Dependence of the increase in the power reserve of an electric vehicle on the season when using a non-flat battery of photovoltaic converters

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Abstract. Due to the fight against CO₂ emissions and other harmful substances, the world's leading vendors of motor vehicles (MV) come back to development of electric vehicles (EV) as the most environmentally friendly transport. But EV has inadequate power reserve from one accumulators charge. One of the ways to increase it is to use additional environmentally friendly electrical energy sources, e.g., photovoltaic converter (PVC) batteries due to the increase in their efficiency. In order to improve aerodynamic, design and consumer properties, the world’s leading EV manufacturers pass from flat PVC battery to non-flat. Non-flat PVC batteries compared with flat have insufficient energy efficiency, which can be increased in several ways, including PVC battery segmentation. In scientific publications, there are no methods for calculating non-flat PVC batteries, which indicates the actuality of the research being conducted. Mathematical modeling of the EV power reserve depending on the season allows us to justify the actuality of segmenting the non-flat PVC batteries installed on the EV. Materials for the mathematical modeling of nonlinear interaction are obtained experimentally, the method of conducting experimental research is scientifically justified. As a result of the mathematical modeling, the dependences of EV power reserve on the season at different standard test cycles were obtained. The obtained dependences of the EV power reserve on the season allow us to assume the feasibility of segmenting the PVC batteries installed on the EV to increase the energy output and EV power reserve from one accumulators charge.

1. Introduction

Emissions of CO₂ and other harmful substances have become one of the serious environmental problems [1], [2]. One of the ways to combat these emissions in large cities is using electric traction drive in motor vehicles. Due to the development of power frequency converter and lithium accumulators all over the world, there is a trend to develop EV [3], [4].

But small emissions of the EV can ensure only their charging from environmentally friendly power plants: hydroelectric power plants, wind power plants, solar power plants and others. At the same time, EVs, while having significant environmental advantages, have a small power reserve [5], [6]. The short power reserve of the EV can be overcome with the help of additional environmentally friendly power sources placed on board the MV.

The use of the environmentally friendly power sources on the EV, for example PVC batteries, has power reserve increasing prospect. Due to the increase in their efficiency, the leading manufacturers of
vehicles, such as Volkswagen, Toyota, Sanyo, Ford, Tesla, Aston Martin etc., began producing EVs using PVC batteries [7].

In recent years, there has been a tendency to use non-flat PVC batteries in EVs, which can be explained by their improved aerodynamic and design-consumer characteristics.

Non-flat PVC batteries have insufficient energy output. The energy yield can be increased either by increasing the area of the PVC batteries or by increasing their energy efficiency. The energy efficiency of the non-flat PVC batteries can be increased in several ways: PVC cells efficiency increasing, by-pass circuit’s optimization, holding power converters at maximum efficiency, PVC battery segmenting.

Electrically, the PVC cells are connected in series to form a battery. The difference in the illumination density with the sequential connection of the PVC cells to the battery leads to a decrease in the current strength to the level of the dimmest PVC cell. When using various bypass circuits, less illuminated PVC cells are disconnected from the rest of the battery circuit by analog switches, which causes a decrease in the voltage generated by the PVC battery. Thus, the interaction of nonlinear volt-ampere curves (VAC) of the differently illuminated PVC cells leads to a decrease in the energy efficiency of the entire PVC battery as a whole.

But due to the division into segments, consisting of equally illuminated PVC cells, each of the segments of the PV battery generates electricity at the maximum power point (MPP) and, therefore, with maximum efficiency. In this case, the interaction of the PVC VAC as part of a battery of arbitrary geometry, complicated by the movement of the Sun during the day, can only be calculated by means of the mathematical modeling.

At the same time, there is a problem of the lack of a method for calculating non-flat PVC batteries in scientific publications. For example, when describing a design with a cylindrical PVC battery, its calculation is carried out according to the formula for a flat PVC battery, the interaction of the VAC of the differently illuminated PVCs when they are electrically connected to a battery is not taken into account [8]. In the same way, other authors ignore this question [9]-[11].

Thus, the relevance of developing a methodology for the mathematical modeling to increase the power reserve of the EM by using additional environmentally friendly power sources on the basis of the non-flat PVC batteries is currently continuously increasing.

This scientific work is devoted to the mathematical modeling of rectilinear motion according to standard test cycles when using a non-flat PVC battery in order to increase the power reserve depending on the season.

The result of the work is the development and scientific substantiation of the dependence of the increase in the power reserve on the season ”El Lada” based on Lada Kalina using a battery geometry close to the constructive with a fixed azimuth of movement.

2. Model description

Formulation of the problem
This research paper is devoted to the mathematical modeling of the rectilinear motion of EV through the standard New European Driving Circle (NEDC) and Worldwide harmonized Light vehicles Test Circle (WLTC) when using a non-flat PVC battery to increase the range of EV depending on the season.

Research progress
Only the straight-line motion of a 4-wheel single-mass the mathematical model of the vehicle is considered. The mathematical models of cooling, pneumatics and brakes systems are not considered. The following mathematical models were considered: electric vehicle motion model, wheel model, transmission model, electric machine model, traction inverter model, on-board consumers model, DC/DC converter model, low-voltage buffer battery model, high-voltage traction battery model, MPP converter model, algorithm MPP model, model of PVC cell and PVC battery, solar illumination model [12], [13]. Relationship between the density of solar illumination from the Byrd model and the PVC VAC [14], [15].
The relationship between the solar illumination model and the geometric position of each PVC cell is carried out through the cosine of the angle at an arbitrary orientation of the cells [15].

The PVC battery model is calculated as the sum of the VAC of the voltage of differently illuminated PVCs. The PVCs are summed by voltages in series according to Kirchhoff's laws.

The power plant model is calculated because of the interaction of several energy sources, energy converters and consumers, each with their own electrical parameters.

The work uses the methods of the theory of movement of ground MV, system design, theory of electrical circuits, mathematical modeling, etc.

To unify the results of measurements of vehicle power reserve, standard test cycles NEDC and WLTC were used.

*Experimental data acquisition of the VAC of a diode and a PVC*

Since the dependence of the short-circuit current of the PVC cell on the illumination density incident on it is close to linear, and the VAC shifts along the current in proportion to the short-circuit current, it is possible to take the VAC of the unlit cell experimentally and shift the characteristic along the current axis during the mathematical modeling, as shown in Fig. 1 and 2 [14], [15].

**Figure 1.** The bias of the PVC VAC by current is proportional to the short-circuit current [14], where:

1 – VAC of an unlit PVC,
2 – VAC of the maximum illuminated PVC,
$I_{sc}$ – short circuit current.
The PVC VAC can be set in a table as a function of voltage versus current $u = f(i)$, current versus voltage $i = f(u)$, and as a set of independent points with coordinates corresponding to voltage and current at each point $(u, i)$. Further, the displaced PVC VACs can be added in voltage according to the Kirchhoff law, similar to the addition of two identical VACs in voltage [12]. This requires the dependence $u = f(i)$.

Since the maximum short-circuit current of the selected PVC cell is 6.2 A, it makes sense to take the PVC VAC only in the range from 0.0 A to 6.2 A. The results of experimental measurements should give the number of the VAC points sufficient for the mathematical modeling and determining the power produced by the PVC battery. At a step of 0.1 A, the number of points is $(6.2 - 0.0) / 0.1 + 1 = 63$. With a step of 0.2 A, the number of points becomes $(6.2 - 0.0) / 0.2 + 1 = 32$, which is quite enough.

**Experimental measurement of PVC VAC**

The scheme of the experiment with a list of accessories and measuring instruments is shown in Figure 3.

![Figure 3](image-url)

**Figure 3.** Schematic diagram of an experiment to obtain the PVC VAC SunPower Maxeon Cell C60, where: 1 – lightproof screen, G1 – adjustable current generator HY5030E, PA1 – multimeter Fluke 287; PV1 – multimeter Fluke 287; VD1 – PVC SunPower Maxeon Cell C60.

**Data obtained during the experiment**

The data obtained are summarized in Table 1.
Table 1. VAC PVC SunPower Maxeon Cell C60. (A)

|   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|
| I, A | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 |
| U, mV | 0  | 567 | 597 | 616 | 632 | 646 | 659 | 669 | 681 | 690 | 700 | 709 | 719 | 729 | 738 | 746 |

(B)

|   | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| I, A | 3.2 | 3.4 | 3.6 | 3.8 | 4.0 | 4.2 | 4.4 | 4.6 | 4.8 | 5.0 | 5.2 | 5.4 | 5.6 | 5.8 | 6.0 | 6.2 |
| U, mV | 755 | 763 | 769 | 779 | 787 | 793 | 803 | 810 | 818 | 826 | 834 | 841 | 848 | 855 | 863 | 871 |

Experimental measurement of bypass diode VAC

The scheme of the experiment with a list of accessories and measuring instruments is shown in Figure 4.

Figure 4. Schematic diagram of an experiment to obtain the bypass diode VAC 80SQ045NRLG, where: G1 – adjustable current generator HY5030E, PA1 – multimeter Fluke 287, PV1 – multimeter Fluke 287, VD1 – diode 80SQ045NRLG.

Data obtained during the experiment

The data obtained are summarized in Table 2.

Table 2. VAC of diode 80SQ045NRLG.

(A)

|   | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|
| I, A | 0.0 | 0.2 | 0.4 | 0.6 | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 1.8 | 2.0 | 2.2 | 2.4 | 2.6 | 2.8 | 3.0 |
| U, mV | 0  | 304 | 324 | 336 | 345 | 352 | 358 | 364 | 369 | 373 | 377 | 380 | 383 | 385 | 387 | 389 |

(B)

|   | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 |
|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| I, A | 3.2 | 3.4 | 3.6 | 3.8 | 4.0 | 4.2 | 4.4 | 4.6 | 4.8 | 5.0 | 5.2 | 5.4 | 5.6 | 5.8 | 6.0 | 6.2 |
| U, mV | 392 | 395 | 399 | 403 | 407 | 412 | 420 | 429 | 436 | 449 | 459 | 479 | 501 | 528 | 553 | 561 |

Computational experiment

The models were implemented in Visual Basic for Applications in Microsoft Excel [12].

The initial data on the NEDC/WLTC cycles were taken from the UNECE Regulations No. 101/115, the semiconductors VAC, refractive indexes and transmittance of the protective glass of the PVC battery were taken experimentally.

The calculations are made for the 1st day of each month with test start time of 9:00.
3. Results
Development and scientific substantiation of the dependence of the increase in the power reserve on the season of the EV “El Lada” based on Lada Kalina when using the geometry of the PVC battery close to the constructive with a fixed azimuth of the MV movement.

**NEDC testing**
The data obtained are shown in Table 3 and illustrated in Figure 5.

| PVC type   | January | February | March | April | May | June | July | August | September | October | November | December |
|------------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| None       | 154.98  | 155.13   | 155.15| 155.02| 155.19| 155.17| 155.17| 155.19  | 155.15    | 155.13  | 155.15   |
| Flat       | 155.78  | 157.30   | 158.63| 159.65| 160.83| 161.14| 161.17| 160.95  | 160.16    | 158.93  | 157.41   | 156.08   |
| Non-flat   | 154.98  | 155.15   | 157.45| 159.07| 160.52| 160.95| 161.01| 160.71  | 159.63    | 158.21  | 155.60   | 155.17   |
| Segmented  | 155.33  | 156.64   | 158.23| 159.35| 160.69| 161.04| 161.07| 160.80  | 159.88    | 158.67  | 157.03   | 155.60   |

**Figure 5.** Dependences of power reserve on the season, km, when tested according to the NEDC cycle, calculated using various methods.

The calculation methods are highlighted in different colors:
- with no PVC battery (for comparison),
- with flat PVC battery,
- with non-flat PVC battery,
- with segmented PVC battery.

**WLTC testing**
The data obtained are shown in Table 4 and illustrated in Figure 6.

Different cycles show different trends: the urban NEDC cycle provides the maximum power reserve due to both the slowest average speed and the maximum time spent in the Sun during which solar energy harvesting is provided. The dependence of the increase in power reserve on the season is obvious as proportional to the time of daylight hours.
Table 4. Power reserve, km, for WLTC.

| PVC type  | January | February | March | April | May | June | July | August | September | October | November | December |
|-----------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| None      | 100.84  | 100.84   | 100.86| 100.84| 100.84| 100.84| 100.84| 100.84 | 100.84   | 100.84 | 100.83   | 100.83   |
| Flat      | 100.93  | 101.07   | 101.45| 102.13| 102.55| 102.75| 102.62| 102.44 | 101.71   | 101.33 | 100.93   |          |
| Non-flat  | 100.84  | 100.86   | 101.21| 101.96| 102.48| 102.64| 102.52| 102.11 | 101.37   | 100.84 | 100.83   |          |
| Segmented | 100.85  | 100.96   | 101.40| 102.02| 102.50| 102.66| 102.54| 102.27 | 101.47   | 101.02 | 100.84   |          |

**Figure 6.** Dependences of power reserve on the season, km, when tested according to the WLTC cycle, calculated using various methods.

цевый тестирования NEDC only City testing.

The data obtained are shown in Table 5 and illustrated in Figure 7.

**Figure 7.** Dependences of power reserve on the season, km, when tested according to the NEDC only city cycle, calculated using various methods.
The graphs show that the methodology for calculating the power reserve of an electric car with a flat PVC battery gives overstated values. The method for calculating the power reserve of an electric vehicle with a non-flat PVC battery gives underestimated values. The method for calculating the power reserve of an electric vehicle with a segmented PVC battery gives values that fall between the values obtained by the previous methods.

### Table 5. Power reserve, km, for NEDC only city.

| PVC type    | January | February | March | April | May | June | July | August | September | October | November | December |
|-------------|---------|----------|-------|-------|-----|------|------|--------|-----------|---------|----------|----------|
| None        | 191.93  | 191.93   | 191.99| 192.04| 192.19| 192.08| 192.15| 191.99  | 191.97    | 191.93  | 191.94   |
| Flat        | 193.55  | 193.55   | 198.64| 203.22| 207.82| 210.86| 208.83| 204.75  | 199.90    | 195.64  | 193.71   |
| Non-flat    | 191.94  | 191.94   | 195.76| 201.08| 205.77| 208.25| 208.74| 202.18  | 197.04    | 192.77  | 191.97   |
| Segmented   | 192.67  | 192.67   | 197.07| 202.12| 206.25| 209.16| 209.27| 207.24  | 203.18    | 198.65  | 194.57   | 192.88   |

### 4. Conclusion

The geometry of the PVC battery, which is close to the MV Lada Kalina design, was used as the initial data. The dependences of the EV power reserve on the season and the standard of the test cycle were obtained. In the future, it is possible to use the mathematical modeling results for further developments in the field of not only electric passenger cars, but also to extend them from cars to trucks or buses. In addition to the developments in the automotive industry, they can also be used in other autonomous devices that consume electricity, such as traffic lights, road signs and markers, street lights, billboards, river buoys, airfield lights, etc.

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