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Influence of the Expected Wind Speed Fluctuation on the Number of Batteries of the Balancing System

Research paper

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Abstract: The article discusses a method of assessing the of dependence of the number of batteries that would be needed to achieve energy balance in distributed generation systems with wind turbines on ambient temperature and on the error involved in predicting the parameters of wind flow (wind speed). To describe the relationship between current rate and capacity in a given current range, Peukert's law is used. Dependence of the Peukert's constant on ambient temperature for the lead-acid battery HZB12-180FA is calculated. Taking the lead-acid battery and wind turbine VE-2 as a reference, dependence of area of controlled operation of the battery on the wind speed forecasting error is calculated. The technique of considering ambient temperature, depth of discharge, and wind speed forecasting error when deciding the size of energy storage of the balancing system (the number of batteries and their capacity) is provided. A family of curves representing the dependence of the number of batteries constituting the balancing system on the ambient temperature and the wind speed forecasting error are presented. It is shown that as the wind speed forecasting error increases from 0% to 15% and the ambient temperature decreases from 20 °C to 20 °C, the number of batteries should be increased by approximately 2.81 times in order to maintain the same area of controlled operation of a battery.

Keywords: *battery • Peukert's law • optimal sizing • forecasting*

1. Introduction

In the energy balancing system of distributed generation systems with renewable energy sources (RES), in particular such as wind turbines, the efficient use of the balancing system depends on the charge–discharge modes that are implemented during operation (Midlton and Paredez, no date). Peukert (1897), Liebenow (1897), and Aguf (1968) describe the dependence of the battery capacity on the discharge current with empirical relations. To be effectively used in the energy balancing system, the battery must be in a state of control, observation, and identification (Herasina et al., 2017; Neusypin and Shen, 2016), which is ensured by the sensors of current (A), voltage (V), and capacity ($A \cdot h$) and the corresponding system connections. The area of controlled operation is the area of energy ranges where controlled charge or discharge (operation) is possible. Expansion of the area of controlled operation is provided by reducing the duration of the full-battery charge/discharge. When the battery is in the intermediate state, it is possible to control the energy balance within some boundaries. Since lead-acid batteries are used in small RES, due to low cost and ease of maintenance (Cui et al., 2016), it is advisable to estimate the energy that can be spent on battery charge in the RES predictive control system to expand the area of controlled operation. Depending on the characteristics of the battery and the accuracy of forecasting energy to be obtained, the battery capacity (or the number of batteries, optimal sizing) that will provide the specified control range needs to be chosen. Mozafari and Mohammadi (2014) give optimal sizing of the energy storage system for microgrids relying on economical analysis.

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Shuaixun et al. (2012) presented a method for optimal sizing of an energy storage system for storing energy at the time of surplus and for re-dispatching. Kwangkaew et al. (2020) presented forecasting techniques in optimal sizing. Therefore, it is important to choose the battery capacity or the number of batteries that will provide a given control range (area of controlled operation), depending on the characteristics of the battery and the accuracy involved in the forecasting of wind speed depending on ambient temperature.

2. Peukert's Law

Peukert (1897) presented empirical equations dedicated to ascertaining the dependence of the battery capacity on the discharge current in lead-acid batteries, known as Peukert's law. Peukert's law describes the relationship between discharge current and capacity (as individually normalised to certain rated current and capacity values) in some current range (Peukert, 1897):

$$C_p = i^k \cdot t \tag{1}$$

where C_p is Peukert's capacity, k is Peukert's constant or coefficient ($k = 1.2...1.7$), i is discharge current, and t is discharge time.

The Peukert's capacity C_p and the battery capacity C at a given discharge time t are connected:

$$\frac{t_p}{t} = \frac{C_p}{C} \tag{2}$$

where t_p is the discharge time of capacity C_p.

The general view of dependence of the battery capacity on the discharge current for lead-acid battery is shown in Figure 1.

Peukert's constant is expressed as:

$$k = \log_{\frac{C_1}{t_1} \cdot \frac{t_2}{C_2}} \frac{t_2}{t_1} \tag{3}$$

where C_1 and C_2 are values by which the output capacity decreases during the discharge times t_1 and t_2, accordingly.

Peukert's constant is the same for the same battery and depends not only on the battery type but also on its design and changes as the battery ages.

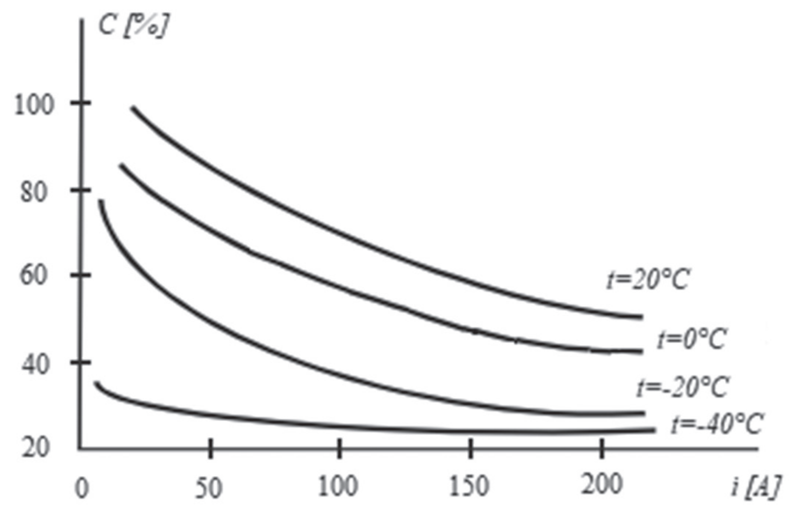

Fig. 1. General view of dependence of the battery capacity as a percentage of the maximum capacity on the discharge current for lead-acid battery.

Peukert's law has limitations, including the following characteristics:

(1) since Peukert's law was developed for lead-acid batteries, and lithium-ion batteries tend to self-heat during rapid charging, and, according to the Nernst equation (Feiner and Mcevoy, 1994), battery voltage increases with ambient temperature, the lithium-ion battery may have approximately the same capacity at 5 *A* and 50 *A*, which makes it impossible to use Peukert's law in its original form; Galushkin and Yazvinskaya (2018) cite Peukert's law for nickel-cadmium batteries. Therefore, applications for lead-acid batteries are used in this paper;
(2) rate of self-discharge is not taken into account;
(3) effect of ambient temperature on the battery is not taken into account; so, in the future, it will be considered separately;
(4) battery age is not taken into account, but it should be noted that the Peukert's constant increases with the battery age;
(5) in considering the battery design properties, they are concentrated in a single parameter – the Peukert's constant, which is not a constant for different batteries and is calculated separately for each type of battery.

3. Taking into Account the Influence of Depth of Discharge

It is not recommended to discharge general purpose batteries deeper than 45%, and deep discharge batteries deeper than 75% (SolarHome, 2021). Figure 2 (RealSolar, 2019) shows changes in battery life depending on charge–discharge cycles. As the depth of the discharge increases, the number of cycles decreases significantly, which affects the value of the Peukert's constant.

Influence of the depth of discharge on the battery capacity and the number of its cycles as well as the discharge current curve are given by the manufacturer (e.g. OOO 'PAUERKONTSEPT', no date). Typical rechargeable batteries are recommended to be discharged with direct current of the same level. In the absence of information from the manufacturer, it is recommended to choose a discharge current that is proportional to the charge current.

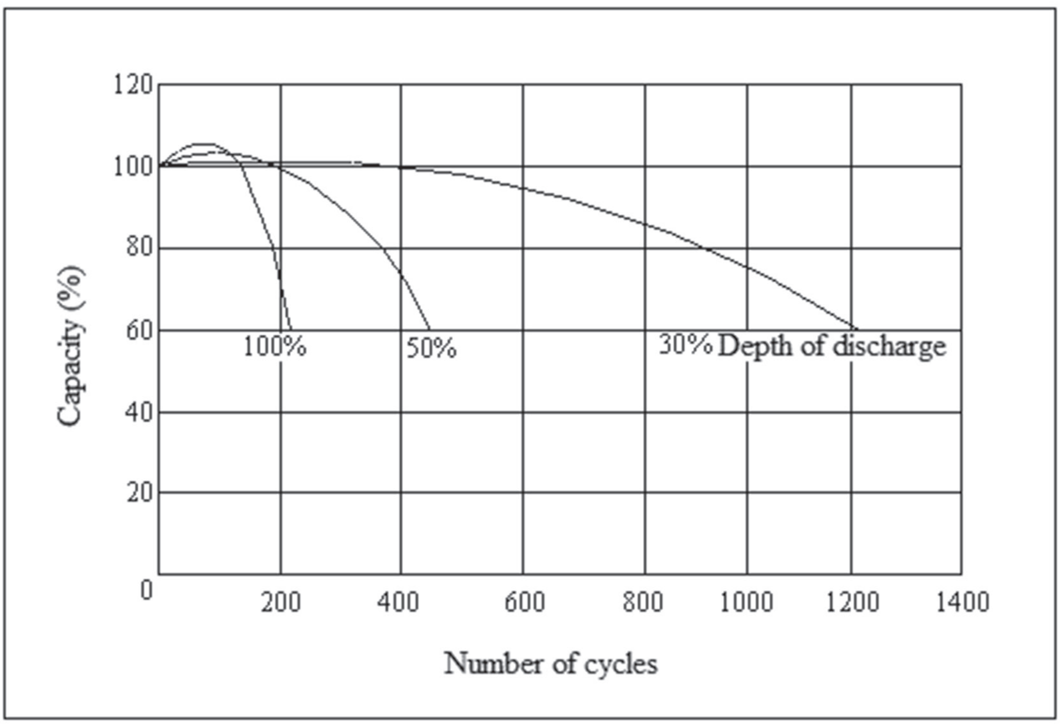

Fig. 2. Dependence of battery capacity on service life in charge–discharge cycles.

Taking into account the depth of charge, the number of batteries can be calculated as follows (Morenko et al., 2019):

$$n \geq \sqrt[k]{\frac{t}{D \cdot \tau}} \cdot \left(\frac{i \cdot \tau}{C_b}\right) \tag{4}$$

where n is the number of batteries that provide operation at the duration t and current i corresponding to the depth of the discharge D, and time taken for the full discharge of the battery is given by τ, provided that the battery was charged to 100% capacity of one battery, this capacity being represented by C_b.

The number of charge–discharge cycles has an effect on the capacity corresponding to the discharge times t_1 and t_2.

4. Taking into Account Influence of the Ambient Temperature

Consider the dependence of battery capacity on the ambient temperature:

$$C_p(T) = i^{k(T)} \cdot t \tag{5}$$

where T is the ambient temperature.

In this case, both the Peukert's capacity and the Peukert's constant depend on the ambient temperature because the Peukert's constant depends on values C_1 and C_2:

$$k(T) = \log_{\frac{C_1(T)}{t_1} \cdot \frac{t_2}{C_2(T)}} \frac{t_2}{t_1} \tag{6}$$

Then, the number of batteries is written as follows:

$$n(T) \geq \sqrt[k(T)]{\frac{t}{D \cdot \tau}} \cdot \left(\frac{i \cdot \tau}{C_b(T)}\right) \tag{7}$$

For example, let us choose the HZB12-180FA series battery from HAZE Battery Company Ltd (HAZE Battery Company Ltd, 2014).

In works of Yang (2019), Chan et al. (2010), and Cui et al. (2018), ambient temperature is taken into account based on empirical dependences. Figure 3 (HAZE Battery Company Ltd, 2014) shows a family of empirical graphs of temperature-capacity versus discharge current for a given battery.

For further calculations, it is necessary to approximate the empirical dependence from Figure 3. The approximation is performed by polynomials of the 3rd order. Graphical results of the approximation are shown in Figure 4.

Analytical expressions of approximation are written as follows:

$$\begin{aligned}
C_1(T) &= C_{nom}(i = 0.05C) \cdot \left(-0.07 \cdot 10^{-6} T^3 - 80.1 \cdot 10^{-6} \cdot T^2 + 8.7 \cdot 10^{-3} \cdot T + 0.86\right), \\
C_2(T) &= C_{nom}(i = 0.1C) \cdot \left(0.67 \cdot 10^{-6} T^3 - 115 \cdot 10^{-6} \cdot T^2 + 8 \cdot 10^{-3} \cdot T + 0.78\right), \\
C_3(T) &= C_{nom}(i = 1C) \cdot \left(0.4 \cdot 10^{-6} T^3 - 136.8 \cdot 10^{-6} \cdot T^2 + 8.6 \cdot 10^{-3} \cdot T + 0.48\right), \\
C_4(T) &= C_{nom}(i = 2C) \cdot \left(0.97 \cdot 10^{-6} T^3 - 126.3 \cdot 10^{-6} \cdot T^2 + 6.2 \cdot 10^{-3} \cdot T + 0.35\right)
\end{aligned} \tag{8}$$

where C_{nom} is the nominal capacity at some discharge current and temperature 20 °C.

To calculate the Peukert's constant by taking into account the dependences $C(T)$, we select the following input data (at temperature $T = 20$ °C during discharge t_1, the capacity of the battery decreases by the value C_i of current i_i): $t_1 = 0.5\ h$, $C_1 = 98.9\ A \cdot h$, $i_1 = 198\ A \approx 2C$, $t_2 = 10\ h$, $C_2 = 179\ A \cdot h$, $i_1 = 17.9\ A \approx 0.1\ C$, minimum voltage is $U_{\min} = 1.85\ V$,

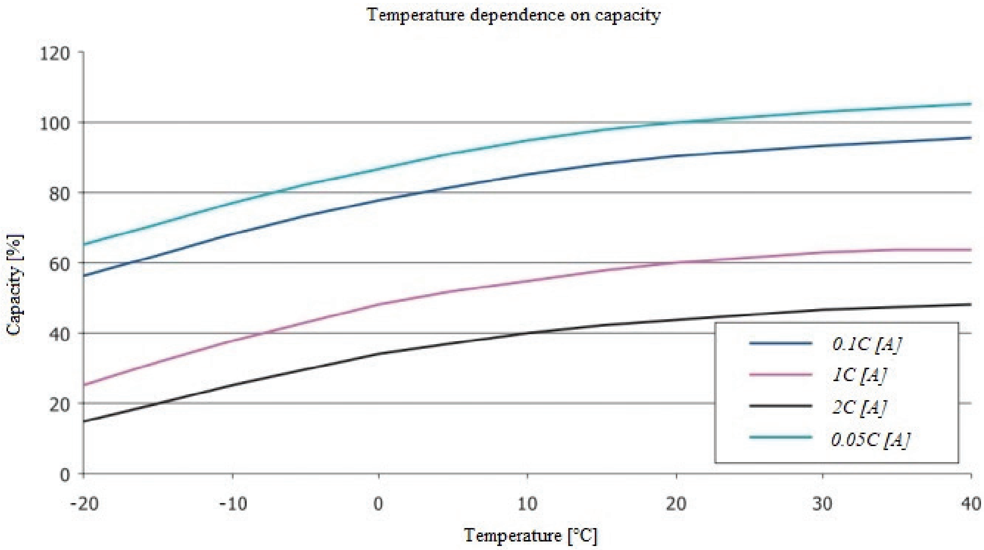

Fig. 3. Temperature dependence of capacity at different discharge currents of HZB12-180FA battery.

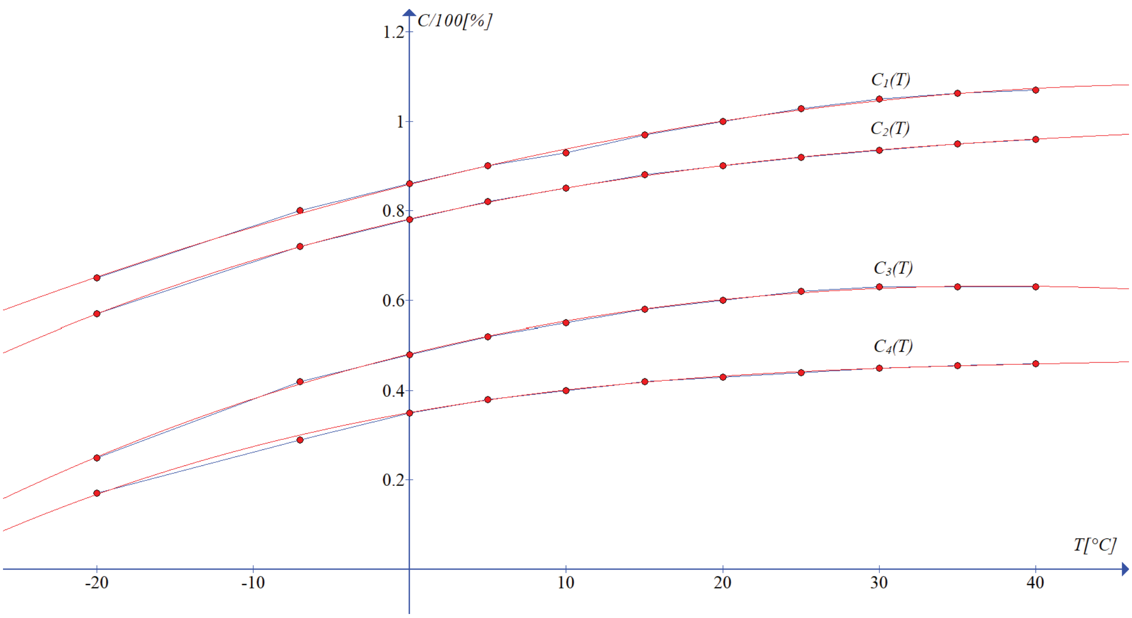

Fig. 4. Approximated empirical dependences from Figure 3.

Temperature T	−20 °C	−7 °C	0 °C	5 °C	10 °C	15 °C	20 °C	25 °C	30 °C	40 °C
Peukert's constant	2.54	1.96	1.87	1.84	1.81	1.80	1.80	1.79	1.80	1.80

Table 1. Peukert's constant.

and maximum capacity that can be obtained is $C_{\max} = 202\ A \cdot h$. Calculated Peukert's constant data are given in Table 1, and the graph of the dependence of the Peukert's constant is given in Figure 5.

Thus, taking into account the ambient temperature of the empirical dependences allows us to calculate the Peukert's constant more accurately.

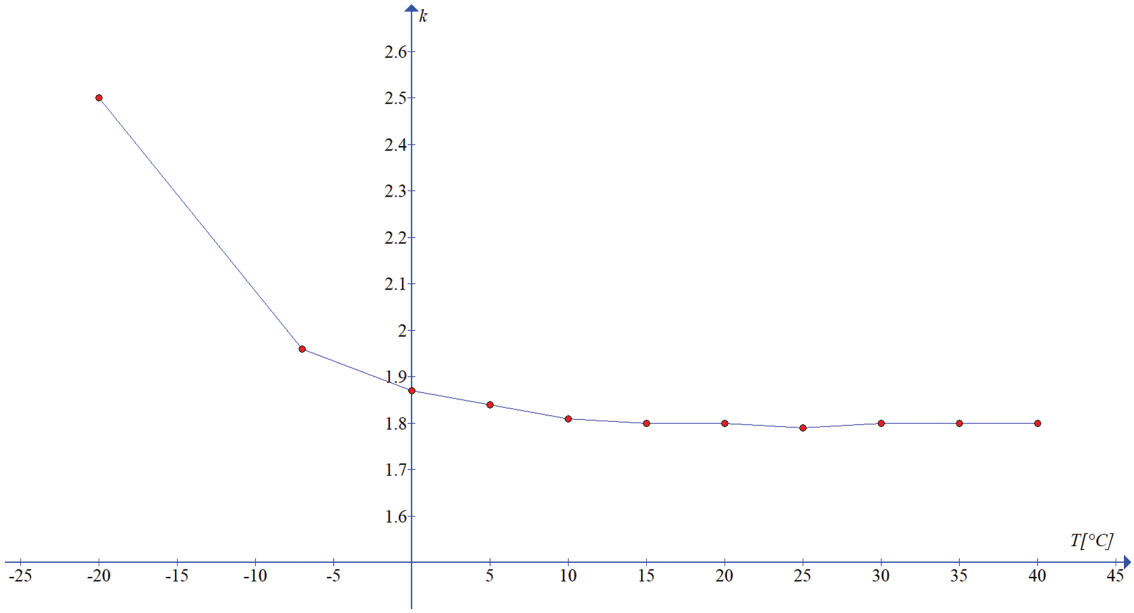

Fig. 5. Dependence of the Peukert's constant on ambient temperature.

5. Taking into Account the Influence of Measurement Error

Power at output of the wind turbine has cubic dependence on wind speed (Krivtsov et al., 2003):

$$P = \frac{1}{2} \cdot C_p \cdot \rho \cdot A \cdot v^3 \tag{9}$$

where v is the wind speed, ρ is air density, C_p is wind utilisation factor, $A = \frac{\pi d^2}{4}$ is effective area of wind wheel, and d is wind wheel diameter. For example, for SV-3.1 wind turbine (Svit Vitru, no date), provided that the air density $\rho = 1.25$ and wind utilisation factor $C_p = 0.5$, the output power is given by $P = 3.77 \cdot v^3$.

To estimate the energy level for battery charge/discharge, it is necessary to calculate the amount of power at output of the wind turbine according to the predicted values of wind speed. Assuming that the wind speed $v = 1$ n.u. (normalised units), the power that can be obtained from the wind turbine is $P = 3.77$ n.u. For example, if wind speed prediction error is $\Delta v = 0.85$ n.u., i.e. power $P = 2.32$ n.u., and the power prediction error is $\delta_P = 38\%$, then the following expression would hold true:

$$\delta_P = \left(1 - \frac{P(\Delta v)}{P(v)}\right) \cdot 100\% = \left(1 - \frac{(\Delta v)^3}{v^3}\right) \cdot 100\% = \left(1 - \frac{0.85^3}{1^3}\right) \cdot 100\% \approx 38\% \tag{10}$$

This means that within ±31% ((100 − 38)/2 = 31) relative to the average energy level, the battery can be controllably charged or discharged (Figure 6). The higher the percentage, the higher the chance of being in a controlled state (for example, with the state of charge equal to 50%), when there is enough unused capacity to be charged from the wind turbine or there is enough charge for a load.

When the wind speed prediction error reaches 20%, the area of controlled operation of the battery disappears. If it is necessary to ensure 80% area, it is necessary that the wind speed prediction error does not exceed 7%.

In order to take into account the effect of the ambient temperature and prediction error on the number of batteries, the following formula was used:

$$\delta n(T) = n(T) \cdot \delta_p \tag{11}$$

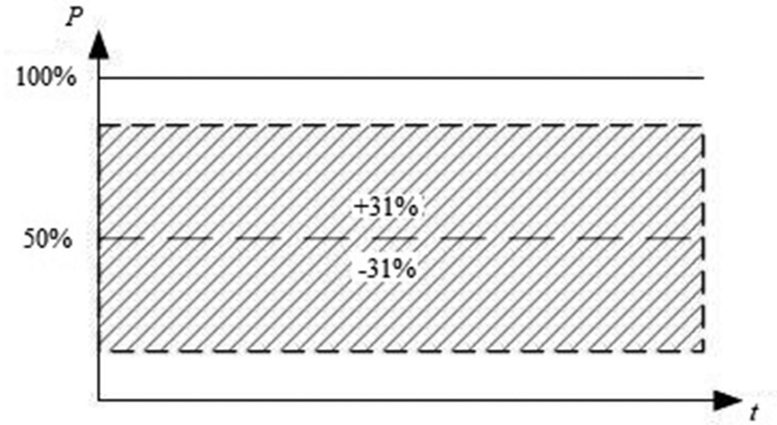

Fig. 6. The area of controlled operation of the battery.

where $n(T)$ is the number of batteries when taking into account the ambient temperature and δ_p is the number of batteries when taking into account the wind prediction error.

Given that increasing the area of controlled operation decreases Δ_p and the required number of batteries, the following expression would then hold true:

$$\delta_p = \frac{1}{1-\Delta_p} \tag{12}$$

Thus, to calculate the number of batteries, we need to consider the depth of discharge, ambient temperature, and prediction error (Klen et al., 2020).

6. Calculation of the Number of Batteries Depending on Parameters

Substituting in Eq. (7) values of the input data such as discharge time $t = 10h$, discharge current $i = 17.9A$, nominal capacity $C_{nom} = 179A \cdot h$, battery operating time $\tau = 20h$, and depth of discharge, we obtain the following expression:

$$D = \frac{C_{\max} - C_{\min}}{C_{\max}} = \frac{202-(202-179)}{202} = 88.6\% \tag{13}$$

We also obtain the dependence of the number of batteries on the ambient temperature and the Peukert's constant:

$$n(T) \geq \sqrt[k(T)]{\frac{t}{D\cdot\tau}} \cdot \left(\frac{i\cdot\tau}{C_b(T)}\right) = \sqrt[k(T)]{\frac{10}{0.886\cdot 20}} \cdot \left(\frac{17.9\cdot 20}{C_b(T)}\right) = \sqrt[k(T)]{0.56} \cdot \left(\frac{358}{C_b(T)}\right) \tag{14}$$

The Peukert's constant also depends on the ambient temperature shown in Table 2. A graph of the number of required batteries depending on the temperature is shown in Figure 7.

Interpolating Figure 7 with a 3rd degree polynomial, the equation for the number of batteries is written as follows:

$$n(T) = -9.8\cdot 10^{-6}\cdot T^3 + 0.79\cdot 10^{-3}\cdot T^2 - 0.025T + 1.89 \tag{15}$$

Tables 3–5 show dependences of the number of batteries on wind speed forecasting error at temperatures –20 °C (Table 3), 0 °C (Table 4), and 20 °C (Table 5), respectively.

Temperature T	−20 °C	−7 °C	0 °C	5 °C	10 °C	15 °C	20 °C	25 °C	30 °C	40 °C
$n(T)$	2.8	2.08	1.89	1.79	1.72	1.66	1.62	1.58	1.56	1.52

Table 2. Dependence of the number of batteries on the ambient temperature.

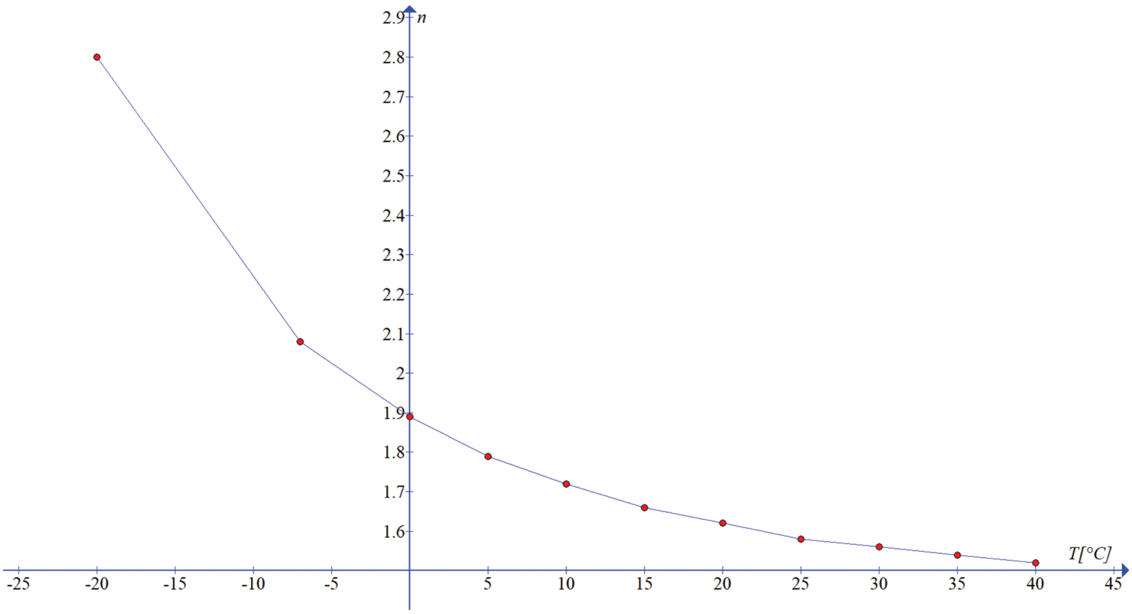

Fig. 7. Dependence of number of required batteries on the ambient temperature.

δ_v	0%	5%	10%	15%
δ_P	100%	86%	73%	38%
$\delta n(T)$	2.8	3.27	3.84	4.56

Table 3. Dependences of the number of batteries on error of wind speed forecasting at a temperature of −20 °C.

δ_v	0%	5%	10%	15%
δ_P	100%	86%	73%	38%
$\delta n(T)$	1.89	2.21	2.59	3.08

Table 4. Dependences of the number of batteries on error of wind speed forecasting at a temperature of 0 °C.

δ_v	0%	5%	10%	15%
δ_P	100%	86%	73%	38%
$\delta n(T)$	1.62	1.89	2.22	2.64

Table 5. Dependences of the number of batteries on error of wind speed forecasting at a temperature of 20 °C.

Figure 8 shows a family of curves of dependence of the number of batteries of the balancing system on the ambient temperature and the wind speed forecasting error.

For example, when the prediction error increases from 10% to 15%, the number of batteries should be increased by 1.17 times, and when the ambient temperature decreases from 20 °C to 0 °C, the number of batteries should be increased by 1.48 times in order to maintain the same area of controlled operation.

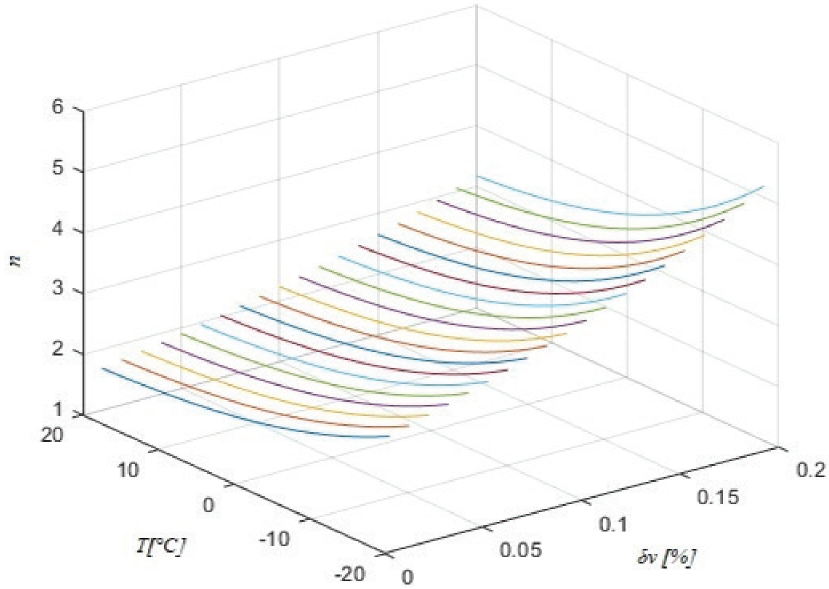

Fig. 8. Dependence of the number of batteries on the ambient temperature and wind speed prediction error.

7. Conclusions

The paper shows the influence of the wind speed prediction error, ambient temperature, and depth of discharge on the number of batteries in the balancing system. The method of calculating the required number of batteries is specified by using as an example the lead-acid batteries series HZB12-180FA, manufactured by HAZE Battery Company Ltd. It is shown that when prediction error increases and the ambient temperature decreases, the number of batteries required to maintain the same area of controlled operation of a battery increases: when wind speed prediction error increases from 10% to 15%, the number of batteries should be increased by 1.17 times, and when the ambient temperature decreases from 20 °C to 0 °C, the number should be increased by 1.48 times. This must be taken into account when designing a RES balancing system and choosing the number of batteries of the balancing system, for example, by examining meteorological data beforehand and adjusting the number of the batteries accordingly. In future work, investigating a higher bound of the number of batteries and taking into account cost of the energy storage system might prove important, giving both lower and higher bounds of the number.

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