Monitoring and charging level alignment system for a vehicle hybrid power unit battery pack

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Abstract. The article is devoted to the actual problem of developing effective means of control and charging level alignment of the vehicle hybrid power unit (HPU) accumulators. A description of the automatic control and charging level alignment system of the battery pack for hybrid power unit developed by the authors, while simultaneously controlling the temperature of each battery, the originality of which is protected by patents of the Russian Federation, is provided. The device is distinguished by the simplicity of the circuit design, its own low energy consumption and potentially low cost. To check the efficiency of the proposed device the computer simulation and experimental study were carried out. As a result of the provided multifactorial experiment, a regression function was obtained, which allows, by the value of the obtained coefficients, to reveal the degree of inhomogeneity of the monitored batteries in terms of electrical parameters and the temperature of influence, as well as to take into account the effects of pair and quadratic interactions.

1. Introduction

When developing electrical circuits for electric vehicles the most problems are connected with providing sufficiently simple, reliable, and inexpensive monitoring and battery pack charging level alignment devices for the vehicle HPU.

Despite of the large number of proposals on various methods and devices for solving this problem, known devices are often distinguished by unjustified redundancy of the used electronic equipment and, hence, increased cost and probability of the reliability drop, therefore, the task of developing simple, reliable and inexpensive devices for monitoring and equalizing the state of charge of a car battery pack remains relevant today.

2. Purpose and Methods

The goal of this work is:

- to design a system for monitoring and charging level alignment of the HPU electric batteries according to the parameters: voltage U, internal resistance R, current I and temperature T, distinguished by the relative simplicity of the circuit design and versatility of use;

- experimental study to evaluate the influence coefficients of the equivalent battery replacement scheme parameters to the output voltage in computer modeling of the system designed.

The method of sequential polling of accumulators of the battery unit by electrical parameters and simultaneously by the temperature of each of them, processing the received information in the controller...
and generating equalization control pulses with a duration proportional to the mismatch and temperature was used. At the same time, a good galvanic voltage isolation between the high-voltage accumulator unit and the low-voltage electronic measuring and control circuit is ensured due to transformer isolation.

To implement the assigned task, an original automatic control system was developed [1,2], the block diagram of which is shown in Figure 1.

The system operates as follows. The signals from the microcontroller are applied to the address switching input of the DMC dual demultiplexer with n outputs. In each demultiplexer, n batteries of the HPU battery are connected in series through n + 1 single-position switches with low internal resistance to the common wires A and B. The positive terminals of the odd batteries are connected to wire A, and the positive terminals of even batteries are connected to wire B. There is an alternation of positive and negative voltage values on the wires A and B, which are transmitted to the information-processing unit.

If the battery's accumulators have the equal charge state, then the voltage at the output of the switching unit (SU) will be near zero. If at least one of the accumulators in the battery is overcharged or undercharged, then respectively, a positive or negative mismatch pulse will appear in the output with an amplitude proportional to the value of the imbalance. This imbalance signal is transmitted to the automatic control system (ACS) and then to the microcontroller (MC). The microcontroller converts the amplitude of the imbalance pulses into a control time-pulse signal and applies it to the final alignment system unit (FAS).

In the FAS block, an original device was proposed for continuous automatic charge alignment of problem batteries both when overcharged or undercharged when pulses are supplied from the microcontroller MC with a duration proportional to the imbalance voltage amplitude.

Figure 1. Block diagram of the control and balancing system.

The temperature of each battery is measured by the measuring thermistors (MT) synchronously and simultaneously with the sequential switching battery unit accumulators of the, moreover measuring
thermistors with an odd index number \( R_{t1}, R_{t3}, \ldots \) are being connected to the commutation bus (C), and each of the measuring thermistors with an even index number \( R_{t2}, R_{t4}, \ldots \) are being connected to the commutation bus (D).

During serial thermistors polling the differential voltage occurs between switching buses C and D, which is the voltage step deviations proportional to the \( A_i \) accumulators temperature of the battery unit with respect to temperature of \( A_n \) accumulator. \( A_n \) battery temperature is being measured with high precision by a separate temperature sensor. Voltage pulses are formed in the TSU unit as well, which are proportional to the battery temperature deviation comparing with an average temperature for all accumulators in the battery unit.

All of the information above is transmitted to the controller through three channels.

Step voltage deviations signals are added at the controller (MC), which signals are in proportion of the accumulators \( A_i \) temperature and accurate temperature meter of \( A_n \) accumulator.

As a result, the full absolute temperature of each accumulator of the battery unit restores with a reduced relative error compared to the option of measuring this temperature using only measuring thermistors of the accumulator battery unit. This information is showed on the display as a bar graph showing the temperature deviation of each accumulator of the accumulator battery unit from the temperature of \( A_n \) accumulator.

When the maximum permissible deviation of the temperature of the battery with a problem is exceeded, the controller MC displays the number of the problem battery on the digital indicator HG2. The temperature of each accumulator in the battery unit is programmatically taken into account when forming the time-pulse alignment signal applied to the FAS unit from the microcontroller MC.

3. Theoretical and experimental research and results evaluation

To determine the operability of the designed electrical circuit when measuring accumulator parameters deviations from nominal values in the Multisim environment [3], a model of the system block was built, including eight controlled accumulators, each of which was represented by the equivalent circuit [4–7]. The input signal was simulated using a virtual pulse generator, and the analysis of the output data was carried out with a virtual oscilloscope. Figure 2 shows the output voltage time oscillogram of the signal processing unit at a 1 kHz polling rate of accumulator.

The first graph shows the connecting order of the accumulators in the unit during their serial polling, where from you can tell which battery is having problems. The second graph shows the voltages dispersion, which is proportional to the temperature of each battery relative to the average value in the accumulator battery unit. The third graph shows the step voltage deviations, which are proportional to battery \( A_i \) temperature of the accumulator battery unit in relation to the \( A_n \) battery temperature, from which it can be seen that the highest temperature was found on the sixth and seventh batteries.
The fourth graph shows how the output voltage of the sixth battery and the internal resistance of the seventh problem battery with problem changes when the corresponding parameters change by 5% of the nominal value. As can be seen from the oscillogram presented the useful signal in all graphs stands out significantly at the noise level.

When determining the influence of three electrical parameters of batteries (U, R, I) on the output voltage for a multivariate experimental study, a B-plan was chosen [9,10], which makes it possible to reveal the second order dependences. Earlier in the studies [1,8] such a study have been carried out and regression function of the second order was obtained in the form of

\[
\hat{y} = -0.033096x_1 - 0.145469x_1x_2 + 3.9089x_2^2 + 0.15675x_3^2 ,
\]

where:
- \(\hat{y}\) – The output voltage predicted by the regression equation,
- \(x_1\) – Voltage U,
- \(x_2\) – Resistance R.

As can be seen from the obtained regression function, not only the impact of single factors (U, R) turned out to be significant, but also their paired effect.

As it is shown in study [8] the output parameter relative error value of the control system in the formula (1) is almost equal to permissible dispersion of the internal parameters of the battery (U, R). Thus, knowing accumulator electrical parameters percentage dispersion, it is possible at the stage of assembly to predict in which limits the output value \(Y\) will be in the manufactured device when using
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the proposed control device. In the present study, an experimental influence assessment of the temperature values of the previous ($X_1$) and subsequent ($X_3$) accumulators on the measured temperature of the middle accumulator ($X_2$) for the three series-connected accumulators ($X_1, X_2, X_3$) was conducted.

To determine the influence coefficients of the three batteries parameters ($X_1, X_2, X_3$), the B-plan [1,5,6] was chosen as a method of multivariate research, which makes it possible to identify second-order dependences. The results of the experiment are summarized in table 1. In the experiments, the output value $Y$ is the signal processing unit voltage, measured in volts. To increase the measurement accuracy, the experiments were carried out with four duplication at each point of the experiment, thus the arithmetic mean values of the output value are shown in the right column of the table.

After checking the approximation according to Fisher's criterion, removing insignificant coefficients according to the Student's criterion and bringing it to the natural values of the influencing factors, the regression function takes the following form:

$$\hat{y} = -0.00382012 x_2,$$  \hspace{1cm} (2)

where:

$\hat{y}$ – the output voltage which is proportional to the average battery temperature,

$x_2$ – the resistance of the middle temperature sensor in kΩ.

As can be seen from the dependence obtained, the temperature indications of the previous and subsequent battery practically do not affect the temperature of the middle battery.

| Experiment # | Normalized factor value | Natural factor value | Output value | Mean output value |
|--------------|-------------------------|---------------------|--------------|------------------|
|              | $x_1$ | $x_2$ | $x_3$ | $X_1$ | $X_2$ | $X_3$ | $y_1$ | $y_2$ | $y_3$ | $y_4$ | $\hat{y}$ |
| 1            | -1    | -1    | -1    | 160   | 160   | 180   | 0.113534 | 0.113578 | 0.113545 | 0.113549 | 0.1135515 |
| 2            | 1     | -1    | -1    | 240   | 160   | 180   | 0.110304 | 0.110308 | 0.109959 | 0.110316 | 0.11022175 |
| 3            | -1    | 1     | -1    | 160   | 200   | 180   | -0.051895 | -0.052048 | -0.051944 | -0.051955 | -0.0519605 |
| 4            | 1     | 1     | -1    | 240   | 200   | 180   | -0.044673 | -0.044805 | -0.044726 | -0.044805 | -0.04475225 |
| 5            | -1    | -1    | 1     | 160   | 160   | 220   | 0.205126 | 0.205125 | 0.205016 | 0.205084 | 0.20508775 |
| 6            | 1     | -1    | 1     | 240   | 160   | 220   | 0.205867 | 0.205852 | 0.205831 | 0.20585 | 0.20585 |
| 7            | -1    | 1     | 1     | 160   | 200   | 220   | 0.039592 | 0.039428 | 0.039571 | 0.039498 | 0.03952225 |
| 8            | 1     | 1     | 1     | 240   | 200   | 220   | 0.051281 | 0.051197 | 0.051259 | 0.051235 | 0.051243 |
| 9            | -1    | 0     | 0     | 160   | 180   | 200   | 0.072734 | 0.072905 | 0.072732 | 0.0728 | 0.07279275 |
| 10           | 1     | 0     | 0     | 240   | 180   | 200   | 0.085506 | 0.085458 | 0.085196 | 0.085391 | 0.08538775 |
| 11           | 0     | -1    | 0     | 200   | 160   | 200   | 0.149609 | 0.149607 | 0.149608 | 0.149616 | 0.14961 |
| 12           | 0     | 1     | 0     | 200   | 200   | 200   | 0.0007407 | 0.0007406 | 0.0007143 | 0.0007407 | 0.00073411 |
| 13           | 0     | 0     | -1    | 200   | 180   | 180   | 0.023593 | 0.023631 | 0.023593 | 0.023614 | 0.02360775 |
| 14           | 0     | 0     | 1     | 200   | 180   | 220   | 0.116014 | 0.116015 | 0.116031 | 0.116037 | 0.11602425 |

4. Conclusion
The designed device allows:

− continuously monitor the state of the accumulator charge level of the battery unit on the main
electrical parameters indicating the sequence number and the nature of the battery fault (undercharging or overcharging);

- provide the ability to work in the modes of energy output and power consumption;
- ensure the relative simplicity of the circuit design with a slight complication of the equipment with an increase in the number of controlled batteries in the unit;
- provide selective recharging and equalization of problem batteries with high current for a certain period of time;
- determine the battery with a problem in temperature from the beginning of the process of its overheating by the value of the relative change in its temperature;
- determine a battery with a problem in temperature in the mode of a temperature field established in time for all batteries of the AB unit according to the criterion of the permissible heating temperature of the battery;
- determine the absolute temperature of the problem battery with a relative error less than the relative error of the thermistors used to control the temperature of the batteries of the AB unit;
- determine the absolute temperature of the problem accumulator with a relative error less than the relative error of the thermistors used to monitor the temperature of the accumulator battery unit;
- simultaneously determine both the electrical parameters (current, voltage) and the temperature of problem accumulators, which is an additional diagnostic criterion when monitoring the accumulators of the battery unit;
- if it is necessary to increase the number of accumulators in the battery, for example, up to a hundred or more, the complexity of the electrical circuit takes place only due to a proportional increase in the number of keys, thermistors and the number of outputs, dual demultiplexers, which slightly rises the cost of the device.

It was also shown that the output voltage of the monitoring system is proportional to the real accumulator parameters dispersion of the battery unit and makes it possible to continuously evaluate their values during the operation of the accumulator battery.

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