a voltage range remains valid from the moment of the first electric networks arose at the end of the nineteenth century. In many ways, these first voltage values determined the ranges of modern voltage standards.

The first values of the operating voltage were defined by the first devices of electrical customers. The first artificial lighting was the arc discharge tube with two carbon rods.

Petrov arc, which someone also calls voltaic arc, requires periodic actions to maintain the light if the voltage is too low.

Experimentally selected voltage of 45 V allows to ensure the rational use of the resource of carbon electrodes. This also reduces the necessary actions to maintain the lamp to periodic adjustment of the distance between them.

A high-powered rheostat can be used to limit the current. The average voltage drop on the rheostat during the normal work of such an arc discharge source of light is about 20 V.

A supply voltage of 65 V is one of the first reproducible supply voltages for practical use. This value is on the margin or a little bit higher of safe voltage for humans of alternating current (AC) or unipolar pulsating current source.

The significant contribution of losses in conductors and lines on the way to consumers on the one hand and the requirements to ensure the possibility of delivering higher power [5] on the other hand led to an increase in the supply voltage in household networks.

One of the factors limiting the maximum voltage in household networks during this period was the quality of insulation materials, the boundary value of which was 150 V.

A rated voltage of 110 V was one of the first standards, most likely as a rational tradeoff value on the way of increasing voltage for reducing losses and limitations of existing insulating materials. With this value of the effective voltage of the unipolar pulsating current, the maximum amplitude corresponds exactly to the upper voltage values for the capability of isolation at that time. The value of the maximum voltage amplitude in this case is equivalent to multiplying the nominal voltage by $\sqrt{2}$ (multiplying by 1.41).

This voltage value also corresponds exactly to the operating mode of a series connection of two carbon arc lamps and a rheostat to limit the current. This nominal voltage also forms a psychologically significant value of 100 V, forming a perception of completeness in the consumer, with the addition of a 10 % margin to compensate for losses in the transmission lines.

Taking into account these considerations, the specified voltage was chosen as a reference value for commercial use by businessman Thomas Edison. He continued to improve the inventions and developments of Pavel Yablochkov and Alexander Lodygin. This led to the mass production of glow lamps with a nominal voltage of 100 V and generators with a nominal voltage of 110 V [6].

The voltage of 220 V originally arose as the value of the phase difference in the delivery lines, the transformers of which had a center tap and provided the consumer with three wires in the form of a center line and two phases with a shift of 180º. The use of any phase and the central line made it possible to connect devices with a rated voltage of 110 V. The possibility of using an interphase voltage of 220 V provided the possibility of doubling the delivered power with the same values of the current.

Three-phase 127/220 V networks have become the new common alternating current standard, with three phases at 120º offset. The implementation of three phases allowed the use of electric motors with greater efficiency. The interphase voltage also allows 220 V appliances to be connected, while the 127 V phase-to-ground voltage (between a phase and the neutral conductor) makes them compatible with the existing 110 V network.

The voltage of 127 V is obtained by accurately dividing the voltage of 220 V by $\sqrt{3}$ (dividing by 1.73), which is due to the voltage amount of shift between phases.

For a nominal voltage of 115 V, the 15 % drop of voltage is 100 V, and the 10 % overvoltage is exactly 127 V. The voltage of 115 V allows better compatibility when all the devices from the entire voltage range from 100 V to 127 V are needed and may be connected to the same electrical supply network.

Voltage deviation values of 15 % voltage drop and 10 % overvoltage are used in standards and for other voltage values.

Three-phase 220/380 V networks allow the possibility of the delivery of higher power for existing networks with the same wire cross-sections. Increasing voltage increases insulation requirements and precautions. Also, such voltage values allow in some cases to increase the length of delivery lines to a particular consumer without a noticeable increase in losses in these lines.

Transition to the 230/400 V standard allows some reduction of the losses in the transmission lines and an increase in the possible value of the delivered power by more than nine percent.

Also, the value of 230 V is the result of doubling the nominal voltage of 115 V, which remains the voltage standard in many countries.

2. Analysis of autonomous power sources and accumulators for them

Household sources of autonomous power supply allow the use of some electrical appliances during a temporary shutdown of the centralized power supply or make a temporary connection where there are no such power lines.

Uninterruptible power supplies (UPS) for a computer are designed for the short-term operation. The main purpose of UPS is to ensure the ability to save the results of work on the computer and to properly shut down the computer. Such a power source will not be able to work for a long time when the battery capacity is increased because it is not designed for high power output.

If an uninterruptible power supply has a power of 500 W, then at a power of about 250-300 W it can work without harm to the battery for about 5-7 minutes. The specified power usually the short-term maximum power allowed.

In addition, such power supply solutions in most cases do not produce a pure sine, which is suitable only for some devices such as a computer.

Inverters with a pure sine are devices for converting Direct Current (DC) to Alternating Current (AC) with the shape of an AC voltage curve over time, which describes the pure sine. This type of inverter is needed to connect a gas boiler or refrigerator.

There are ready-made solutions with pure sine output for connecting such devices. At the same time, the cost of such devices is much higher than that of UPS for office computers. This is partly because the power of such ready-made solutions must be greater than that of computer UPSs.

A power inverter is a device that allows the transformation of low-voltage DC to high voltage AC, including pure sine. This type of device is dedicated and supports long work under normal load if enough supply.

Increasing the source power is often achieved by connecting batteries in series. To provide more power and reduce losses, these solutions use the series connection of batteries from the UPS to increase the voltage at the input of the inverter.

Using 12 – 13.5 V to obtain 230 V is reasonable only in a simple low-power UPS. More powerful solutions perform conversions with voltage from 24 to 27 V when two batteries are connected in a series or from even higher voltage. In this case, the losses are significantly lower.

The existing popular solution of UPS is composed of six 12 V batteries of 9 A. One possibility is to connect them in parallel in groups of 3 batteries, then connect 2 groups in series to obtain a voltage of 24 V. Another option is 3 groups of 2 in parallel to obtain 36 V.

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Lead-acid accumulators use cells in series with an operating voltage range of 1.75 V to 2.25 V. Most of them assume charge at 2.4 volts per cell. The most common are series assemblies of 3 and 6 cells which correspond to batteries labeled 6 V and 12 V. The 3-cell version has an operating voltage of 6 V. The discharge voltage of 6-cell version is considered to be 10.5 V.

Automotive lead batteries or car batteries allow a normal discharge of up to 50 % capacity, and the use of 70 % capacity is already critical for battery life. Car batteries should not be used indoors due to fumes as they are not sealed. Also, non-traction batteries are not designed for a long load and assume a short-term, high-intensity current output. This means that such batteries do not provide sufficient operating range to deliver a significant power for long time. All lead accumulators are sensitive to deep discharges, especially car batteries.

UPS batteries are a special type of lead-based battery. They are more resistant to discharge and allow the indoor use. With the same nominal power this type is capable to provide much more energy than a car battery.

Absorbent Glass Mat (AGM) batteries are the most widespread type of UPS batteries. The specifications for these batteries may vary from one manufacturer to another. For some, the capacity is indicated in amperes, and for others, the stored power in watts. For this case, these values correspond to a constant power discharge. This parameter shows how much energy UPS battery can deliver during 15 min with constant power. After that, a battery will be discharged to 1.7 V per cell (10.2 V for the assembly of 6 cells).

Gel battery is an accumulator with a gelated electrolyte which is characterized by higher number of cycles and price. As well as AGM, this type of accumulator easily provides high current values during a few seconds that are more than ten times higher its capacity.

The main advantage of such accumulators is their relatively high resistance to spontaneous ignition and possible indoor use, while the disadvantages are their large weight, size, heavy metal and acid components.

Lithium-based batteries are actively used to build autonomous power supplies [7]. The most common are lithium-ion and lithium-polymer (Li-pol) with different compositions [8]. Lithium-iron-phosphate and lithium-titanate batteries are not too common yet, but they have many advantages including number of cycles, fire safety and wide temperature ranges of operation. There are other types of lithium-based power devices.

Modifications of Li-ion batteries are produced with difference in the chemical composition. Currently, the following types of elements are prevalent: IMR/LMO (lithium-magnesium); INR/NMC (lithium manganese nickel); ICR/LCO (lithium cobalt); IFR/LFP (lithium phosphate); NCA (lithium aluminum); NCO (lithium nickel cobalt) [9].

Li-ion batteries ICR 18650 are the most common. Usually laptop batteries use them, unlike INR which are used in tools with battery power. The numerical marking 18650 consists of two numbers of physical dimensions of a cylindrical battery: diameter of 18 mm and a length of 65 mm. Traditionally, INRs have a lower capacity than ICRs, but allow discharge with a peak current of up to 10C (where C is the cell capacity). Normally max discharge current of ICR cells is 2C [10].

Detailed information about the allowable charge and discharge modes is contained in the documentation for each type of battery [11]. Most of ICR cells have a full charge voltage of 4.2 V, but there are modifications with the full charge voltage of 4.3 V, 4.35 V, and 4.4 V.

Increasing the upper allowed voltage makes it possible to increase the amount of accumulated energy in the cell. Also, the documentation from the manufacturer shows information about the conditions under which the power element can give the declared capacity.

The key factors are the discharge current and temperature. When discharging in the cold, it is possible to get only about 50 % of the declared capacity. Temperature dependence is a feature of Li-ion batteries. It should be taken into account when using of ICR cells in winter.

Portable power sources or power banks often use Li-Ion batteries. One of the characteristics of each such power source is the total capacity of the batteries. However, manufacturers often do not specify at what discharge current this capacity in milliamps was registered. It is also not clear what voltage value corresponds to this measured current equivalent of the capacity because there are two voltages: output and on the battery.

The simplest electronic part of such a portable power source or power bank implements two functions: control of the charging process of the internal battery and the function of a step-up voltage converter. The input voltage is the range from 3 V to 4.2 V. Typical output voltage is 5 V to ensure the charging process of the connected device with this nominal voltage.

When the voltage on the cells drops, the converter begins to increase the current to maintain the constant voltage and the current at the output. The result is that the accumulated power in cells decreases faster with every minute. The electronic converter in such devices exhausts all the resources from the cells and at the same time its efficiency is not too high.

Serial production of such portable sources also reduces the cost per unit. At the same time, the competition among manufacturers brings the portable power supplies with the lower price. As a result the price of the installed accumulators decreases, as well as the capacity and quality components of voltage converter.

All of the above actualizes the task of the research characteristics, processes of charge and discharge and finding ways to build autonomous power sources.

3. Research of efficiency of use of accumulated energy

To increase the efficiency of the use of stored energy and to improve the understanding the processes of battery discharge, it is necessary to describe models of different types of loads. Some physical processes can be described by means of similar formulas. Use of analogy helps to increase visibility. It allows illustrating the physical meaning of the models described [12].

The water analogy of current in some cases makes it possible to clearly demonstrate the processes occurring in direct current electrical circuits. The liquid analogy is a universal form of comparison, suitable for process of price formation and Ohm's law.

In this analogy, water is the equivalent of charge (e.g., electrons). A pipe or water channel is an analog of a wire. Pressure in this comparison corresponds to voltage.

The pressure in the water supply system can always be. Even when the valve is closed, there is constant pressure inside the pipe like a voltage on a battery.

The current is the process of water movement (how much water flows through the pipe). If the tap is closed, there is no current.

Resistance in this analogy is the equivalent of the multiplication of pipe length and cross-sectional area. The larger the diameter of the pipe, the greater the current at a fixed pressure (voltage).

Such a visual explanation of Ohm's law makes it easier to understand part of the processes. The main thing in such analogies is the exact correspondence of the physics of the process.

The area as an analogy of the capacity makes it possible to clearly represent the amount of stored energy when describing the processes of battery discharge. As part of this equivalent, one of the coordinates in the plane, usually the vertical, is the battery voltage, and the horizontal is the current.

For battery-powered devices, a mechanism for estimating the remaining energy reserve is required. Some devices do not require high accuracy of capacity measurement and the use of an expensive charge controller.

For such solutions it is enough to use the voltage-based remaining battery reserve estimation. The relatively linear discharge path of Li-ion batteries in the operating voltage range makes this possible.

The linear part of the discharge process of Li-ion accumulators for two operating voltage ranges is represented in the diagram in figure 1. This is achievable by discharge currents in many times less than cell capacity.

The shape of the discharge curve of lithium-ion accumulators in the defined voltage ranges is close to linear. It allows to use the analogy of a linear process to simplify the calculation of the average capacity.

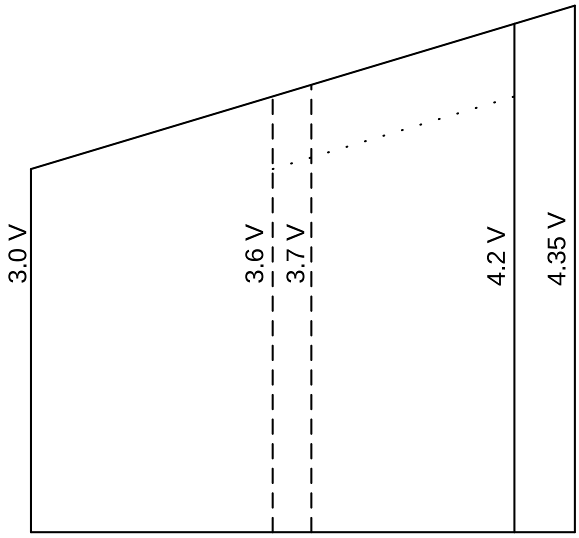

Fig. 1. Representation in area equivalent figures of the use of stored energy by Li-ion batteries with a voltage of 4.2 V and 4.35 V

The battery voltage values are plotted vertically to estimate the energy reserve (left part of area at figure 1) and its decrease when moving toward lower voltage during discharge.

The model of constant current consumption by the load during the Li-ion discharge process allows to estimate the middle of the energy reserve by the average voltage (dashed vertical line 3.6 V in Figure 1).

This type of consumption is typical for devices without inductance-based voltage converters, including LEDs with current limiting based on resistor and semiconductor components. In this case, the LED operates within the range of its operating voltage and the unused voltage difference is converted into heat on the resistor.

The model of constant power load consumption describes the process of discharging the battery when the result of the current and voltage multiplication is constant. When the battery is fully charged, the current is small and increases as the voltage decreases to keep constant the result of their multiplication. For this type of load, the midpoint of the battery capacity will shift to higher voltage value (e.g. 3.7 V instead of 3.6 V).

Converting the extra voltage into current with inductive converters allows to use 16 % more of the stored power in case of work in the considered voltage range from 3.0 V to 4.2 V.

For batteries with maximum voltage of 4.35 V, this efficiency gain for this load type is more than 18 %.

Consequently, depending on the type of load, the average voltage may differ. Thus, with a known type of the load, the remaining energy in accumulator can be approximately estimated by the voltage (remaining left part of the area of the figure 1 that represents capacity). This method of estimation is applicable only for the linear part of the discharge curve.

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The internal resistance of accumulator affects the shape of discharge curve. The perfect battery model has the minimal possible internal resistance. In this case the total capacity corresponds to the area of whole figure. The range of 3.0 V to 4.2 V is approximately linear for most of these batteries.

An ideal battery can be obtained by discharging an ordinary accumulator (new or used) with a current more than 10 times less than its capacity. In this case, losses on the internal and external lines will be negligibly small and will not change the shape of capacity curve.

To increase the operating current with saving of this effect, it is necessary to increase the number of cells connected in parallel. It will minimize the contribution of internal resistance to the discharge processes.

In general, high current values are undesirable for batteries, as they accelerate the degradation of the cells and, as a result, lead to an increase in internal resistance.

Large internal resistance values change the shape of battery discharge curve with high currents and allow only a fraction of the stored capacity to be used.

Parallel connection of lithium-ion cells allows to reduce total internal resistance of the battery pack with reducing the current through the individual cell. This brings the capacity of the assembly closer to the sum of actual capacity of all cells.

One of the main advantages of such assemblies is the possibility of discharging of individual cell of the pack by small current. The total internal resistance also decreases in such type of cell connection.

Thus, the parallel connection reduces the load on the individual cell and increases discharge efficiency.

4. Finding relations in voltage ranges to ensure compatibility of devices

As in the case of the history of the development of AC voltage standards for household appliances, the history of the formation of DC voltage series is related to power supplies and consumer devices.

The galvanic cell voltage of 1.5 V defined the voltage parameters of the first battery-powered devices. First voltages in rage are 1.5 V, 3 V, 4.5 V, 6 V, 7.5 V, 9 V, 12 V, 13.5 V, 15 V, 18 V, 22.5 V, 24 V, 27 V. There are batteries with 3 batteries in one package with voltage of 4.5 V, and batteries with 6 cells in the package with voltage of 9 V.

A lead-acid accumulator of 6 V and 12 V defined voltage ranges of 6 V, 18 V, 30 V, 42 V, 54 V and 12 V, 24 V, 36 V, 48 V. There are further voltage values in these series, but they are already sensitive to humans. The charge-keeping voltages of these batteries determined the on-board voltage standards of 13.5 V, 27 V, and 54 V.

The 3.3 V and 5 V voltages are based on a reference to the logic levels of digital devices and are also related to fundamental values. In this case, the standard was formed by the consumption devices, not the voltage sources.

The 4.2 V and 4.35 V voltages of fully charged lithium-ion batteries and the range of their operating voltages to full discharge allow a series of correspondences to be found for the rational and most demanded options for direct connection of devices without conversion (Table 1).

Table 1

Series of voltages for comparability of cascading of Li-ion cells with maximum voltages of 4.2 V and 4.35 V, lead-acid 6 V batteries and 12 V LED assemblies (3 LEDs in line)

Num. of Li-ion cells	Full discharge voltage (V)	Average voltage on 3 lines (V)			Maximum voltage (V)		Equivalent number of 6 V UPS batteries	Possible number of 12 V LED assemblies
		3.6 V	**3.7 V**	**3.8 V**	**4.20 V**	**4.35 V**		
1	3.0	3.6	3.7	3.8	4.20	4.35	–	–
2	6.0	7.2	7.4	7.6	8.40	8.70	>1	<1
3	9.0	10.8	11.1	11.4	12.60	13.05	**2**	**1**
4	12.0	14.4	14.8	15.2	16.80	17.40	>2	<2
5	15.0	18.0	18.5	19.0	21.00	21.75	**3**	**2**
6	18.0	21.6	22.2	22.8	25.20	26.10	4	<3
7	21.0	25.2	25.9	26.6	29.40	30.45	**4**	**3**
8	24.0	28.8	29.6	30.4	33.60	34.80	5	<4
9	27.0	32.4	33.3	34.2	37.80	39.15	**6**	**4**
10	30.0	36.0	37.0	38.0	42.00	43.50	6	<5
11	33.0	39.6	40.7	41.8	46.20	47.85	**7**	**5**
12	36.0	43.2	44.4	45.6	50.40	52.20	7	<6
13	39.0	46.8	48.1	49.4	54.60	56.55	**8**	**6**
14	42.0	50.4	51.8	53.2	58.80	60.90	>8	<7

It is important to understand that there were no DC converters and semiconductor voltage regulators (line stabilizers) when the first rows were formed. Therefore, each device required a certain number of batteries.

The need for a direct connection without voltage converters also arises in the organization of autonomous power supply during periods of centralized power outages. The choice of rational voltage ranges during the creation of the autonomous power supply allows direct connection of devices with compatible supply voltages.

The possibility of using LED lighting without voltage conversion allows to simplify the connection. Also of interest is the possibility of organizing compatibility to provide power from both lithium-ion batteries and lead batteries for the UPS. In some cases, it is even possible to use the same range to charge different types of batteries. For the considered ranges any number of cells can be connected as parallel or cascade connection.

To identify such battery pack architectures, the designations with numbers and letters are used S, P (S – serial, P – parallel). S denotes the number of cells connected in series (cascades or supercells, which consist of parallel connected cells), and P denotes the number of parallel connected cells in one supercell or cascade.

Popular laptop battery architectures include 3s2p (three pairs of cells connected in series), 3s3p (three groups of three cells in series) and 4s2p (four pairs in series). It was this architecture with 4 elements in series that led to the appearance of a common laptop charge voltage of 19 V.

The feature of serial connection of lithium-ion batteries is the importance of balancing each cascade to avoid the possibility of overcharging. The existing research results of cascading battery failures in packs show the importance of balancing [13].

There are also studies on the effect of the chemical coating of the cathode on the behavior of the pack in the case of a single cell failure [14]. The consideration of the possibility of the failure of a cell is necessary when building such packs.

For batteries from the UPS, balancing is not necessary when charging with low currents. In extreme cases, they can be connected in series without it.

Both types of accumulators allow the use with renewable energy sources, including solar panels and wind turbines [15]. To charge 12 V UPS accumulator it is necessary no less 27 solar cells sequentially connected. For lithium-ion cell it is necessary 8 solar cells.

Serial connection of LEDs allows to summarize the voltage drop of each diode chip of 2.7 V – 3 V [16]. It allows to use 12 V LED assemblies with 3 chips in line to create artificial lighting without extra elements.

The memory effect of lithium-ion cells is too small so this type of charge cycles not changes original properties of the accumulator [17].

The 3s pack corresponds to 12 V and is equivalent to the voltage of a single 12 V battery from UPS. Devices with this operating voltage can be connected directly, including LED strips and assemblies with 3 diodes in series. This pack supports direct charging by solar panel with 24 cells and 27 cells for UPS battery.

The 5s pack corresponds to 19 V and is equivalent to cascaded connection of three 6 V batteries from UPS. This range allows the connection of laptops, nettops, monitors and other devices with an operating voltage of 19 V, including a 24 V LED strip or two 12 V LED assemblies in cascade connection. For direct charging, it is possible to use solar panel with 36 cells, but it is better to use panels with 39 or 40 cells.

The 7s pack corresponds to 27 V and is equivalent to cascaded connection of two 12 V batteries from UPS. This unique range suited for 24 V automotive onboard devices with support the full voltage range including charging. It allows connection of three 12 V LED assemblies and charging from solar panels with 60 cells.

The 9s pack corresponds to 36 V and is equivalent to cascaded connection of three 12 V batteries from UPS. This voltage range is suitable for connecting a power inverters and devices from this range including four 12 V LED assemblies in series. Charging from two 19 V laptop power supplies connected in series or from solar panels with 72 cells is possible.

The 11s pack corresponds to 42V and is equivalent to connecting seven 6 V batteries in series from the UPS. Allows connecting five 12 V LED assemblies in series and charging from solar panels with 80 cells.

The 13s pack corresponds to 48 V and is equivalent to cascaded connection of four 12 V batteries from UPS. This voltage range is suitable for connecting high-power autonomous power supply devices and six 12 V LED assemblies in series. It is possible to charge directly from solar panels with 96 cells. It is standard range for electric bikes with a rated voltage of 48 V [18].

The found relations are magic numbers because they correspond to an integer number of lithium-ion cells, 6V batteries, and supported assemblies of 3 LEDs in a line for lighting.

The full set of rows in Table 1 allows to find the right voltage for particular model of solar panel to charge the assembly directly from it without charge controller. A powerful silicon diode or Schottky diode in series is needed to prevent the discharge of the accumulator pack through solar panel at night.

Also, it is possible to use 3 equal 3s packs to create a 9s pack or use 2 equal 5s packs for 10s pack.

Thus, the choice of voltage for an autonomous DC household network should be based on a rational consideration of the operating voltage of the main consumer devices, the voltage conversion for which is not efficient or not possible in the context of limited resources.

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5. Charge controllers and balancers

Battery Management System is an electronic board designed to monitor the processes of charge and discharge, and to monitor the state of the battery cells. BMS can disconnect the battery due to high current or accumulator overheating [19].

Battery balancer is an electronic board designed to equalize the voltages on the different cascades of the battery, which allow to use the battery capacity safe and as efficiently as possible.

Passive balancers discharge independent cascades only if voltage on it higher than the threshold.

Active balancers can work in the entire voltage range, moving the charge from cascades with the highest voltage to battery cells with the lowest voltage.

Both circuits BMS and battery balancer can be combined into one electronic board.

During long lifecycle independent cascades of accumulator may changes the capacity in different proportions because of different temperature of operation. It is recommended to use an active balancer in this case [20].

BMS boards are capable to disconnect the entire battery pack from an external charger. This is a standard charge controller for electric bikes. These boards have separate inputs for connecting a specialized charger. BMS without balancing disconnects the charger as soon as any cascade of accumulator is charged with 4.2 V.

5.1. Circuit of a passive balancer

Passive balancing assumes a small overcharge of battery cascades that have already reached the full charge voltage [21]. If the voltage at the cascade is higher the threshold the balancing resistor is activated to discharge it and reduce the voltage to the standard full charge level. Repeating the accumulator charge cycles many times with this circuit allows to equalize the voltage on all cascades after the charger is turned off.

This integrated circuit activates the balancing at 4.15 V to make possible the combining the use in parallel with existing BMS circuits (Fig. 2).

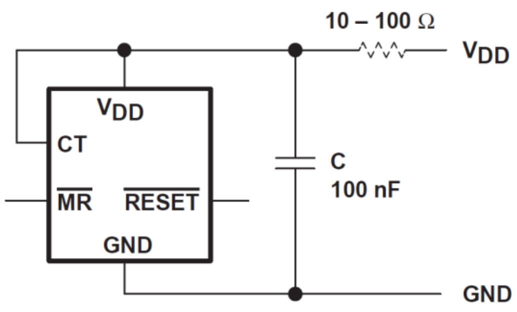

Fig. 2. Supply voltage supervisor circuit for passive balancing of Li-ion cells

5.2. Proposed technique of adjusting voltage of passive balancer to reduce losses

The performed research shows that there is a way to increase the activation voltage of a circuit based on a passive balancing chip with threshold voltage of 4.15 V.

To increase the actuation voltage, it is necessary to add to the circuit a low-voltage Schottky diode with voltage drop that not exceeds 0.25 V. This diode should be placed between voltage source and balancing circuit. Then the chips of the passive balancer circuit will be triggered at a slightly higher voltage of 4.18 to 4.20 V.

This is due to the nonlinear effect of the diode voltage drop impact on the passive balancing chip voltage measurement.

This solution is not directly compatible with most BMSs because it allows low currents to continue charging when most cells reach 4.2 V.

For series assemblies, adding one low-voltage diode to the passive balancer circuit on each cascade increases the pickup voltage of each chip.

If the cascades are initially balanced and the resistors activating in range from 4.18 to 4.19 V, then even with an average unbalance, such circuit will not charge the cascades above 4.22 V. After the end of the charging process, the voltage on all cascades will be decreased due to the enabled balancing resistors up to voltage level of threshold of 4.18 – 4.20 V.

The applicability of such increasing of balancer trigger voltage depends on the specific chip and requires additional experimental testing before use.

Experimental research showed that this practical solution really works. This solution requires the use of cascades with equal capacity in the battery pack of and increases maximum charged voltage of entire assembly.

Even with simulated unbalancing after many cycles battery pack equalizes the voltage on the cascades.

Even if on one of cascade the voltage rises above 4.20 V, after some time it will again be 4.19 V.

An increase of 0.05 V for the final part of the battery charge diagram corresponds to the addition of up to 4.5 % of the stored power.

6. Proposed steps of choice and reproducible reuse of Li-ion laptop accumulators

Demand and price for autonomous power sources during periods of crises and power outages increase significantly. Often, such an increase in demand is associated with the impossibility of delivering new products, so such solutions may not be available at all or their cost increases in many times.

Some recycling companies process old laptop batteries and sort the accumulators of the same types. This is best way to find a lot of batteries of the same type.

The use of the secondary goods market to purchase original components allows to reduce the cost of creation of solutions many times, especially if the sequence of actions is well described. In the case of bulk purchases of materials for recycling, the cost of one piece can be many times lower than the new component.

If the components of the same type and the method of building solutions based on them are available, it is possible to build reproducible affordable autonomous power sources based on the reuse of materials.

For a successful and predictable result, it is necessary to correctly select only proper components among all the variety of many offered products at the secondary goods market.

Non-original cells are not acceptable for use and are not even considered for reproducible solutions. The properties of such elements are heterogeneous and can not be classified. The number of cycles and capacity for such cells in the same package size are in several times less than for original cells, and the quality of manufacture does not meet the requirements of safe operation.

Usually the capacity of such cells in the 18650 package is about 1000 mA, with a labeled capacity of about 4000 mA, the weight is less than the original cells, and the internal resistance is very high.

It is common to find sand, soil and small stones inside such cells in 18650 package of unknown manufacturer added to emulate the weight of original cell.

In the case of limited resources, such cells can find applications in flashlights and autonomous lighting. At the same time, the charging process of such cells must be controlled and carried out by small currents.

Accumulators from electric bicycles are also often presented in the secondary goods market. These include elements from hoverboards, electric bicycles and electric scooters.

The reuse of cells from electric transport is not considered as a priority or at all undesirable for household applications because these batteries worked under high current discharge cycles with intensive shock and vibration influence [22]. This is unsafe for use at home.

Used batteries from laptops allow obtaining the original lithium-ion cells, reduce the cost of creation of power sources based on them, and reduce labor costs for connecting the individual cells because they are already combined into small packs. It this case soldering of individual cells is often not required.

Laptop batteries should be considered as the main type for reuse because they often use original high-quality cells. New original cells are expensive, but only originals are suitable for mobile and portable solutions.

It is reasonable to use only original materials from the secondary goods market if it is important to obtain a large energy capacity of final assembly with lower price for stationary power solutions.

Non-disassembled laptop accumulators reduce the labor cost of building a larger Li-ion pack because if there is no degradation and corrosion in the cells [23], there is almost no need to disassemble plastic housing. This is the best scenario of the reuse. Batteries can be assembled directly in their plastic housing. It's possible not disassemble the battery and leave the biggest part of its plastic housing if the voltage after disconnecting the charge controller is higher than 2 V.

Locking the charge controller of laptop battery is the main reason why the accumulator is moved to recycling. Frequently it is happening because of crossing the low voltage threshold under high current load during constant power consumption by laptop. The cells may be almost new and even with low internal resistance. Usually the retaining capacity is more than a half of the initial capacity declared by the manufacturer [24]. The loss in capacity can be compensated by increasing the number of cells in parallel to allow high current load.

Self-discharge is the most critical parameter. New cells lose about 10 % of their original charge in a year. Cells with high self-discharge should not be connected in parallel with other cells, only isolated use is possible.

If the laptop accumulator does not hold a charge it is possible that one cascade lost capacity. It is possible to reuse it with disassembling of plastic housing and saving of working cascades. The housing of battery can be carefully disassembled from the side of the connectors where the charge controller is usually located.

It is possible to charge each serial cascade separately with a TP4056 controller or other tools. In case of degradation the cells charging and discharging quickly. Completely degraded cells will not be charged at all.

It is necessary to be extremely careful with lithium batteries, especially with charged. Such cells may ignite.

7. Practical application of proposed method of creation of power sources for home appliances

Creation of 3s pack to connect devices with 12 V supply voltage can often be easily made using non-disassembled laptop batteries with configurations 3s1p, 3s2p and 3s3p. Depending on the maximum cell voltage, the pack can support charge voltage from 12.3 V to 13.2 V. Most often, maximum voltage is 12.6 V.

Creation of 5s pack for connection of laptops and other devices powered from 19 V to 20 V. It allows use less diameter of wires. This is one of the most rational power ranges for building a home autonomous power supply if there is a suitable laptop to connect. USB powered devices can be plugged into the ports of such portable computer for power supply or charging. It is also possible to use step-down DC-DC converters to get 12 V, 9 V or 5 V to power other low-voltage devices.

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It is also possible to assemble such accumulator pack from non-disassembled 3s1p, 3s2p, 3s3p laptop batteries with disconnected charge controllers. In order to obtain five cascades, 40 % of these housing need to be separated: separate one cells group from other two.

Often a partial opening of the housing and visual inspection is required to check that the cells are not corroded. Frequently one of the cascades is considerably degraded and needs to be replaced. It may be caused by overheating [25]. After removing of one cascade, some of laptop batteries remain as separate set of cascades of parallel cells. Then, it is necessary to make the assembly of 3 intact housings and two pairs of pieces with 1 and with 2 cascades. There are several options for their placing for initial capacity balancing of the cells connected in parallel (Figure 3). This permutation helps to ensure near equal final capacity for each cascade of parallel connected cells. It is better to ensure capacity balance of cascades of the pack [26].

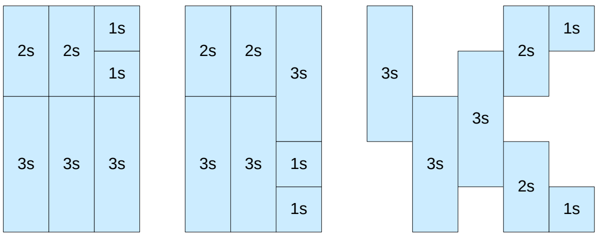

Fig. 3. Possible configurations of connection of 5 laptop accumulators to compose a single balanced 5s pack

If there are enough batteries of the same type from laptops, it is possible to make such packs from group of five batteries, and then combine them in parallel. Other configurations of combining are possible.

Passive balancing of cascades of the pack is necessary to allow the charging of entire pack sequentially from power supply with output voltage of 19 V to 21 V. Passive balancer or BMS circuits are suitable for this purpose. If such solutions are not available, it is possible to independently charge each individual parallel cascade with use of TP4056 controllers [27] or connect simplest circuits from autonomous power supplies or power banks for a single 18650 cell. In emergency cases, it is possible to check the charge manually using a voltmeter and balance cascades manually by connecting a load.

Creation of autonomous lighting using created packs allows long operation of artificial lighting. The suggested light sources are 12 V LED strips for 3s pack and 24 V LED strips for 5s pack. Two pieces of 12 V strip can be connected in series to operate from 19 V. It is also possible to use 12 V LED assemblies with 3 LEDs in series. These LEDs require current limitation both when connected in parallel to 3s pack and when connected as serial pairs to 5s pack. It is recommended to use LEDs of cold and warm spectrum as serial pairs.

Use of 10 W LEDs without a heatsink is the easiest way to create distributed interior lighting with any kind of wires including internet and telephone cables. To prevent overheating it is necessary to avoid current greater than 150 mA through each LED. If no heatsinks it is better to use a lot of LEDs with current less than 100 mA [28]. The use of 6-8 such LEDs with placement in the lampshade of a household light source under the ceiling can replace a regular light bulb. The difference between these types of lighting will not be appreciable.

Current limiting for such light sources can be done using powerful 5-7 ohm resistors. It is also possible to connect such light sources with long thin wires, for example, using unused twisted pair lines. This practical solution allows to use existing wired Internet lines to connect the described LED lighting in different parts of the room or building. If these lines are long enough, the use of additional current limiters is not required.

High-power single-chip LED can be used instead of a resistor as long as voltage on the pack is above half of the range. Then, the LED pins can be short-circuited.

Inductive drivers allow the connection of a different number of LEDs in series. The use of this type of LED drivers is preferable because LED lights by current, and extra voltage can be converted not into heat but into additional current using an inductive converter.

TP4056 charge controller can also be used to limit LED current. This is not efficient version of the driver because there are inductive ones that increase the current. However, it is affordable way that ensures the work of LED without overheating. When it is used extra voltage is converted into heat. The required current must be set by the change of appropriate resistor [27]. This solution is suitable only for connection of a single LED or parallel LED array with the input voltage in the range of 4V to 8V.

8. Discussion

This study considers the possibility of reuse of Li-ion accumulators for creation of independent sources of power supply and interior lighting for home appliances.

The increase in the popularity of portable power supplies or power banks in recent years is caused by the increase of number of different portable devices that require periodic recharging, including cell phones and tablets. A significant increase the accumulator capacity for consumer applications and a decrease the cost of compact low-voltage converters are also the factors.

Thus, the increasing popularity of lithium-ion accumulators implies the creation of efficient recycling methods for this type of batteries.

The research of correspondence of voltage series for connection of lithium-ion accumulators in series allows to ensure the compatibility with existing devices.

One of the determining factors in the choice of supply voltage during the creation of household network is the correlation between the main supply voltages of most consumer devices and available energy production and storage devices. The choice of voltage for an autonomous DC household network should be based on rational ideas of the operating voltage of the main consumer devices, the conversion of voltages for which is not possible in conditions of limited resources.

Lead-acid accumulators assume that they can be connected in series to charge directly from a high-voltage, low-current source, such as a solar panel. This allows the series charging without balancing for further parallel discharging of the batteries to ensure different voltages of charger like solar panel and the consumer.

The main advantage of such accumulators is their relatively high resistance to spontaneous combustion, while the disadvantages are their large weight, size, heavy metal and acid components.

The main indicators of accumulator quality are capacity, internal resistance, and self-discharge rate. Only new cells are suitable for mobile solutions because they have highest energy density. For stationary solutions, cells extracted from laptop accumulators can be used.

Conclusions

This research solves the problems of analysis and proposes solutions to create autonomous power supplies for specific consumption devices based on the reuse of available materials. An analysis of the history of the development of voltage standards for household AC networks and DC sources allows to move on to consider not only to individual voltage values, but to compare of the compatibility of voltage ranges for different sources.

The proposed use of the water analogy of current and area as an analogy of accumulator capacity allows a visual consideration of electrical processes and models of accumulator discharge. Determining the type of the device based on constant current and constant power consumption models allows to estimate more accurately the remaining stored energy in the accumulator by the voltage and to propose the recommendations to improve the power system as a whole.

The found rational correspondences of the rows provide compatibility with voltage ranges of acid batteries and allow charging directly from solar panels without charge controller with the required number of cells.

The proposed set of steps makes it possible to create reproducible power supplies based on secondary goods market materials. The use of the parallel connection of lithium-ion accumulators when reusing them reduces the internal resistance of the pack. Improvement of this methodological and technological basis is the direction of further research and development.

Further research might consider adding an intellectual monitoring system for accumulator packs, communication over the power lines, control of temperature, capacity measurement using current measurements, and performing the estimations based on voltage measurements with considering the type of load, that might be sufficient for practical applications.

It is also interesting to apply the results of the research for perspective accumulators and energy storage systems based on supercapacitors or ultracapacitors. Common variants of ionistors use a maximum voltage of 2.7 V, so getting packs with higher voltages also requires a series connection with balancing of cascades. The dependence of the voltage on the part of the stored energy in capacitive systems follows Coulomb's law and differs from considered models, so continuing research in this direction is perspective and of great interest.

Contribution of authors: tasks formulation, proposing the concept of voltage ranges for comparability of lithium-ion and acid accumulators for direct connection of laptops and LEDs, analysis the voltage ranges, proposing the idea of adjusting of passive balancing, analysis of different load models to evaluate the efficiency, description the method – **Artem Perepelitsyn**; analysis and classification of lithium-ion batteries and charge controllers, experimental research of process of the reuse 18650 cells, creation of few full scale power sources prototypes including architecture 3s and 5s for experimental approval of theoretical results, iterative testing of discharge processes with different loads, analysis of publications and translation – **Artem Tetskyi**.

All authors have read and agreed to the published version of the manuscript.

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МЕТОД СТВОРЕННЯ ПОБУТОВИХ ДЖЕРЕЛ ДОПОМІЖНОГО ЖИВЛЕННЯ В УМОВАХ ОБМЕЖЕНИХ РЕСУРСІВ

Артем Перепелицин, Артем Тецький

Предметом вивчення в даній статті є діапазони напруг, методи та засоби створення автономних джерел живлення побутової техніки та штучного освітлення з повторним використанням лише поширених компонентів. **Метою** роботи є підвищення ефективності створення та використання автономних джерел живлення побутової техніки. **Завдання:** проаналізувати історію розвитку стандартів напруги побутових мереж; проаналізувати існуючі автономні джерела живлення та типи акумуляторів; проаналізувати різні моделі навантаження; знайти раціональні діапазони напруг, засновані на фундаментальних значеннях; проаналізувати схеми контролю заряду та балансування акумуляторів на основі літію; сформулювати набір кроків створення джерел живлення на основі матеріалів вторинного ринку; навести приклад практичного застосування результатів. Відповідно до поставлених завдань, були отримані наступні **результати**. Проаналізовано історію розвитку стандартів напруги побутових мереж змінного струму. Обговорюються види автономних джерел живлення, у тому числі такі, що формують чистий синус. Виконано аналіз акумуляторів для автономних джерел живлення з різним хімічним складом. Запропоновано використовувати водну аналогію струму та площу як аналогію ємності акумулятора для наочного представлення електричних процесів. Розглянуто моделі споживання константного струму та споживання постійної потужності. Запропоновано використовувати паралельне включення літій-іонних акумуляторів при повторному застосуванні для зниження внутрішнього опору збірки. Досліджено відповідність рядів напруги при послідовному включенні літій-іонних акумуляторів для забезпечення сумісності з існуючими пристроями. Знайдено раціональні відповідності діапазонів напруг для забезпечення сумісності літій-іонних і кислотних акумуляторів з можливістю здійснювати заряд безпосередньо від сонячних батарей без контролера заряду. Проаналізовано схеми контролю заряду та балансування акумуляторів. Сформульовано набір кроків створення джерел живлення із використанням літій-іонних акумуляторів із вторинного ринку. **Висновки:** Головний внесок цього дослідження полягає в тому, що запропонований метод створення джерел автономного живлення та освітлення на основі повторного використання акумуляторів з використанням мінімальної кількості перетворювачів. Знайдені та детально розглянуті виділені значення 3, 5, 7, 9, 11 і 13 послідовно з'єднаних літій-іонних акумуляторів для отримання еквівалентів стандартних напруг 12 В, 19 В, 27 В, 36 В, 42 В і 48 В. Запропонований набір кроків з налаштування напруги пасивного балансира дозволяє додати 4,5 % потужності, що запасається. Описані рішення дозволяють побудувати повноцінну автономну низьковольтну електромережу, що масштабується, з можливістю зарядки безпосередньо від сонячних батарей без дорогих контролерів заряду.

Ключові слова: діапазони напруг; акумулятори; контролер заряду; сонячні панелі; джерело живлення; пасивне балансування; літій-іонний акумулятор; система керування батареєю; вторинний ринок; повторне використання електроніки.

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