

Article

Method of Reproducible Scalable Construction of Autonomous Power Sources for Home Appliances

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Abstract

This work proposes the construction of autonomous power supplies for specific home electronics based on reusing available materials. This would allow most standard electrical consumers, solar panels, and accumulators to connect directly and without any charging drivers. The proposed set of steps allows the creation of reproducible power supplies. The use of lead–acid accumulators enables series connection and charging directly from a high-voltage, low-current source, such as a solar panel. This will allow serial charging and discharging of accumulators without balancing, as well as support the direct connection of consumer devices and solar panels without converters. The proposed direct current (DC) operating voltage range, with a center voltage of 100 V, allows the use of eight sequentially connected 12 V accumulators for direct charging from three of the most common solar panels, with 72 cells connected in series (nine accumulators for four panels with 60 cells). At the same time, most home electronics with switched-mode power supplies (SMPSs) are designed for a voltage range of 100 V to 240 V and are capable to work from direct current starting with 15–30% less voltage. This guarantees support of the full voltage range of 8–9 lead–acid accumulators or 26s–32s lithium–ion accumulators for the reproducible construction of home power sources without extra converters. In addition, the reproducible construction of a power inverter with a true sine wave, with recommendations of how to adjust the supported input range to the required voltage for powering the fridge, is proposed. The proposed scalable circuit and assembly instructions for the power inverter based on EGS002 and widespread electrical transformers RT-1000B1 allow reproducible creation of inverters with a true sine output and a wide input voltage range, including 96 V DC. The application of the proposed method allows to reduce energy consumption up to 10% by removing converters.

Keywords: autonomous power supply; solar panel; direct current; power inverter; home microgrid; accumulator; passive balancing; direct powering of home electronics; 96 V; DC power distribution; converterless connection method; SMPS connection to DC input

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1. Introduction

Most households require the use of electrical power to reduce required efforts and increase the quality of life [1]. Mass production of electrical light sources, fridges, kitchen and climate equipment reduces the price of electrical home appliances and makes them available for wide use everywhere [2].

The rise of the secondary goods market with proper reuse allows to extend the effi-

cient period of operating and the entire lifecycle of electrical home appliances, including accumulators for various types of electronics [3,4]. Also, such electrical materials allow the creation of cheap and reproducible power sources. But to do this, a validated technique of creation is required.

Normally, for proper operation, it is better to use the centralized power grid [5] for powering home appliances. But there are critical situations during outages when the principle possibility of using electrical equipment or electronics is critically important [6], and the knowledge of how a smartphone or laptop charger can be powered directly from a not intended for this purpose power source, like a set of accumulators [7] or solar panels, without converters can save lives during emergencies and natural disasters [8].

The autonomous operation of such home appliances during probable outages is quite important issue [3], especially for areas without a centralized power grid. The reuse of accumulators [9] and the creation of own power sources is a possible solution.

Understanding the operating principles of switched-mode power supplies [10] used in most modern household electronics [11] allows to power them directly from any available direct current source with a voltage above 80 V–90 V DC and without any extra converters [12] (p. 107), which can be practically used during outages and critical situations.

The use of unified, widespread SMPS chargers for portable electronics with a wide supported input voltage range and the fact of possibility of operating such power units from direct current means that they can be connected directly to a high-voltage DC source [3].

But this feature can be used not only in critical situations but also for the creation of an experimental powering scheme with minimal components and a low price, as well as during periodic planned outages.

At the same time, the growing interest in the use of solar panels, the rising number of electric vehicles, and charging stations actualizes direct current distribution [13]. Avoiding extra converters can improve the efficiency and reduce the price of such DC power grids. Multiple datacenters also use direct current or mixed power distribution [14,15]. The manufacturers of electric equipment and power units for such datacenters already provide the possibility of connecting such power supply units to servers from both types of supplies. The interest to such direct current microgrids is practically reasonable [16].

Since direct current distribution within local areas and microgrids is starting to become the focus of interest for companies, it can also be applied to autonomous power supply for home microgrids [17] because it allows to reduce the price of the entire setup by avoiding the use of converters. It also allows the minimal working implementation that can be created iteratively, but with the requirement of possibility of partial operation from the moment of first installation of solar panels or accumulators.

The choice of DC distribution for solar panels as a source becomes reasonable [18] if there is no need to transfer the produced energy using a wide grid. If only one or a few buildings are connected to a microgrid, small-scale DC distribution can improve the efficiency and avoid the use of converters in distribution [19].

The low-voltage DC distribution [20] of different voltage ranges, including 48 V [21], allows connecting electronics with this voltage range directly without using of extra power units for each of them.

It is also important to keep in mind that the safe direct current voltage is higher than the alternating current (AC) safe range, and the considered voltage of 110 V DC can be conditionally identified as the upper end of the noncritical voltage range for electrical shock.

Thus, the use of direct current distribution for the home microgrid is a relevant and economically grounded solution for creating a small, autonomous power supply.

The proposed autonomous power supply construction compatible with 96 V DC voltage range is the rational variant for creation of autonomous household power supply. For this voltage range, it is enough to connect the three most widespread solar panels in series for direct connection of cell phones or laptop chargers without a converter. In the same way, it is possible to connect most modern electronics and LED bulbs with SMPs, which act as built-in converters that support a wide input range up to 380 V DC.

The goal of this study is to simplify the process of creation reproducible power sources for home appliances with the use of widespread components.

To achieve this goal, it is necessary to perform the following tasks:

1. To analyze the possibility of direct powering electronics without extra converters;
2. To propose the technique of constructing autonomous power supplies for home;
3. To propose models of scalable solar panel connection for required voltage or power;
4. To propose steps of construction and adjusting to the required input voltage range of the transformer and power inverter with true sine wave output for powering the fridge;
5. To propose a sequence of steps for the selection of acceptable autonomous power supply;
6. To provide a practical example of implementation of the proposed method.

The article is organized as follows: The analysis of the risks of blackouts, growing demand on autonomous power sources and the possibilities of connecting widespread home appliances directly to high voltage local DC distribution is performed in Section 2. Section 3 proposes the concept of autonomous 100 V direct current home distribution with proposed models of solar panel connection for scaling voltage and required power. Section 4 provides the proposed sequence of steps to build variants of proposed power sources for home appliances and a true sine power inverter with adjusting input voltage and transformer ratio. A practical example of a created system based on the proposed method is provided in Section 5. Sections 6 and 7 discuss and conclude the results of the study.

2. Analysis of Rising Demand and Problems of Autonomous Power

2.1. Problem of Outages

Almost everything is powered by electricity [22,23]. In the case of centralized power supply, the failure of one connected node of the power grid system leads to a chain overload of nearby ones, which leads to large-scale outages [23,24]. Local and global blackouts are a permanent potential problem for all regions with centralized energy systems [25]. Periodically these happen everywhere, but for remote rural areas or locations they are frequent events caused by multiple reasons, including weather conditions [26].

Most households use fridges that require continuous power from a pure sine wave alternating current mains supply [3]. After a half-hour outage, such devices require ten times higher peak power to resume operation [23]. In the case of a centralized mass outage, this leads to an almost tenfold increase in the required power to start the entire power system [27] (p. 90), which is unattainable for the current form of grids that are based on only weather-dependent renewable sources. The cold load pickup is a significant problem for restoring after some period of outage [28].

During normal operation of the power supply grid, the events of switching on the fridges are distributed in time and do not lead to the need to provide additional power reserve to maintain the operation of the power system, but even in this manner of work the optimization of consumption is possible [29].

Because of that, after a long mass power outage, switching on is possible only by separate small sub-grids [30] in order to distribute in time start-up events of fridges and other constantly plugged in devices with a high starting current [28,31]. The use of a delayed start of appliances after energy supply restoring also simplifies this process [29].

2.2. Autonomous Power Supply

The use of autonomous power sources can help during periodical power outage and reduce the dependence from and the workload on the centralized power system [3,32]. For some households the use of autonomous power supply is the only possible way to ensure the work of electrical appliances [33,34].

2.2.1. Problem of Commercial Autonomous Power Systems

There are ready-made autonomous power supply systems that can be installed and maintained by qualified companies. The systems themselves, their installation and maintenance are expensive relatively and in absolute terms [35]. A significant part of the cost is the components of the intellectual property of the specific company, the cost of work (installation and maintenance), the capacity of accumulators and expensive high-quality converters as part of autonomous power supply systems.

Ready-made autonomous power supply systems usually include energy-generating components such as solar panels together with wind and water turbines, accumulators, converter units for charging of accumulators from these energy-generating components, the converter unit for charging accumulators from the centralized power grid, and a power inverter with true sine AC on the output based on a massive transformer with pure copper windings for powering the home microgrid and connected home appliances (Figure 1).

Such systems assume the possibility of both the power supply from energy-generating components and from the centralized power grid to reduce consumption from this grid based on energy tariffs and to obtain the possibility of completely autonomous operating during low consumption and high generation periods [36,37].

Systems that provide the generated power back to the centralized grid use a more complicated transforming scheme [38] and are not a subject of interest within this study.

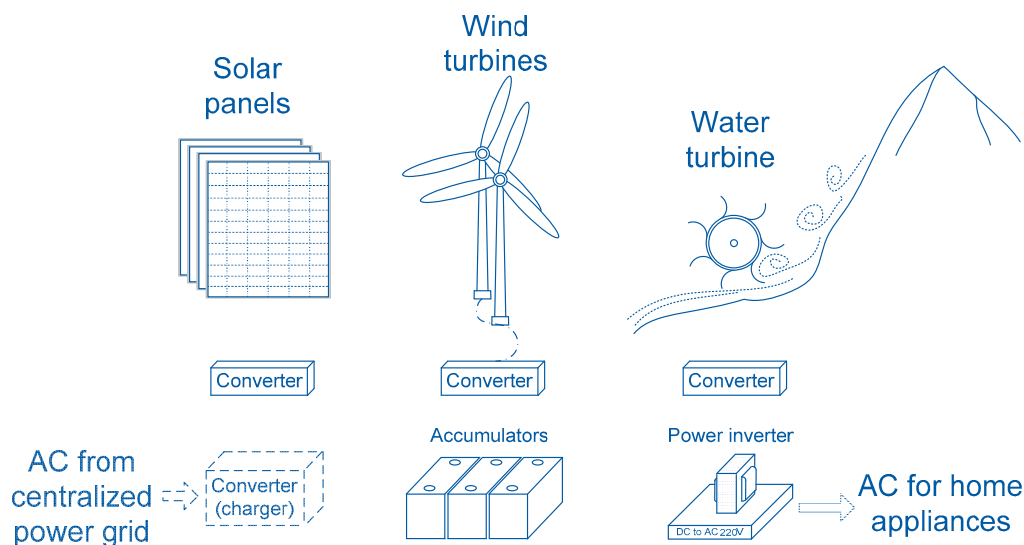


Figure 1. The generalized scheme of an autonomous power system that includes energy-generating components and converter units for charging accumulators and passing the power to the output

power inverter, allowing the connection of home appliances within the home microgrid with true (pure) sine AC.

When a stable centralized power supply is available, the demand for such expensive ready-made autonomous power supply systems is too low, but during a period of systematic outages, the price of all involved components and installation works increases many times, because such companies are not able to provide an instant multiple increase in demand. This prevents the mass production of ready-made autonomous power supply solutions, which could significantly reduce the price of such systems for households.

An obvious solution would be to build reproducible autonomous power supply systems, using the components with significantly lower prices or using already existing components.

2.2.2. Problem of Converter Units in Autonomous Power Systems for Home Appliances

The price of high-quality maximum power point tracking (MPPT) converter units for charging accumulators [39] from solar panels is comparable to the price of both a set of accumulators and the price of multiple panels [40]. Such converters can convert an extra voltage into additional current to ensure the entire operating voltage range during the charging process of accumulators, as well as use the efficiently changing voltage of solar panels depending on their temperature (Figure 2) [41] and light intensity [42,43] (both are the key problems that should be considered during the creation of such systems).

Also, the angle between the perpendicular to the solar panel and the sun influence the resulting current (and as the result the power) as the multiplier of cosine of this angle:

$$I_{\text{angle}} = I_{\text{perpendicular}} \cdot \cos \alpha, \quad (1)$$

where $I_{\text{perpendicular}}$ is the achievable current value in the case of zero angle to the sun with the same rest conditions, α is actually this angle value, and I_{angle} is the resulting current.

In difference to pulse width modulation (PWM) converters, which are only capable of limiting the current using a controllable semiconductor switch [44], MPPT converters perform efficient power conversion [45]. But even in this case, the total loss during conversion is usually up to 10%.

Also, it is necessary to remember that such converters can operate in a wide input voltage range and for serial connection of solar panels with current control (for maximum power). If the higher current at the local maximum power in conditions of different light intensity of different solar panels or segments of the same panel is mistakenly identified as the main maximum, it will result in those segments being shorted by the installed bypass diodes and the system operating at a lower voltage [46].

Depending on the implementation, the converter can continue work at this local maximum even after removing such temporary partial shadowing if the local current remains higher than the possible current in all sequentially connected independent panel segments, which excludes them from operation at all.

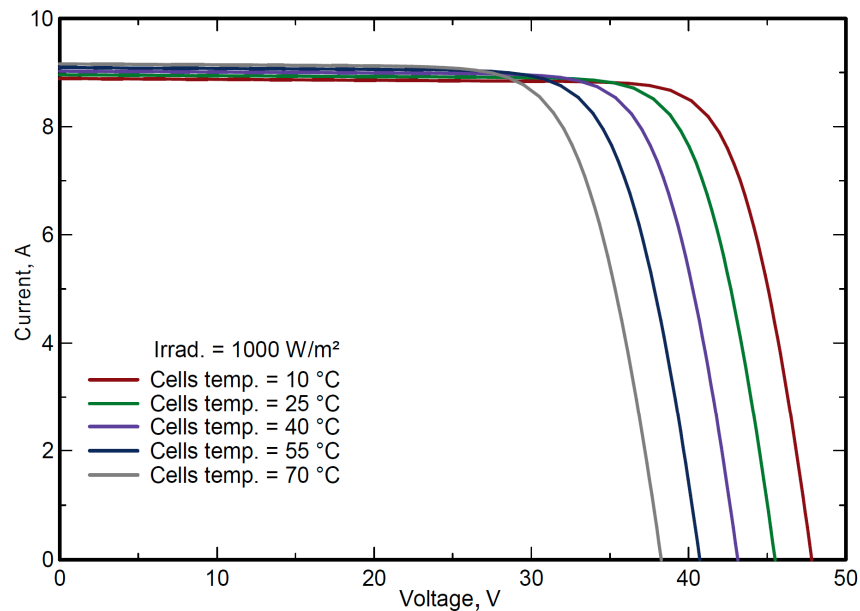


Figure 2. The dependence of current from voltage at fixed conditions of light intensity and five different temperatures of SRP-315-6PA solar panel from the official specification of company [41] shows the reason of requirements of continuous tracking of maximum power at varying conditions.

2.2.3. Direct Powering of Home Electronics Based on Switched-Mode Power Supply

If the principle possibility to use the individual components of the autonomous power supply system is the priority, then it is possible to directly connect most household appliances with an AC switched-mode power supply unit directly to solar panels or to accumulators with the suitable DC voltage ranges [3,12]. Direct current powering reduces the number of intermediate power conversion stages [3,47] in DC distribution systems [48]. Since appliances are connected without extra converters like MPPT or any power inverters, there is no power loss on them, and already built-in switched-mode power supply units within home electronics themselves are used for conversion.

Most of these modern technologically intensive appliances and home electronics are produced to operate in a wide range of alternating current, 100–240 V (even up to 250 V), with the permissible voltage deviation range from −10% to +15%, which corresponds to range 90 V–276 V (or even up to 287 V AC). They are based on SMPS voltage converters.

The direct current voltage equivalent of the maximum voltage amplitude of AC can be obtained by multiplying the AC nominal voltage by $\sqrt{2}$ (multiplying by 1.41) [3]:

$$U_{\text{amplitude}} = \sqrt{2} \cdot U_{\text{AC}}, \quad (2)$$

where U_{AC} is an average AC voltage, and $U_{\text{amplitude}}$ is a maximum voltage amplitude for it. The DC distribution assumes 320 V [49] equivalent to 230 V AC, which is less than 400 V nominal of widespread film capacitors (it can be considered as maximum for such SMPSs).

Operation of such AC power supplies from DC may even be preferable due to a more gentle mode of operating for the input capacitor, as well as for the entire input cascade within the switching unit of the SMPS, except the diode bridge. In case of connection of direct current on the input, the diode bridge (called a rectifier) constantly uses only one pair from four diodes, which is typical of the most widely used full-bridge rectifier scheme [50]. The power dissipation on diodes in the bridge can be estimated by the multiplication of forward current and voltage drop characteristics [51] (p. 3) and [52] (p.

2), which reduces or stabilizes the rise in temperature because of a negative temperature coefficient (Figure 3).

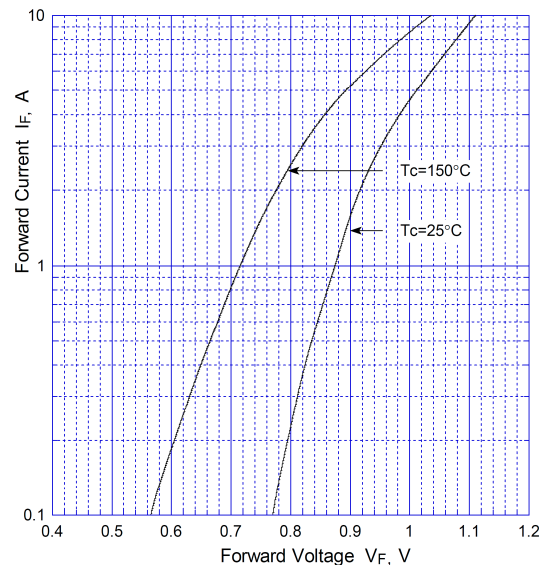


Figure 3. The dependence of the voltage drop of a diode from the current and temperature values.

But it is also necessary to keep in mind that highly efficient SMPS architectures are bridgeless or use an active-bridge with the specific Power Factor Correction (PFC) method [53,54] that excludes a reactive component from the power consumption [55] by means of additional transistors that can operate wrong from DC (as well as AC fuse [56]).

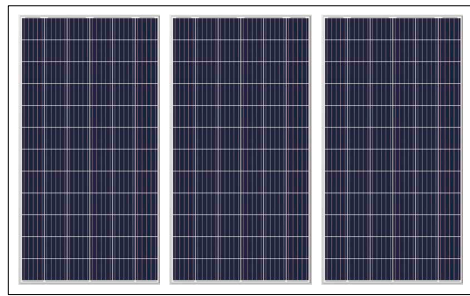
3. Proposed Construction of Autonomous Power Sources for Home

3.1. Proposed Concept of Autonomous Power Source for Home Appliances

Based on the assumption that converters are unavailable, by any reason, it is possible to propose a surprisingly simple circuit for autonomous power supply without additional converters. It is enough to sequentially connect any three solar panels with 72 cells in each and connect them to eight, equal 12 V acid accumulators connected in series (Figure 4).

This connection method ensures the direct current voltage range with the center at 100 V (working range is 85 V to 115 V). This is almost the existing voltage standard, so most electrical appliances with a switched-mode power supply already support it and will work directly even from direct current (that is even preferable for multiple applications). These are widespread Light Emitting Diode (LED) lamps and SMPSs to any equipment, and almost all electronics. This is enough for most household tasks. Only the fridge, washing machine, microwave (all with AC motors) and some heating appliances will not work directly. A power inverter is required to connect such AC appliances to the proposed source.

3 solar panels with 72 cells connected in series



8 lead acid 12V accumulators connected in series

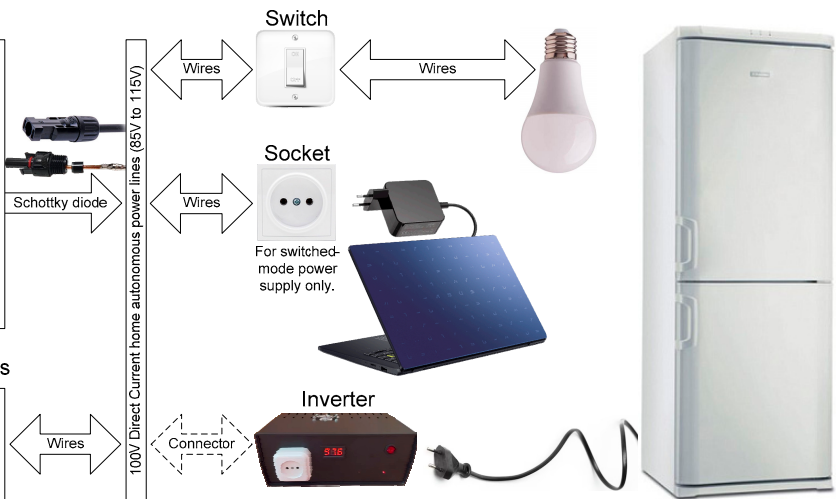


Figure 4. The entire structure of the proposed autonomous power system for home appliances allows the direct connection of electronics with built-in SMPs and use of power inverter for AC ones.

This proposed concept of connection combines the exact match of the total number of cells for one of most widespread solar panels with 72 cells (or the equivalent of 144 half cells) divided by 27 precisely, to meet the model ratio of 27 solar cells per each 12 V lead–acid accumulator for direct charging without converters, and the direct current voltage range with the center at 100 V, which is less than the upper limit of the relatively safe DC voltage range (in difference to AC of the same voltage), but at the same time allows the direct powering of most widespread LED light bulbs and electronics with switched-mode power supply.

The other widespread solar panels with 60 cells (or the equivalent of 120 half cells) are also capable of providing a rational match of four solar panels and nine lead–acid 12 V accumulators connected sequentially to obtain near the same voltage range with the center at 110 V DC (working range is 96 V to 127 V). This is the scalability of the possible components and voltage ranges within the proposed construction method (Figure 5).

To avoid the discharging of the accumulators at night, the high voltage powerful Schottky diode can be added to the connection line from solar panels to implement the requirement of disconnection of solar panels for the night period.

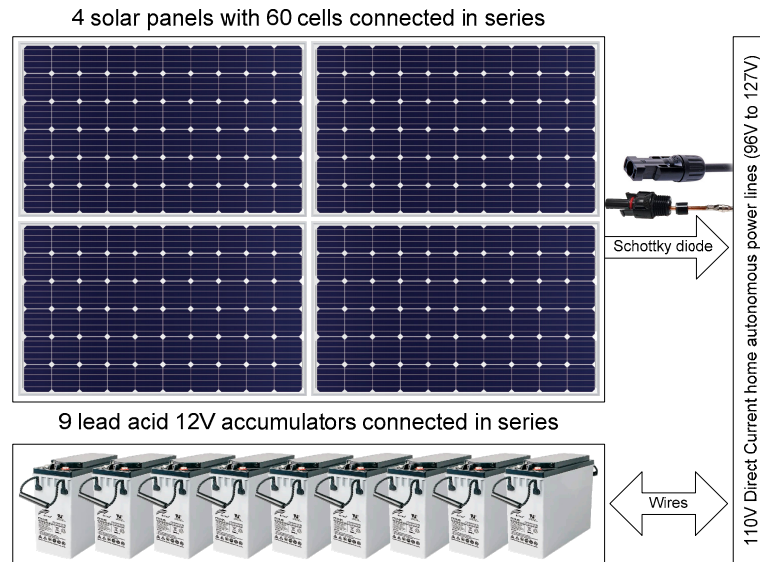


Figure 5. The proposed method of construction of autonomous power sources for home appliances without additional converters provides the scalability of the working voltage range to allow the use of widespread solar panels with 60 cells to obtain the rational match of 4 panels to 9 accumulators.

The proposed diagram can be extended by adding the charger for accumulators from the centralized power grid in the form of the power supply connected to the system over a high-voltage Schottky diode in parallel (in the same way as solar panels).

The balancing of lead–acid accumulators connected in series must be ensured based on the initial structural (constructive) balancing stage that assumes the selection of equal accumulators with the same condition and capacity, which should be ten times higher than the average working current in solar panels. The shape of the curve (Figure 2) of current from voltage dependency ensures the limited current during the charging process and rapid reducing of the current when accumulators are charged with reaching near open-circuit voltage. The lead–acid accumulators (except gel ones) are capable to maintain a balancing current even when charged, but it exhausts the amount of electrolytes and as the result the number of cycles. At too bright and cold weather without additional consumption in the system, the voltage on each accumulator can rise up to 15 V or even up to 16 V (that is completely unacceptable for gel accumulators, but can be periodically done for desulfation of the maintainable accumulators where renewing of electrolyte is possible). To avoid it, adding balancing circuits to each accumulator is possible.

But if additional circuits are unavailable based on the same assumption, the voltage of the accumulators can be visualized by 24 V segments of LED strip to know when to manually stop the charging from solar panels. To each 12 V accumulator, it is proposed to connect such 24 V white LED strip segment to visualize the voltage on each element (Figure 6). This is the proposed way of visual identification of the overvoltage of the accumulators during sequential charging of constructively balanced serially connected accumulators.

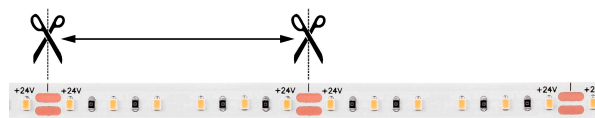


Figure 6. One segment of ordinary 24 V white LED strip can be used as a simple visual indicator of the voltage on each accumulator, because typically the light starts to become visible after crossing

13–14 V. Overcharging of individual serially connected accumulators can be identified by too bright such segments, compared to brightness of segments connected to the rest accumulators, and vice versa.

3.2. Proposed Models of Scalable Solar Panel Connection

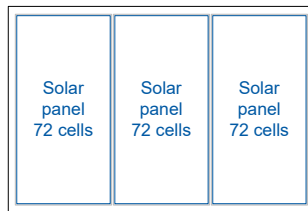
Since the solar panels with 60 and 72 are the most widespread for creation of the autonomous power supply for home purposes, there is a finite number of voltages of sequential connection and possible placements. These parameters can be represented in the form of models of solar panel connection for a reasonable number of considered panels in order to obtain the minimal operating voltage above and a maximum open circuit voltage not too much higher than the direct current equivalent of the operating voltage range of most switched-mode power supplies.

For solar panels with 72 cells, the number of proposed models are in the range from 3 (max. power voltage above 108 V DC) to 8 (open circuit voltage is up to 367 V DC).

For solar panels with 60 cells these numbers of proposed models are in the range from 3 (max. power voltage above 90 V DC) to 10 (open circuit voltage is up to 384 V DC).

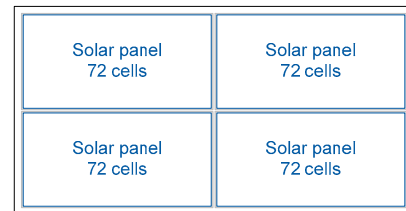
Figures 7 and 8 provide models for connecting panels with 72 and 60 cells.

3 solar panels (max. power at 108 V, up to 138 V)



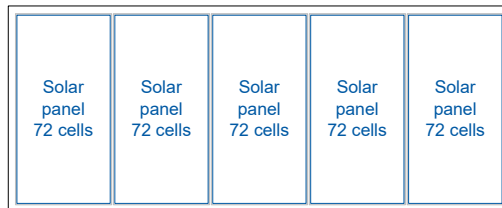
(a)

4 solar panels (max. power at 144 V, open circuit up to 184 V)



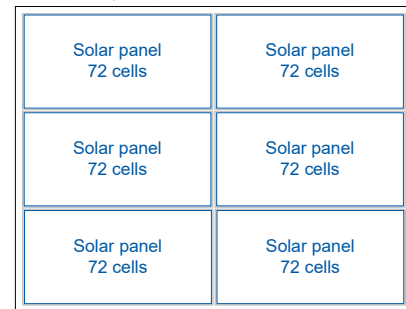
(b)

5 solar panels (max. power at 180 V, open circuit up to 230 V)



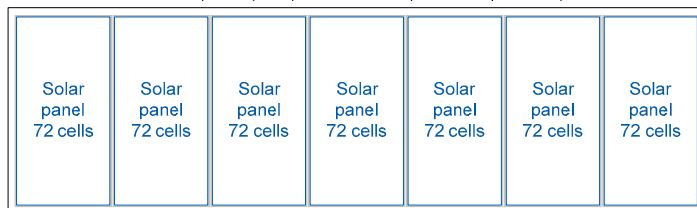
(c)

6 solar panels (max. power at 216 V, open circuit up to 276 V)



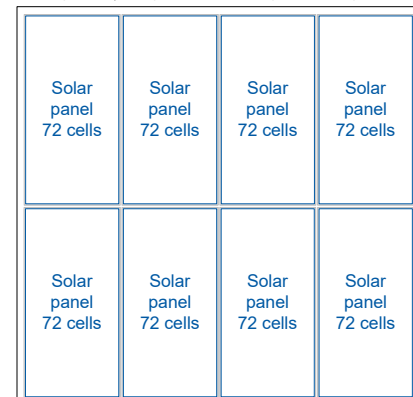
(d)

7 solar panels (max. power at 252 V, open circuit up to 321 V)



(e)

8 solar panels (max. power at 288 V, open circuit up to 367 V)



(f)

Figure 7. Models of sequential solar panel connection with voltages and placement for 3, 4, 5, 6, 7, 8 solar panels with 72 cells in each: (a) model with 3 solar panels for 108 V DC; (b) model with 4 solar panels for 144 V DC; (c) model with 5 solar panels for 180 V DC; (d) model with 6 solar panels for 216 V DC; (e) model with 7 solar panels for 252 V DC; (f) model with 8 solar panels for 288 V DC.



Figure 8. Models of sequential solar panel connection with voltages and placement for 3–10 panels 60 cells: (a) model of 3 panels for 90 V DC; (b) model of 4 panels for 120 V DC; (c) model of 5 panels for 150 V DC; (d) model of 6 panels for 180 V DC; (e) model of 7 panels for 210 V DC; (f) model of 8 panels for 240 V DC; (g) model of 9 panels for 270 V DC; (h) model of 10 solar panels for 300 V DC.

3.3. Proposed Reproducible Construction of Power Inverter with True Sine Output

If the purpose of the autonomous power supply is the powering of the fridge, then the inverter with the pure sine wave (with the use of the massive transformer) and a battery that is capable of providing the starting current are required. For such inverters it is better to select a voltage range of at least of 36 V, for example, 10s lithium-ion packages or three lead-acid 12 V accumulators in series connection. A lower voltage range for the inverter is not reasonable because of the increase in the current in low-voltage circuits and transistors.

The design of the inverter is quite simple (Figure 9). The main two components are the inverter board based on the discrete EGS002 module board and a set of transistors with a radiator, and the massive transformer for the required voltage range. Such boards are usually produced for operation in the 24 V and 48 V ranges but can be redesigned to work from another voltage, including 96 V. The main difference is the higher voltage of the capacitors in the supply lines.

The EGS002 module is based on the EG8010 chip [57], which was designed specifically to generate SPWM (Sinusoidal Pulse Width Modulation). Based on such a board, it is possible to create an inverter with a pure sine wave to allow the starting and working of fridges or other electrical appliances with motors that need AC with pure sine.

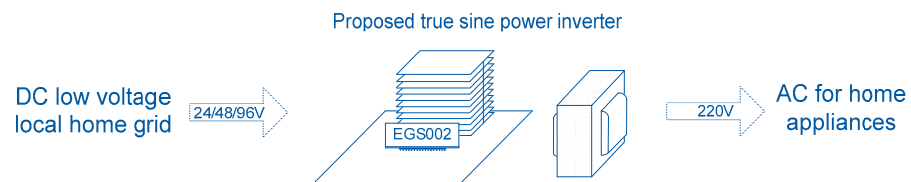


Figure 9. The proposed construction of a power inverter with a true sine output is based on two main components, the board with power transistors controlled by the EGS002 module based on the EG8010 chip, and the massive powerful transformer or a few transformers for the required voltage range.

It is also necessary to find a massive transformer that can be also modified for a specific voltage range. If a suitable transformer is found, then the reproducible inverter can be assembled. Adding such large enough transformer that fits to the selected voltage range of the inverter board allows to ensure the pick power and starting current of the fridge, which is actually one of the key purposes of adding this inverter to the proposed autonomous home power source description.

If such a transformer is connected by high-voltage winding to a centralized AC power grid, then the AC voltage on low-voltage winding should be lower (at least 20%) than the lowest voltage of the operating voltage range of the inverter. For example, it should be 30 V AC for the 48 V DC operating voltage range (39 V to 54.6 V) of the inverter.

If a connection of 220 V AC to a high-voltage winding produces 15 V AC voltage at low winding, it matches the 24 V DC voltage range of the inverter (like the considered 30 V AC fits to the 48 V DC range). To the proposed voltage range of 96 V DC corresponds a voltage of 60 V AC at low-voltage winding. Such experiments of winding connection to

the centralized power grid to measure the voltage require experience and can be done over the fuse or with true incandescent light bulbs in series connection.

The proposed connection of two transformers allows to increase the total power or to increase the required voltage range (Figure 10). The parallel connection of low-voltage windings allows increasing the resulting power at the same voltage. The serial connection of such transformers allows increasing the resulting voltage at the low-voltage winding.

On the wire from low-voltage winding directly before a massive transformer it is better to add a massive inductor to reduce its own consumption and the heating of the transformer itself.

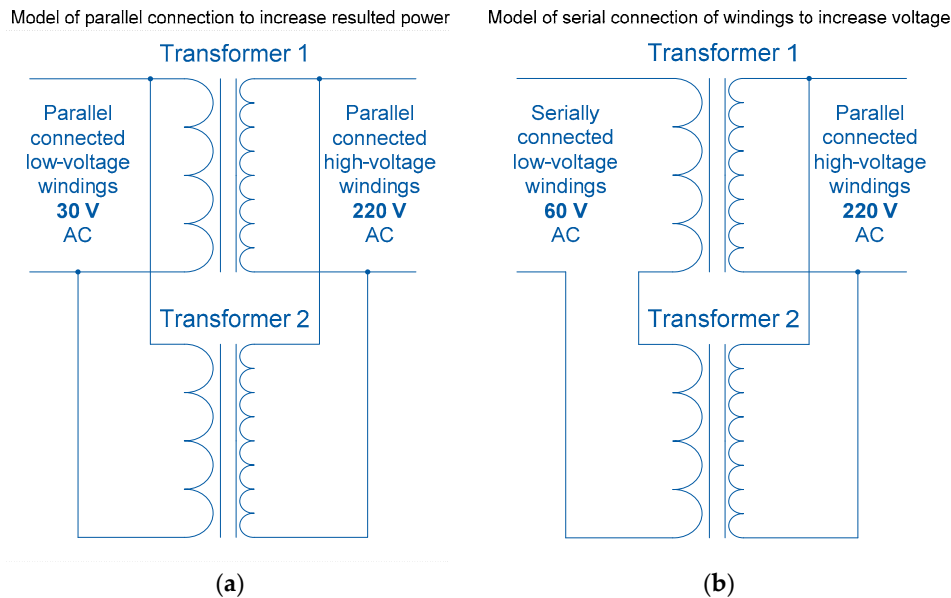


Figure 10. Models of connection of equal RT-1000B1 transformers to increase resulted power using (a) parallel connection with saving the same input and output voltage ranges as for a single transformer, and (b) sequential connection of the same type of windings with parallel connection of other windings to increase a voltage range in 2 times. The inverter input ranges are (a) 48 V and (b) 96 V.

The widespread pure sine inverter board model designed for work in 24/48 V with power 1000/1800 W and contains the EGS002 module in its composition with the EG8010 chip. Also, it is possible to create completely unique implementation using only this module [58].

The inverter price is determined by two components, the cost of this 48 V inverter board and the cost of one or two transformers. It is better to choose transformers for (or already from) inverters. The proposed models for selection are RT-1000B1 and RT-1200B. Also, it is possible to use several transformers of lower power. It is possible to find the acceptable transformer on the secondary goods market with the power of 1000 VA. If only few identical smaller transformers are available, the proposed connection models can be used together.

To allow the work directly from popular solar panels with 72 cells with directly connected 10s lithium-ion packages for charging, the construction of these transformers requires simple modification to support the voltage range of 36 V (30 V to 42 V). In this case, it is enough to connect an additional separate thin winding (dual connector with green and black wires) in series with the high-voltage winding in a correct direction. This modification is simple and reproducible.

In the same way, such transformers can be converted to operate in the proposed 96 V range. To do this, it is necessary to find the version of the RT-1000B1 transformer in which the low-voltage winding is made of parallel connection using double wires. The modification of it and sequential connection of two parts of such dual low-voltage winding allows to modify the transformer from the 48 V version into a unique 96 V version.

But, much more reproducible way of the modification of the transformer is the use of the proposed model of sequential connection of low-voltage windings of two such transformers and parallel connection of their high-voltage windings in a correct direction (Figure 10b). This connection increases voltage and power, and provides support of 96 V.

Similarly, the connection of both windings in parallel increases only the resulting power with saving the same operating voltage range 48 V as for single transformer (Figure 10a).

4. Proposed Technique for Selection and Build of Autonomous Solution

4.1. Creation of Low Voltage Direct Current Power Grid for Home

If all the appliances or electronics are low voltage (12 V or 24 V compatible for car onboard system, or with laptop and nettop voltage range 19 V–20 V, or the specific voltage under 36 V–42 V), it is enough to use the autonomous accumulator package with the exact required voltage range or higher if low-cost DC-to-DC converters will be connected after the accumulator to maintain the same output voltage for home low voltage local DC power grid within the entire operating voltage range of the accumulator.

In this case the solar panel with an equivalent of 60 cells or 72 cells can be connected to such a system. If higher current values are required, two or more equal solar panels can be connected in parallel using a Schottky diode. For two panels, the paired powerful diodes like LT745S from the computer power unit are well suitable. But for sequentially connected panels, only high-voltage diodes are acceptable. The proposed barrier diode is 20A10.

The use of the diode is preferable even if only one panel is involved. It is required to avoid discharging the accumulator at night through the connected solar panel.

This connection model assumes three possibilities, the autonomous work only from the solar panel, the periodical powering during outages from the accumulator that charges from the centralized power grid, and the use of both, the accumulator and solar panel, together.

Thus, depending on the available components and the operating voltage ranges of the autonomous low voltage home power grid, the accumulator, and the solar panel, four variants of implementation are possible: with the DC-to-DC converter after the accumulator, with the converter before the accumulator (after the panel), and with both and without DC-to-DC convertors at all.

4.2. Creation of High Voltage Direct Current Local Power Grid for Home

For creation of an autonomous system based on the proposed method, it is necessary to decide which available components for building the system are available. Based on these components, it is possible to assemble the parts of such system as a partial configuration.

Depending on the requirements and the available resources, a specific model of the autonomous power system should be selected.

It is possible to calculate the required voltage for a specific accumulator installation for direct charging from solar panels based on the proposed equation:

$$U = 0.5 \cdot n_{\text{cells}}, \quad (3)$$

where U is the resulting voltage at the maximum power point for the required number n_{cells} of cells connected in series. Practically, it means that if the voltage on the accumulator connected to the solar panels is less (if the accumulator is discharged), the voltage difference will not be converted to extra current, as in the case of the use of DC-to-DC converters or chargers, but will be dissipated in the wires that connect the panels and also in the internal resistance of the panels. But within the formulated assumption of the minimally involved components, this is a unique and elegant solution of a nontrivial problem of maintaining the constant current during the charging process of accumulators with increasing voltage during the charge.

It is also possible to calculate the voltage at maximum power point for a few panels:

$$U = 0.5 \cdot n_{\text{cells}} \cdot n_{\text{panels}}, \quad (4)$$

where n_{panels} is the number of panels with n_{cells} cells in each connected in series. It should be noticed that the open circuit voltage is more sensitive to the temperature change than the voltage of maximum power, but the current at this voltage can vary significantly.

After the mounting of solar panels it is necessary to add a Schottky diode to avoid discharging of the accumulator at night and organize the installation of communication lines for consumption elements within the house. The connection can be done using ordinary wires or using a few portable extension cords. If the wires are connected using twists, the isolation of such places of connection is required.

To organize work with the accumulators, it is necessary to assemble the specified number of batteries of the selected type, connect them in series and connect them with wires to the DC distribution system. The selected accumulators must be of a capacity up to ten times bigger the average current from the solar panels, or bigger. The accumulators must be constructively balanced at this stage.

4.2.1. Proposed Reproducible Solution for Visual Monitoring of Voltage on Accumulators

The work of such systems requires monitoring the voltage on individual elements within the accumulators to prevent them from overdischarging or overcharging. Adding a 24 V segment of ordinary white LED strip allows to visualize the voltage on each 12 V accumulator when it crosses 14 V, with a rapid increase the LED brightness when the voltage on the accumulator moves to 15 V.

Modification of such 24 V segments with six LEDs by shorting one of them allows additionally to visualize the operation voltage range of 12 V lead–acid accumulator with the lowest voltage of visible light of such modified segments with five remaining LEDs at 10 V. The consumption of such modified segments even in a fully charged state of the accumulator is no more than a few mA, which is negligible compared to its capacity. Such segments practically not discharge the accumulator.

The connection of two such segments in parallel (one normal and one modified) to each of the 12 V accumulators provides the possibility of a visual check of the approximate voltage on each accumulator to verify that there is no misbalance and that accumulators can continue operating in the proposed manner of connection and charging.

Different light intensities on the sequentially connected accumulators indicate the different voltages and capacities. In this case the maintenance of such accumulators or adding the balancing circuit is required. If the brightness of the modified segments (with five active LEDs) is significantly vary on different accumulators, it is better to perform manual rebalancing of accumulators by connecting an extra load to the overcharged and to allow the charging the rest.

4.2.2. Proposed Power Inverter with True Sine Wave for Selected Voltage Range

ated based on laptop accumulators of the same model from the secondary goods market (Figure 12).



Figure 12. Creation of 27s lithium-ion package to obtain the accumulator compatible with the proposed voltage range and to simplify verification of the work of the created 96 V inverter in a wider voltage range.

The rational combination for creation of a 27s package is the serial connection of nine groups of equal 3s (with three cascades) laptop accumulators with disconnected battery controllers and proper state of individual 18650 elements inside. Such lithium-ion package requires adding passive balancing circuits to each cascade for maintaining charging voltage no higher 4.2 V. This type of accumulator is critically sensitive to over-voltage.

To allow the connection of the fridge to the created autonomous power sources, the power inverter was created in the few modifications to study the parameters. It was found that it is necessary to add a metal wired connection at the weak place of such boards to reduce heating of the board that can cause the third transistor to fail (marked in Figure 13).

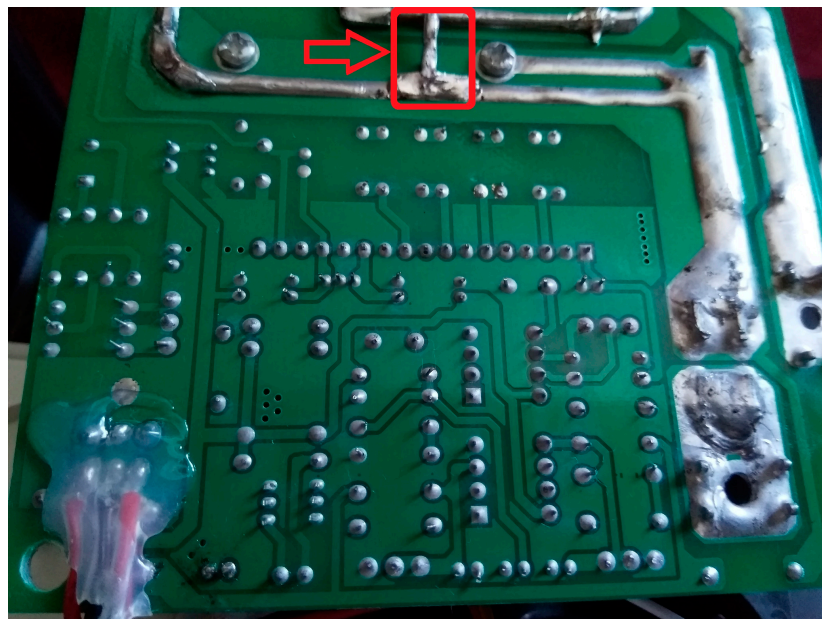


Figure 13. The proposed modification of the EGS002 based board includes not only assignment of the parameters to resistors to configure the voltage, but also adding extra improving wired con-

nection to reduce heating the board and transistors during increased load (a common issue of such boards).

Installing the inverter to the housing is not a requirement, but in case of the use of the proposed voltage range of 100 V, placing it in housing is the consideration of both the safety and the convenience of the use (Figure 14). Widespread empty housing was adopted to install the inverter board inside, placing an indication of it on the front.

The transformers RT-1000B1 were found on the secondary goods market (such transformers are periodically available and can be found for reproducing the proposed system). Initially, they correspond to the voltage range of 48 V of the inverter (this is the 13s lithium-ion package operating range from 39 V to 54 V).

To validate the proposed method, both variants of transformer modifications are implemented. The variant with two RT-1000B1 transformers connected based on the model provided in Figure 10b is most reproducible because it does not require reworking of winding, only the connection of existing wires connected to windings (Figure 15).

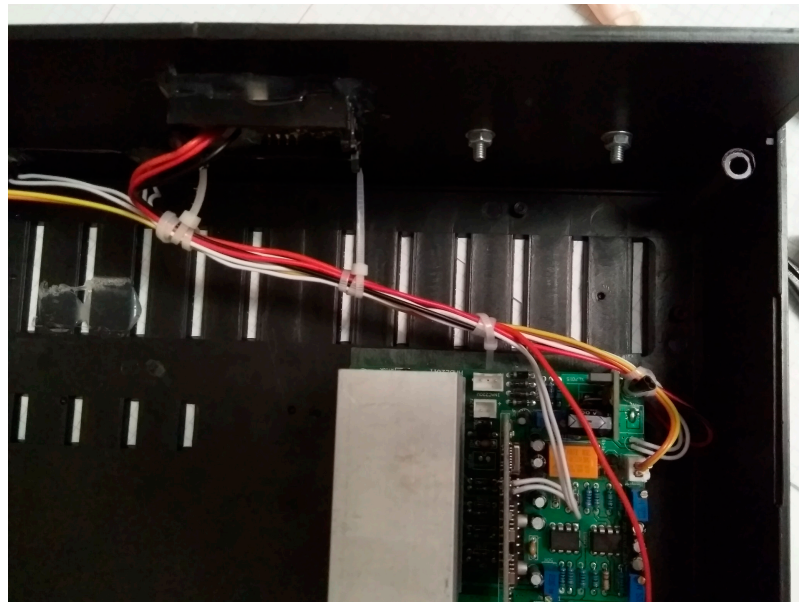


Figure 14. Installing the modified 48 V version of the EGS002-based board to create a 96 V inverter.

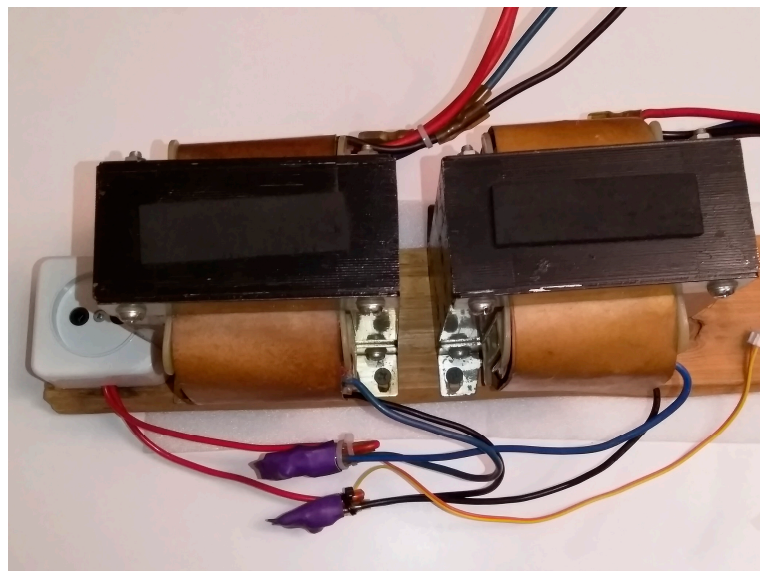


Figure 15. Combining of two RT-1000B1 transformers based on the proposed model with parallel connection of output windings and serial connection of input windings to increase voltage range (allows to obtain 96 V operation range of the inverter instead of 48 V).

The created power inverted based on EGS002 and widespread transformers model RT-1000B1 allows to validate the entire set of components of the autonomous power system.

The work of the inverter assumes standby mode with consumption of only 15 mA and normal operation (Figure 16) when the fridge is connected.



Figure 16. This is the normal operating of the inverter with the connected fridge.

6. Discussion

The practical results obtained during the study and experimental implementation allow to share the steps of building possible variants of autonomous power supply. This is really important, since there is demand and an understanding of how to do it at a significantly lower cost due to the use of materials from the secondary goods market.

The 100 V center of the proposed voltage range is selected to identify the difference from the widespread 96 V DC voltage range but highlight the compatibility of most of the electronic components from this range (entirely or at least within a greater part of the range). Most of the LED lamps that use built-in SMPs are working well, starting 90 V DC.

All the proposed and described solutions with solar panels can be created step by step and then extended into a larger solution. It is possible to gradually add components of autonomous power supply. Online shops and secondary goods market platforms offer components for proposed solutions, and the prices of solar panels are fundamental here for selection of an autonomous power source variant. The choice of a specific solution affects the rest of the system components, so the remaining described solutions depends on this decision.

It is better to use the centralized power supply where it is possible and economically reasonable. But where it is unavailable almost everything can be powered and connected autonomously from solar panels. Existing high-quality charging systems for use with the solar panels (no matter PWM or MPPT) currently are unacceptably expensive, but this is the variant of good ready-made solution for home. But the use of solar panels directly with direct connection allows to avoid use of converters or expensive charge controllers.

Most of the widespread solar panels are 36 cells, 60 cells (or 120-half cells), 72 cells (or 144-half cells), 80 cells and 96 cells (or 192-half cells). The minimal nominal operating voltage can be calculated by dividing the number of cells by 2 (multiplying cells by 0.5 V). But it depends on the temperature of the panel and intensity of the light. The open-circuit voltage can be up to 25–27% higher when it is cold and the sun is bright (up to 0.64 V per cell).

For the solar panels with 36 cells it is enough to double the number of sequentially connected panels to use the proposed concept and models for panels with 72 cells. Three such panels exactly match the required number of cells for direct charging of four lead–acid 12 V accumulators, which is half of the proposed concept and is available only for 36 cells.

For the solar panels with 60 cells, the nearest match is four solar panels and nine connected accumulators, which is equal to a range with 110 V at the center (working range is 96 V to 127 V). The next acceptable match for 60 cells is five panels and 11 accumulators, and the exact match is nine solar panels and 20 sequentially connected lead accumulators of 12 V (the center is 250 V, the working range is 210 V to 287 V, and the open circuit voltage is up to 345 V DC).

For solar panels with 80 cells there is no exact match at all (in the range less than 1000 V) and the possible combinations are based on the multiplication of an acceptable match of two solar panels with six accumulators (the working range is 63 V to 85 V for each such serial group). The use of four panels with 12 accumulators is the rational variant within the proposed method.

For the solar panels with 96 cells, the nearest match is two solar panels with seven connected accumulators (the working range is 75 V to 100 V with the center near 90 V). This range is partially acceptable, but the possibility of operating under 90 V depends on the specific SMPS.

In general, for operating with the direct connection, the perfect match for the solar panel is 27 cells per one 12 V widespread lead–acid accumulator. This is based on the assumption of a not too significant change in panel temperature (and voltage) during all seasons of the year, as well as the requirements to limit the average current from solar panels to no more than 0.1C of the nominal capacity of accumulator, measured in Amperes (taking into account the placement, because in case of static mounting of the panels, the nominal current is multiplied by the cosine of an angle to the sun at each moment of day). If another type of accumulators is used, a rational or even optimal number of cells should be calculated additionally.

If the use of solar panels is planned, it enables the combining them with one of the proposed variants for autonomous power supply, which can be done with any of them. If the decision to install solar panels is made, then only a large in size and weight panels should be selected. The cost of panels less than 1 square meter is usually several times higher in terms of power and cost. It is better even not to consider such options, as well as the flexible or film panels in current state of its quality.

By the price, the most rational variants are large panels with an area of more than 1.5 square meters (size is about 1 m × 1.5 m, or 1 m × 2 m), and with a weight near 20 to 25 kg. It is not very easy to install them, so it is necessary to know the location, and the proposed placement models can help in this. The weight of 25 kg at one point with a 1.5 m lever can turn into much larger efficient force (to carry the panel weight), so it is better to use the rope system and protection to simplify the installation process.

In summer, when the panels are heated, their efficiency decreases. It is possible to attach water tubes using sealant or glue on the bottom side of a panel. It can provide two results at time: cool the panels and heat the water. Both results are practically significant,

the heating of water and increasing the efficiency of panels due to cooling. In summer, it can increase the generated power up to 20–30%. This cooling method is reproducible.

The inverter and 36 V accumulator with an operating range of 30 V to 42 V can be connected to the solar panel with 72 cells directly or through a powerful Schottky diode (or at least through a powerful silicon diode) to avoid the battery discharging at night through the panel. The switch on the wire or a plug (that can be turned off at night) can be used instead of a diode. Typically, for panels with 72 (also 144) elements, the maximum power point is 37–38 V, which is quite suitable for charging directly the 10s lithium-ion pack or the battery from an electric scooter, bike or gyroboard, or even two 5s lithium-ion packages in series. The converter is not required for such connection, which is practically reproducible.

The sequential doubling of such installation with two solar panels and two 10s lithium-ion packages is an interesting and promising perspective, because modification of the inverter board for such installation mainly requires only replacing of capacitors, and the transformer can be leaved without modification as for the 48 V range (or to exclude small part of the high-voltage winding to reduce the transformation ratio by 10%).

The number of cells in a solar panel affects the possible voltage of an accumulator that can be connected directly without the use of a charge controller. For the panels with 72 (or 144) cells, the 10s lithium-ion packages fit. For 13s lithium-ion packages, the panels with 96 cells should be selected. For the inverter and transformer, in most cases only the lower voltage within the operating range is important for possibility to maintain 220 V AC output during a decrease of the input voltage because of battery discharge or an increase of the load.

A lot of low-cost inverters are available on markets in the form of a metal rectangle block with a cooler. These inverters it is better even not to consider for any application. For use with a fridge or a boiler there are no good inverters with a small transformer.

If an inverter is required, then it is better to implement it based on the massive transformer and the special control board, such as EGS002 with the EG8010 processor. Using such an inverter, it is possible to connect any AC appliance, even a fridge and a washing machine (without water heating). In this case, the inverter does not heat up and works even without an active cooling. The only sign of its operation is the quiet hum of the transformer at peak consumption while the washing machine engine is running.

RT-1200B is the preferable transformer model. This is a powerful transformer of 1500 VA with a weight of 7 kg if pure copper is used for windings, which is preferable to reduce transformer heating and increase the conversion efficiency (all versions of the RT-1000B1 transformer involved in the study were with non-copper windings).

If two transformers are installed together, it can ensure the working power of the inverter up to 2.5 kW (this is enough power for a home with autonomous power supply, and for long-term operation at this power, it is better to modify the inverter board by adding one more set of four transistors on the same radiator at top, as it is expected in the documentation to EGS002 module). Two fridges start well even with one transformer. A fridge with two compressors also starts well with one transformer. For a conventional fridge it is definitely enough to use one transformer.

7. Conclusions

The main contribution of this work is the proposed method of creation of scalable autonomous power supply systems for home that can be easily reproduced and applied.

The paper provides reproducible experience of exclusively own solutions (not ready or manufactured). The proposed set of steps involves the possibility of choosing possible implementation and making a decision, including the need for any of the autonomous power supply systems (whether they are necessary and why). This is the most important

question that needs an answer before making a decision. The described solutions are unique, and they are not available in the form of completed products and are significantly cheaper than ready-made or finished ones.

The proposed variants assume the possibility of performing constructing actions on their own by own efforts to build an autonomous power supply in order to reduce the cost of the solution in 5–7 times (up to 10–15 times during the period of demand) compared to the ready-made solutions with understanding and a guaranteed quality of the result.

If it is really possible to perform part of the installation and assembly work, then in order to reduce the initial efforts, it is possible to create the autonomous power system step by step based on the most ready-made components, but much cheaper than the assembled ready-made solutions. For certainty to arise, it is necessary to decide whether a homemade system is suitable. In many cases it is more practical and better than non-modifiable ready-made solutions.

If there is a readiness to build such systems, then the determining will be based on the presence of a solar panel and its voltage, determined by the number of cells in series in the panel. The possible battery pack and the voltage range depend on this decision to allow the proposed direct charging without a charge controller. It depends on the voltage and defines which parameters of transformer or inverter should be selected.

For an inverter, a voltage of 24 V is too small. The range of 42–48 V is preferable, but it is possible and even desirable to double the voltage to work in the proposed 96 V range. In this case the appliances with SMPs can work without an inverter at all by connecting directly to the same accumulator or the same power source as in the proposed method.

On the basis of the 48 V inverter board with EGS002 module and a transformer, a fully working inverter can be obtained from a minimum set of components that almost does not require adjustment and from which the fridge starts and works. Both the board and the transformer RT-1200B initially correspond to the 48 V range.

To allow the transformer to operate in the 36 V range, several already existing separate windings can be used in series to change the voltage. The ratio of the number of turns on the primary (low voltage) and the secondary (high voltage) windings of the transformer determines the minimum voltage at which the inverter can work.

There is no better inverter for home use than the one proposed in a comparable price category. It is a fully reproducible solution and a complete analogue of ready-made solutions with pure sine wave output that are 10–15 times more expensive.

To implement support of the 96 V range by the inverter, use two similar transformers with the connection of low-voltage windings in series and the connection of high-voltage windings in parallel. Such modification allows for obtaining an inverter with a pure sine for this voltage. The main advantage is that it can be connected to the solar panels directly without expensive charge controllers, on which part of the energy is lost.

The only drawback of this solution is the lack of housing. The housing can be made from any large food container, or even made from available isolator materials. But it can be left open for passive cooling, or it is possible to find the housing after assembly. It is important is to isolate the high-voltage parts and not touch the inverter during the operation (it can be spatially placed in an inaccessible place).

Thus, the proposed method of construction is focused on the principle possibility of the connection of currently available components to allow the connection and use of electronics without additional converters.

One of the advantages of the proposed method of direct current distribution is the possibility to exclude the energy consumption of the converters or continuously working

inverters. This method allows the use of appliances with SMPSs via convenient connection to the socket and the use of LED light bulbs controlled by an ordinary wall switch without all the time working additional converters that continuously discharging the accumulators, which is especially critical if the autonomous system includes only the set of accumulators or if main usage of the autonomous power supply is distanced in time from the charging.

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Abbreviations

The following abbreviations are used in this manuscript:

AC	Alternating Current
DC	Direct Current
LED	Light Emitting Diode
MPPT	Maximum Power Point Tracking
PWM	Pulse Width Modulation
SMPS	Switched-Mode Power Supply
SPWM	Sinusoidal Pulse Width Modulation

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