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Optimization of the balancer for $LiFePO_4$ battery charging

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Abstract. Balancers of various constructions are currently used for the operation control of the batteries connected in series. Unidirectional balancers ensure proper charging of all battery cells in a way that the first loaded cells should not be overcharged. Active balancers distribute the power, supplied to already-charged cells, to other cells; the power is further consumed by the passive balancers. Bidirectional balancers enable distributing the power between the cells during the discharge process, as well. This process thus protects the fastest discharging cells against the deep discharge. Passive balancers are most often used in batteries charged by the currents up to 20 A. If there are not big differences between individual cells in the battery, passive balancers reduce the efficiency of the charging process by only a few percent. They are the cheapest and most reliable. Optimally adjusted balancers with very low internal resistance deteriorate the efficiency only by about 1%. Commercially available balancers, working on the principle of a switch, periodically connecting the load resistor to the cell, deteriorate the efficiency to a greater extent, by about 5%. Optimized balancers, whose construction is described in the paper, work on a principle of a linear feedback controller. They can work with a maximum charging current up to 20 A, they have very low dynamic resistance of about 1 mΩ, and are absolutely stable. Their properties are further compared both with previously used circuits and commercial circuits.

Key words: balancer, $LiFePO_4$ accumulator, isolated solar power system.

INTRODUCTION

$LiFePO_4$ batteries in operation must be meticulously protected against overcharging. The manufacturers specify a maximum terminal voltage at the accumulator cells during charging. After achieving it, the charging must be ended. In charging a set of cells connected in series, the charging based on the total voltage in the entire battery will be markedly inaccurate. If the method were used, the cells with minimum capacity or maximum charge cycle efficiency could be overcharged. Reliable protection against overcharging can be guaranteed only by evaluating the voltage of each single cell and by terminating their charging after reaching the maximum terminal voltage. The battery can be controlled, only if the cells are absolutely identical. The voltage characteristic of two not entirely identical batteries of the same type in the cyclic charging and discharging is shown in Fig. 1.

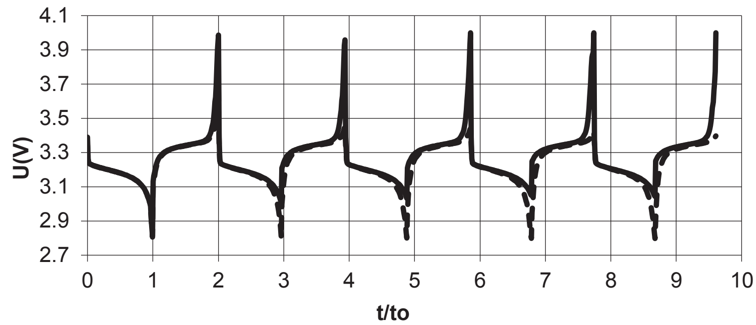

Figure 1. Voltage characteristics at two cells in the cyclical charging and discharging without balancers.

A voltage characteristic in Fig. 1 is based on the assumption that the cells are discharged and charged by a constant current, which corresponds to the charge and discharge of the first cell (a green curve) per time t_0. The charging efficiency of the second cell is by 3% lower than that at the first cell. The battery is controlled both by the total voltage (8 V for the charge and 5.6 V for the discharge) and by the minimum and maximum voltages of individual cells 4 V for the charge and 2.8 V for the discharge (Winston, 2017; Thunder Sky, 2017). In the first part of the characteristic, both cells are fully charged; discharging ends when the total battery voltage drops to 5.8 V. Subsequent charging is unbalanced. It ends after the first cell is charged, while the second cell does not reach full charging and is discharged to the lower voltage than the first cell. The total available capacity of the battery gradually decreases, and the difference between the voltage levels of the two cells gradually grows. Multi-cell battery cannot be effectively operated in this way (Papez & Papezova, 2015).

The solution lies in cell balancing. Each cell is connected in parallel to the electronic circuit. If a cell terminal voltage reaches the desired value during charging, the circuit consumes charging current supplied from the cell and stabilizes the terminal voltage at a desired value. Therefore, the battery charging is not necessary to terminate immediately, and other cells connected in series are still charged by a charge current to the maximum voltage.

Currently, passive and active balancers of various constructions are commonly used. Passive balancers simply consume the superfluous power, supplied to the already charged cell. Electric energy is converted to heat, which reduces the efficiency of the charging process (Albertronic, 2015). An active unidirectional balancer distributes the superfluous power to the terminals of other cells or to the entire battery. In this way the power is utilized for charging other cells. The balancer includes an isolated flyback converter that enables transferring the power between two ports of different voltages and voltage shift in between.

An active bidirectional balancer enables transferring power between the cells both in charging and discharging processes (Linear technology, 2017). In charging, it works as a unidirectional balancer. In discharging, it can transfer the power from the terminals of the whole battery or other cells to the terminals of the earliest discharged cells. Therefore, the discharging process may not be completed by discharging the cells with the lowest capacity. Thus the bidirectional balancer ensures that all cells are discharged evenly to the required minimum voltage. The balancer includes a bidirectional isolated flyback converter that allows transferring the power between two ports in both directions.

MATERIALS AND METHODS

The balancer function analysis is based on its expected use for the operation control of the battery with 10 $LiFePO_4$ cells with the capacity of 300 Ah in the isolated solar power system. The battery is composed of cells of a small difference. The battery is charged from the photovoltaic generator by a relatively small current which is less than one twentieth to one tenth of an ampere-hour cell capacity. Sometimes the battery has to supply a high short-term power during the discharge. The maximum discharge current can reach up to a third of an ampere-hour cell capacity. A full discharge (100% DOD) is not expected due to the requirement to achieve maximum battery lifetime.

The charging process should be optimized over a wide range of charging currents, because the output of the photovoltaic system is determined by the instantaneous intensity of solar radiation, which strongly varies during charging. The battery can be charged many tens of hours by small currents. Therefore, the balancer may consume only the current in the region of a maximum cell voltage. At a lower cell voltage or at times when it is not charged, the current consumed by the balancer from the battery must be minimal, at any circumstances, i.e., the long-running charging process must be minimally affected by the balancer.

As shown in Fig. 2, the charging process is completed by reaching the maximum defined value of the cell terminal voltage. To reach minimal dependence on the termination of charging on the instantaneous charging current, the real voltage value at the balancer terminals should be minimally affected by the passing current. Only this way, the charging can terminate under the condition that the cell terminal voltage is close to its defined maximum value, and the cells will be charged by the charge, close to their maximum capacity.

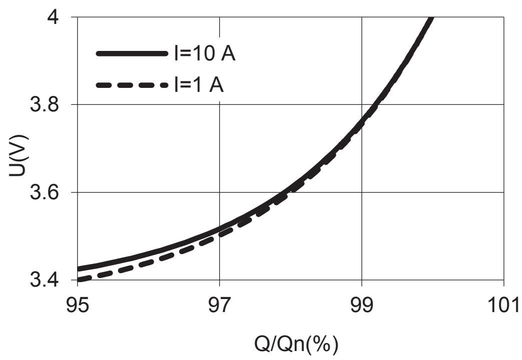

Figure 2. Cell terminal voltage at the end of the charging process.

Such a state is evident from the courses of the charging processes of the cells with the balancers having different internal resistances and being charged by different currents, as shown in Figs 3. The waveforms depicting a cell charging process are compared. The cell is charged by 2 A (Fig. 3, a, b) or 10 A (Fig. 3, c, d) currents and is connected to the balancer with the internal resistance of 10 mΩ (Fig. 3, a, c) or 40 mΩ (Fig. 3, b, d). Both balancers are adjusted to 4 V voltage, at the current of 10 A. The thin curve in Fig. 3 represents a cell charge waveform at the end of charging by a constant current without using the balancer (at a scale of a proportional charge). The thick curve shows the cell charge waveform with using the balancer. The dotted curve on the right axis depicts the charge consumed by the balancer during charging (at a scale of a proportional charge).

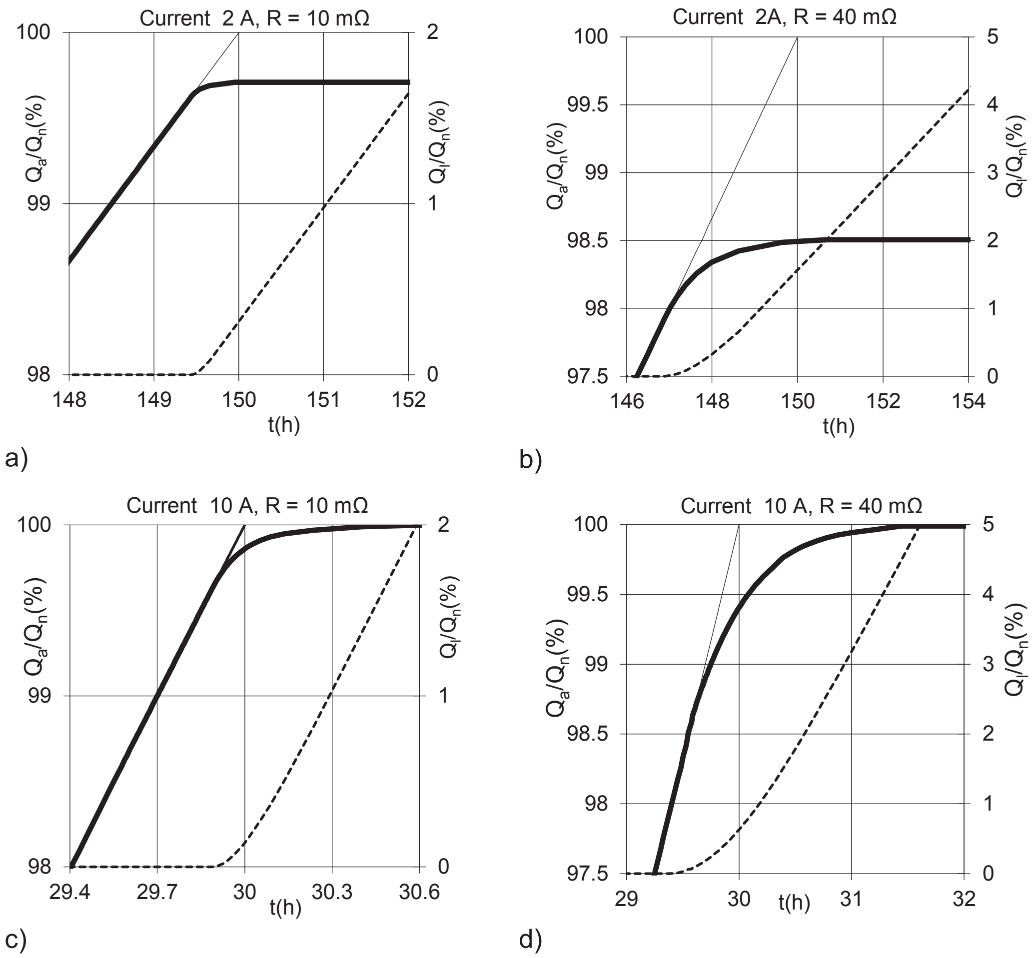

Figure 3. Charging process of the cell by 2 A or 10 A currents with balancers with internal resistance 10 mΩ or 40 mΩ; Q_a – instantaneous charge of the cell, Q_n – nominal charge of the cell, Q_l –charge consumed by the balancer.

To exploit effectively the supplied power, a minimal internal resistance of the balancer is important. At the end of the charging process, in a certain voltage range, whose width corresponds to the internal resistance of the balancer, the current consumed by the balancer increases up to the value of the charging current, and, at a constant voltage, the charging circuit is then balanced. Figs 3 show that the balancer with low internal resistance consumes the current for a shorter time and the stability is reached earlier. At the end of the charging process, it consumes less energy supplied to the battery in all cases. If there are not big differences between the individual cells in the battery, the balancers with very low internal resistance consume from the terminals cca 1% of energy that was supplied by the battery throughout the charging cycle.

At the end of the charging process of the battery with more cells, which are not completely identical, the energy, dissipated from the terminals of each cell, will be higher by the value corresponding to the difference between the charge of the longest charged cell and the charge of the reference cell. The size of this energy at all cells reaches cca 2.5% of the energy needed for charging the battery, provided the battery is in a standard condition, when the differences between charges, which charge single cells, do not exceed 3% of the total charge. In case of active balancers, this energy will be redistributed between cells, while in case of passive balancers it will be lost.

All cells will reach the same level of charging that corresponds to the terminal voltage at the balancers, if the mean value of the current passing through equals to the charge current. A balancer with less internal resistance allows achieving less dependence of the degree of charging on the charge current. The balancers can control the discharge process of the battery with difficulties due to the expected size of the discharge current. They should be designed for the current exceeding 100 A, which would be very costly. In doing so, they could extend the potential discharge time by about 2–3 minutes only.

In the first phase of designing autonomous photovoltaic power system, commercially available balancers were observed for their potential use. Primarily, the possible devices are passive balancers working on the switchable principle with fixed bypass resistors. They differ in their connection in series, adjusting or programming, and by the maximum operating currents ranging from 0.5 A to 20 A. Balancers with dissipated power higher than c. 5 watts use external load resistors that are placed on the coolers (HS series, 2017).

Two types of commercial balancers were tested: balancing module CBM1 (CBM1, 2017) for $LiFePO_4$ cell and current of 1.7 A and balancing module BS1V4 (BS1V4, 2017) for $LiFePO_4$ cell and current up to 13 A. Both balancers operate on the same principle of a switch that is controlled by the Schmitt trigger, as shown in Fig. 4.

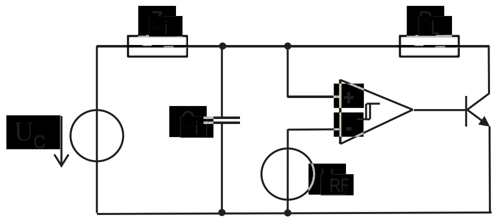

Figure 4. Block diagram of the balancer operating on the principle of trigger and switch.

The cell is replaced with power supply U_c, equivalent internal impedance Z_i and capacity C_i. The circuit works as a relaxation generator. When the voltage of the capacitor C_i increases above a reference voltage, a Schmitt trigger starts working and opens the output switch. Current passing through the load resistor R_L starts discharging the capacitor C_i. If this current causes sufficient voltage drop at the impedance Z_i, and Ci voltage drops below the reference voltage, reduced by the trigger hysteresis, the output switch is closed. This way, R_L current is extinguished, C_i starts recharging and after charging above the reference voltage, the process periodically continues. Balancer relaxation oscillations are mostly determined by the impedance in the cell circuit. The impedance may affect the voltage-current characteristic, which can be shifted even by several tenths of V.

The first mentioned balancer CBM1 is tested in a static mode, when it is connected to a voltage source with an internal resistance of the order of milliohms. The balancer switches up at a terminal voltage of 3.65 V and disconnects at the voltage of 3.55 V. When switched, the value of the current is 1.7 A. Due to a high Z_i impedance and the own Schmitt trigger time constant, the balancer will get into a regime of relaxation oscillations when it is connected to a voltage source with a high Z_i impedance of about 0.5 Ω.

Voltage and current characteristics for the balancer CBM1 are shown in Fig. 5. If the voltage is 3.8 V, the passing current reaches only c. 0.25 A. In contrast, the manufacturer declares thse current of 1.7 A at a voltage of 3.6 V. The waveforms for the second tested module BS1V4 with external load resistor 0.33 Ω, 50 W are shown in Figs 6 and 7. The source has an internal resistance of 30 mΩ, and capacity of 15 mF; open-circuit voltage is 3.6 V and 3.75 V. The mean value of the supplying current is controlled by the switching time of the power switch at an approximately constant period. The internal resistance of the balancer, set up according to the average values of its terminal voltages and currents, is relatively high, i.e. c. 36 mΩ. Following the above mentioned analysis, such a value would cause c. 5% charge loss during the charging of every single cell.

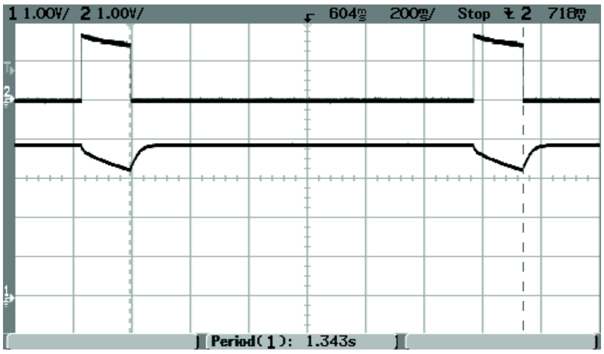

Figure 5. Current-voltage characteristics of the balancer CBM1 for the current 0.25 A.

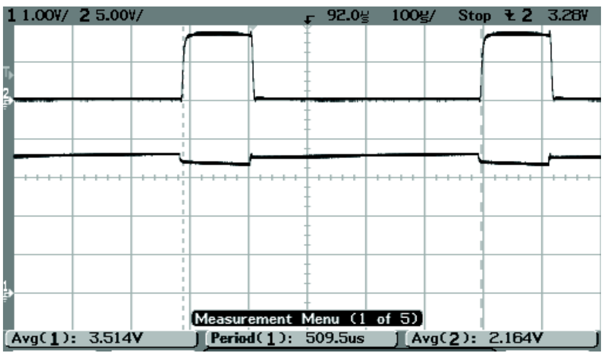

Figure 6. Current-voltage characteristics of the balancer BS1V4 for the current 2.16 A.

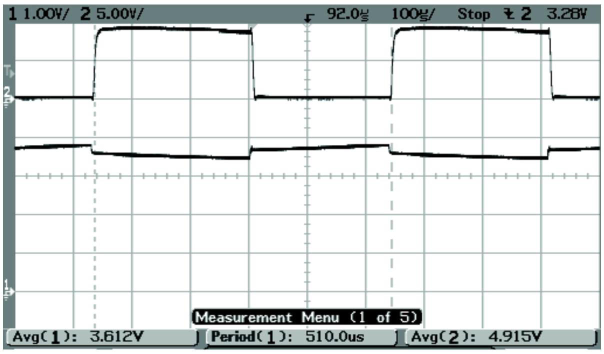

Figure 7. Current-voltage characteristics of the balancer BS1V4 for the current 4.9 A.

Using an active bidirectional balancer is, due to the large discharge current, unrealistic. In charging, the active balancer causes shortening the charging time of the battery by c. 2.5%.

As the price of an active balancer is 2–4 times higher than the price of a passive balancer and equals, in principle, the price of the entire photovoltaic generator, it is twenty times more efficient to slightly increase the power of the photovoltaic generator.

Design and construction of an optimal balancer

The design and construction of an optimal balancer is based on the following conditions. The balancer is passive and operates on the principle of the linear feedback controller. In the voltage range, corresponding to that at the end of the charging process, its current-voltage characteristic must show very low dynamic resistance in the order of mΩ units; for lower voltages, the passing current must reach only hundreds of μA. Further, it is also necessary to prevent the balancer from oscillating in any of the regimes. If the balancer starts to oscillate, its current-voltage characteristic will significantly divert from the desired static characteristics, and the balancer will lose its function. Specifically, the stability condition can be expressed, e.g., by the immittance criterion (Gajdosik, 2011). It states that if the balancer with the admittance $Y_b(\omega) = G_b(\omega) + j\,B_b(\omega)$ is connected in parallel with the cell with the admittance $Y_a(\omega) = G_a(\omega) + j\,B_a(\omega)$, it will start oscillating (in case that conditions (1) and (2) apply for some of the frequencies), see Fig. 8.

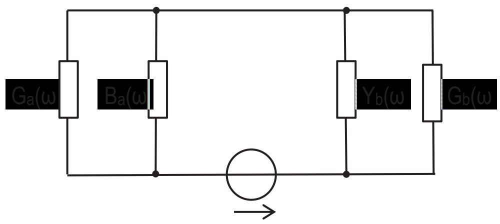

Figure 8. Immittance stability criterion in the battery – balancer circuit.

$$G_a(\omega) + G_b(\omega) < 0 \tag{1}$$

$$B_a(\omega) + B_b(\omega) = 0 \tag{2}$$

As $G_a(\omega) > 0$ applies to the cell absolutely, the balancer will be stable (without any further conditions), if is valid that $G_b(\omega) > 0$. The balancer must be designed also with respect to achieving the maximum operation reliability. The possibility of any defect of the components increases the probability of the failure of the entire device. The refore the balancer should be constructed with a minimum number of components. Then the components will work at significantly lower operating temperatures than their maximum operating temperature.

The first balancer constructed according to the above mentioned conditions was used in $LiFePO_4$ battery systems, which were designed in 2015 (Papez & Papezova, 2015; 2016a; 2016b). The basic configuration of the balancer consisted of a reference voltage stabilizer, differential amplifier with a double transistor, Darlington power transistor and five resistors. The balancer could operate with currents up to 10 A. For higher currents, the circuits were arranged in parallel. A current-voltage characteristic of a pair of circuits is shown in Fig. 9 (a thin curve). The balancer works quite well in the current range greater than c. 2 A, where its dynamic resistance is less than 10 mΩ and may be loaded by the current up to 20 A. In the range of smaller currents, a fuzzy knee of a current-voltage characteristic is basically very disadvantageous, because it may cause undesired current leakage from a charged cell.

The other construction of the balancer uses a rail-to-rail operational amplifier to increase the gain in a feedback loop. Simple differential amplifier is replaced with the operational amplifier and power Darlington transistor is controlled from its output (see Fig. 9).

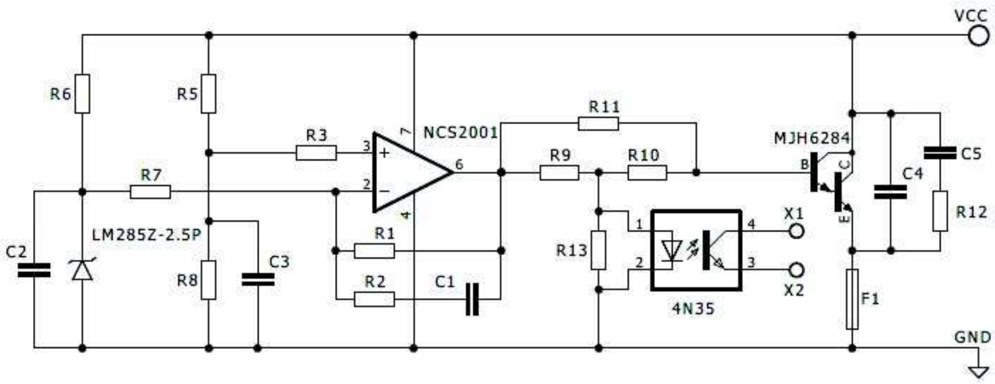

Figure 9. Circuit diagram of the new balancer.

The balancer in this modification has a very low dynamic resistance (c. 1 mΩ), as shown in Fig. 10 (a thick curve). The stability of its feedback loop was solved by using typical frequency compensation in a negative feedback loop, i.e., by an operational amplifier. The achieved characteristic of complex admittance, which satisfies the condition of absolute stability, is shown in Fig. 11. The balancer can be loaded by the current of up to 20 A.

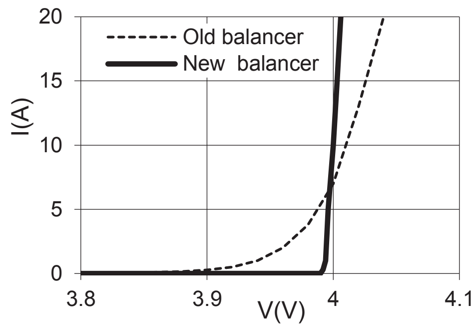

Figure 10. Current-voltage characteristics of the balancers.

The problem of cooling the power transistor, which is loaded with the power dissipation of 80 W, must also be strongly solved. The example of the prototype of the balancer with a cooler is shown in Fig. 12.

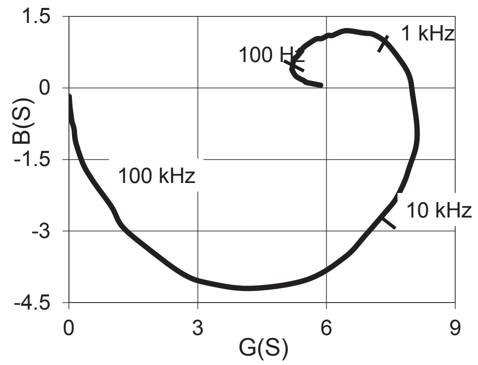

Figure 11. Complex admittance characteristic of the balancer.

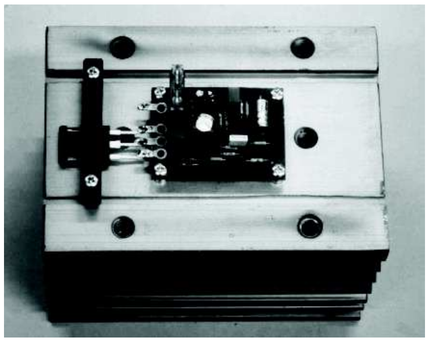

Figure 12. Prototype of the balancer with a cooler.

For using the balancer in the automated measuring station for testing accumulator (Papez & Papezova, 2016b) there was implemented a simpler construction, controlled by a circuit of three-terminal adjustable shunt regulator, whose output amplifier is extended by another external amplifier which allows loading the balancer with the current of 10–16 A (see Fig. 13). The external amplifier stage further reduces the dynamic resistance of the shunt regulator by 2–3 orders, in proportion to its current gain, thus achieving a very small value, i.e., c. 1 mΩ. A simple connection of an external amplifier, however, causes also the input admittance with a negative real part in a frequency range of tens to hundreds kHz, as illustrated in Fig. 14 (a dashed line). In the situation, when the internal frequency compensation at the amplifier shunt regulator cannot be changed, two external damping Boucherot RC circuits are applied to reach system stability. The characteristic of the balancer complex admittance with the frequency compensation is shown in Fig. 14 (a solid line).

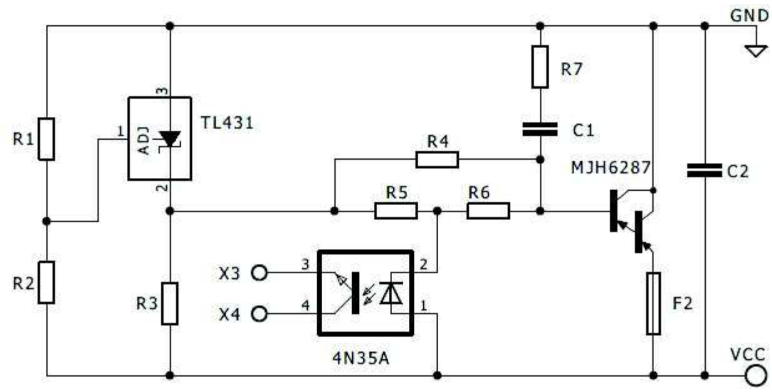

Figure 13. Circuit diagram of the simple balancer.

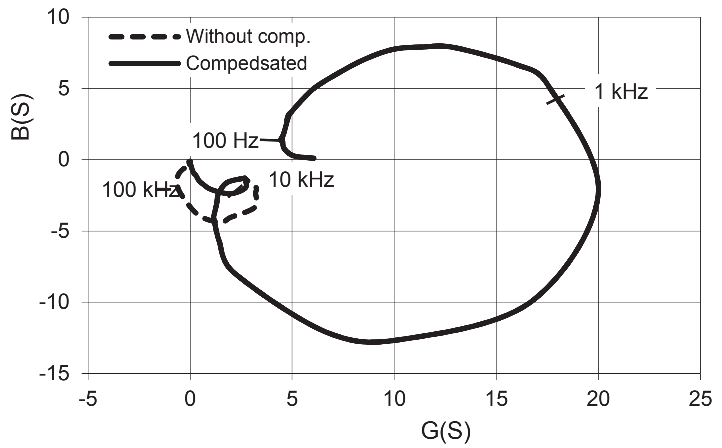

Figure 14. Complex admittance characteristic without frequency compensation (dashed line) and with frequency compensation (solid line).

RESULTS AND DISCUSSION

The analysis of the functions of balancers designed for the controlled charging of $LiFePO_4$ batteries has been carried out. The worst operating parameters are exhibited by the balancers working on the principle of a switch that periodically connects load resistor across the cell terminals. The relaxation oscillations are completely determined by the impedance in the cell circuit, which can shift the current-voltage characteristic even by 0.5 V.

Better parameters show the balancers working on the principle of a dipole with a nonlinear static current–voltage characteristic. Simple circuits, however, show a large internal resistance. Moreover, the circuits operating on the principle of feedback control regulator are often potentially unstable.

Both the implementation and construction of the two types of balancers optimized for the maximum charge currents of 16 A and 20 A, operating on the principle of feedback controller are described. Their properties are further compared with the previously used circuits and commercial circuits. The designed circuits contain 20 components at maximum, their internal resistance is approx. 1 mΩ and they are absolutely stable.

CONCLUSIONS

At the passive balancers, a minimum internal resistance is necessary for the efficient power utilization during charging. The balancer with a lower internal resistance consumes the current for a shorter period of time and the stability is reached earlier. In all cases of the charging process, it consumes less power at its end than the balancer with a higher internal resistance. If there are not big differences between the single cells in the battery, the balancers with a very low internal resistance consume from terminals c. 1% of the energy supplied to the battery throughout the whole charging cycle. At a lower cell voltage, off the battery charging, the current consumed from the battery must be at such a level not to cause an apparent increase in self-discharge.

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