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The Impact of Wind Power and Load Power Fluctuations on Energy Storage Sizing

M. K. Yaremenko[f], 0000-0001-8782-1642
K. S. Klen[s], 0000-0002-6674-8332

National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute" 00syn5v21
Kyiv, Ukraine

***Abstract*—The study presents a method of taking into account the impact of wind power and load power fluctuations on the energy storage sizing, comprised of batteries of identical capacity. To account the impact, two methods of calculating the difference between wind power generation and load consumption were presented over some time interval: 1st and 2nd order difference methods. Each of the methods can be parameterized and non-parameterized method with and without taking into account parameters respectively, where the parameters are: discharge current, required discharge duration, depth of discharge, battery capacity, Peukert's constant, discharge time from 100% capacity, ambient temperature and wind power prediction error. Using the parameterized method compared allows to refine the value of the number of batteries. Using the 2nd order difference method compared to the 1st order difference method can significantly reduce the required number of batteries.**

***Keywords* — energy storage system; battery; optimal sizing; wind; load; predictive energy balancing**

I. Introduction

The annually increasing level of energy consumption, with a growth rate of about +1.4%/year from 2010 to 2019 [1], and the limitations of relatively cheap energy sources such as uranium and oil highlight a pressing situation. For example, the planet's uranium reserves for nuclear power plants, estimated at around 4 million tons for nuclear power plants, along with oil reserves, are projected to be depleted in 25 to 30 years [2]. This situation underscores the importance of decentralization and diversification of existing sources and leads to necessity for the development of renewable energy. Wind turbines, as a part of renewable energy sources, take a significant part in energy generation, contributing 7.5% to the total energy production in 2022 [3], while also committing to reducing power generation carbon footprint, but the challenge of wind turbine usage is unpredictable nature of wind as a primary source energy is obtained. Wind doesn't blow constantly, nor does it adhere to daily consumption patterns. Hence crucial component of distributed generation systems with renewable energy sources is energy storage. Energy storage acts as a buffer, storing excess energy generated during gusty wind periods and releasing it during energy shortages, ensuring a consistent and reliable energy supply [4]. Energy storage consists of batteries of predefined capacity. With large-sized storage system, consisting of high number of batteries, the probability of obtaining insufficient energy to meet the consumer's demand decreases, but the cost of installing such a system increases and vice versa. Therefore, the number of batteries affects the cost and profitability of distributed generation systems with wind turbines [5], [6].

According to previous research [7], the number of batteries in energy storage depends on the parameters: required discharge current, required discharge duration, depth of discharge, battery capacity, Peukert's constant, discharge time from 100% capacity, ambient temperature and wind power prediction error. In addition, energy storage sizing depends on statistical nature of wind power and load power, both of which can be modeled as stochastic processes that change in time. Depending on selected time interval and its length, different minimum number of batteries might be required to compensate for the difference between wind power generation and load consumption. Thus, it is important to estimate the energy storage sizing, consisting of batteries of equal capacity, depending on wind power and load power fluctuations, while also taking into account all the previously mentioned parameters.

II. Methods

A. Minimum energy storage sizing

Energy storage is used to compensate for the difference between wind power generation and load consumption. Since energy storage capacity C can be high, energy storage is usually comprised of batteries of capacity C_a, hence total capacity is calculated as following:

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$$C = C_a \cdot n, \tag{1}$$

where: C_a – single battery capacity, n – number of batteries.

But available battery capacity varies depending on parameters like ambient temperature, depth of discharge and wind power prediction error that depends on wind speed prediction error [8], Peukert's effect and the equation (1) doesn't take them into account. In 1897 Peukert presented empirical equations (Peukert's law) dedicated to ascertaining the dependence of the battery capacity on the discharge current in lead-acid batteries [9]:

$$C_p = i^k \cdot t, \tag{2}$$

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.

Peukert's constant is the same for the same battery, but depends on the battery type, battery design and changes as the battery ages [7]. Additionally, the Peukert's capacity usually is not provided by battery manufacturers and the Peukert's law doesn't consider impact of the above mentioned parameters.

In order to calculate the number of batteries depending on the parameters, a modified version of equation (1) was used, which, when taking into account the above parameters and Peukert's law, takes form [7]:

$$n(T) \geq \sqrt[k(T)]{\frac{t}{D \cdot \tau}} \cdot \left(\frac{(i \cdot \tau)^{k(T)}}{C_a(T)} \right), \tag{3}$$

where: $n(T)$ – minimum number of batteries, that can provide energy at required discharge duration t with discharge current i and depth of discharge D provided that the battery was charged to 100% capacity C_a of 1 battery when full discharge time is τ, k – Peukert's constant or coefficient, T – ambient temperature.

Both battery capacity and Peukert's constant depend on temperature [7]:

$$\begin{aligned} C_a(T) &= C_a \cdot c(T) \\ k(T) &= k \cdot k_T(T) \end{aligned}, \tag{4}$$

where: C_a and k – battery capacity and Peukert's constant are provided during temperature $T = 20$ °C, $c(T)$ and $k_T(T)$ – adjustment factors for battery capacity and Peukert's constant accordingly, depending on ambient temperature.

Since wind power generation vary with time, it can only be estimated with some prediction error. When taking into account uncertainty in wind power prediction, number of batteries formula takes form:

$$\delta n = n(T) \cdot \delta_P, \tag{5}$$

where: $\delta_P = \dfrac{1}{1 - \Delta_P}$ – number of batteries factor, taking into account the wind power prediction error; Δ_P – wind power prediction error.

Equation (5) determines the minimum energy storage sizing. Total energy storage capacity can be obtained from:

$$C \geq \sqrt[k(T)]{\frac{t}{D \cdot \tau}} \cdot (i \cdot \tau)^{k(T)} \cdot c(T). \tag{6}$$

However, in equations (3) and (6) there are 2 aspects that significantly reduce accuracy of the number of batteries calculation:

1. it is assumed that there's no power management: all the energy obtained from wind turbine, is stored in batteries, and all the energy in batteries is given to the load;
2. duration t is not known in advance and it depends on energy obtained from wind turbine and energy spent to the load under specific conditions during specific time interval.

In other words, the equations do not take into account statistical nature of the energy that is accumulated and given to the load, so to amount of energy to be stored, need to take into account wind speed and load power probability distributions, estimate energy production and consumption and find the difference between them.

B. Determining wind and load energy difference

The cumulative distribution function $F_v(v)$ gives the fraction of time or the probability that the wind speed is equal or lower than v. It is defined as the integral of the probability density function [10]:

$$F_v(v) = \int_0^v f_v(u)\,du. \tag{7}$$

where: v – wind speed in m/s, $f_v(u)$ – probability density function of wind speed.

The probability density function f_v indicates the fraction of time or the probability that the wind speed is equal to or lower than a given wind speed v. For example, with Weibull distribution it is given by the following equation [11]:

$$f_v(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[\left(-\frac{v}{c}\right)^k\right], \tag{8}$$

where: k – Weibull shape parameter, c – scale parameter.

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The total energy production, contributed by all possible speeds in a wind regime, available for unit rotor area and during specific time interval may be expressed as [12]:

$$E_{in} = t\int_0^{\infty} P_{in}(v) f_v(v) dv\,, \tag{9}$$

where: $P_{in}(v)$ – power curve of wind turbine, expressing wind power at wind speed v, t – time interval.

Part under the integral represents average power at time interval t.

The total energy consumption can also be obtained from equation (9) by replacing $P_{in}(v)$ with $P_{out}(t)$ - load power at time t.

Difference between energy consumption and energy generation, called 1st order energy difference, shows the insufficient energy ΔE for the load:

$$\begin{gathered}\Delta E(t) = E_{out} - E_{in} \\ = t\int_0^{\infty} P_{out} f(v) dv - t\int_0^{\infty} P_{in}(v) f(P) dP \\ = t\int_0^{\infty} P_{out} f(P) dP - t\int_0^{\infty} P_{in}(v) f(P) dP \\ = t\int_0^{\infty} \left(P_{out} - P_{in}(v)\right) f(P) dP\end{gathered}\,. \tag{10}$$

The wind turbine and the load are selected in such a way that the inequation is satisfied:

$$\Delta E(t) \le 0\,. \tag{11}$$

Ideally, the probability distributions of wind power and load power should be equal. If they are not, their difference can be found using measures of distance between probability density functions [13].

Further on, determining the number of batteries involving equation (11) will be called the 1st order difference method.

To compensate for the difference between the probability distributions over a time interval t, a modified equation can be used that takes into account the difference between the theoretical energy value and the empirical or obtained energy value:

$$\begin{gathered}\Delta E_{out} = E_{out} - E_{avg} \\ \Delta E_{in} = E_{in} - E_{avg} \\ \Delta E^2(t) = \Delta E_{out} - \Delta E_{in}\end{gathered}\,, \tag{12}$$

where: ΔE_{out} and ΔE_{in} – the difference between theoretical energy value E_{avg} and the obtained energy value from the wind power generation and load consumption respectively, $\Delta E^2(t)$ – 2nd order energy difference.

Further on, $\Delta E(t)$ denotes the energy difference of either 1st or 2nd order, unless not specified explicitly.

Further on, determining the number of batteries involving equation (13) will be called the 2nd order difference method.

This method is aimed to reduce temporal differences over time between theoretical and empirical distributions of wind power and load power instead of covering sporadical power bursts. This should be taken into account when designing energy storage control algorithm.

For simplicity of calculations E_{avg} was assumed to be equal to the average energy value over all time intervals. In real usage scenarios, E_{avg} can be equal either to a random value from the theoretical probability distribution or to a predefined value, for example, the value of load power according to the planned load of devices. The more accurately the values of ΔE_{out}, ΔE_{in} and E_{avg} are defined, the smaller the energy difference will need to be balanced and the smaller the required number of batteries will be. The smaller the time interval duration is, the more accurately it is possible to determine the values of ΔE_{out}, ΔE_{in} and E_{avg}, but at the same time the more often it may be necessary to charge-discharge the batteries to adjust the planned charge-discharge cycles according to possible future energy shortages or excess energy cases, which will negatively affect their service life.

For the empirical probability distributions equation of numerical integration using the Trapezoidal rule [14] was used:

$$\Delta E = \sum_{i=2}^{m} \Delta S_i = \sum_{i=2}^{m} \frac{\Delta P_{i-1} + \Delta P_i}{2} \cdot \Delta t_i\,, \tag{13}$$

where: $\Delta P_i = P_{outi} - P_{ini}$, $\Delta t_i = \frac{t}{m}$ – subinterval; m – number of subintervals.

In this case sampling rate of P_{out} and P_{in} must be the same.

Then the total energy storage capacity $E_s(t)$ for a particular time interval of duration t:

$$E_s(t) \ge \Delta E(t)\,, \tag{14}$$

where: $\Delta E(t)$ – difference between energy consumption and energy generation for empirical data for a selected time interval t in hours.

If batteries with battery power capacity E_a are installed, then their number in energy storage system for a selected time interval t without taking into account depth of discharge and battery efficiency will be [15]:

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$$n(t)=\frac{E_s(t)}{E_a}=\frac{\Delta E(t)}{E_a}, \tag{15}$$

where: E_a – battery power capacity:

$$E_a=C_a\cdot U_a, \tag{16}$$

where: U_a – battery voltage.

Further on, determining the number of batteries using equation (16) will be called the non-parameterized method or method without taking into account the parameters.

When choosing the maximum time interval t duration while keeping inequation (12) true, it turns out that the batteries are not needed because all the energy imbalances are ignored. Therefore, the time interval duration is selected in such a way as to compensate for temporal differences or imbalances between wind power generation and load consumption.

In the case when, for the selected time interval, wind energy is higher than the energy required for the load, equation (16) shows the number of batteries that allows to compensate for the difference between wind power generation and load consumption. Otherwise, when the calculated number turns out to be negative, it means that there is free energy that can be given to the grid, and amount of the energy is equivalent to a certain number of batteries. Hence the required number of batteries for the load balancing is equal to 0.

Aspects of the equation (16) that significantly reduce the accuracy of battery calculation are:

1. the fact that it does not take into account parameters from formulas (5)-(3);
2. when choosing a short time interval the number of batteries will be unrepresentative due to the probabilistic nature of wind and load power, and when choosing a long time interval, the energy and the required batteries number values increase, without taking into account the fact that during some time intervals excess energy may be accumulated without "transferring" to other time intervals.

C. Number of batteries taking into account energy difference

Operating time of the batteries can be found in the following way:

$$t_b=\frac{\Delta E(t)}{P_{out}}=\frac{\Delta E(t)}{U_a i}, \tag{17}$$

where: i – battery discharge current.

Then after substituting (18) into the formula (3), minimum number of batteries becomes:

$$\begin{aligned} n(t) &\geq \sqrt[k(T)]{\frac{\frac{\Delta E(t)}{U_a i}}{D\cdot\tau}}\cdot\left(\frac{(i\cdot\tau)^{k(T)}}{C_a(T)}\right)= \\ &=\sqrt[k(T)]{\frac{\Delta E(t)}{U_a\cdot i\cdot D\cdot\tau}}\cdot\left(\frac{(i\cdot\tau)^{k(T)}}{C_a(T)}\right)\end{aligned}. \tag{18}$$

Power capacity of the energy storage system:

$$\begin{aligned} E_s(t) &\geq \sqrt[k(T)]{\frac{\frac{\Delta E(t)}{U_a i}}{D\cdot\tau}}\cdot(i\cdot\tau)^{k(T)}\cdot U_a= \\ &=\sqrt[k(T)]{\frac{\Delta E(t)}{U_a\cdot i\cdot D\cdot\tau}}\cdot(i\cdot\tau)^{k(T)}\cdot U_a\end{aligned}. \tag{19}$$

Further on, determining the number of batteries using formula (19) will be called the parameterized method or method with taking into account the parameters.

When calculating the number of batteries for a long time interval $t_N=t\cdot N_t$, it is divided into N_t smaller subintervals of duration t and for each subinterval $i=1...N_t$ the number of batteries $n_i(t)$ is calculated according to formula (19), constructing a data sample, from which a certain value $n(t)$ is selected:

$$n(t)\leq n_{\max}(t), \tag{20}$$

where: $n_{\max}(t)$ – the maximum number of batteries at any time subinterval t_i.

Suppose that the wind blows constantly with a low amplitude with oscillations and the standard deviation is low, then the battery energy system with a selected number of batteries $n(t)=n_{\max}(t)$ will be responsible for compensating fluctuations relative to the average power from the wind turbine during each individual time interval, assuming that the time intervals are independent.

The data for the calculations were taken from open sources and processed.

D. Wind speed and load power data processing

As an example, wind speed data were taken from the report from Phu Yen province, Vietnam [16]. Wind speed data are given for 5.7 years with a resolution of 10 minutes at altitudes of 40, 60, and 80 m. 55-day long data at an altitude of 60 m were selected from the wind speed data sets. Wind data resolution has an impact on wind power calculations [17]. One-hour interval wind speed data resolution is generally considered to provide adequate accuracy [18].

Wind speed data has diurnal variations [19], therefore the time interval was selected to be $t_i=24$ hours.

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For further calculations, the VE-2 wind generator [20] with a nominal power of 2 kW at a nominal wind speed of 8 m/s was used as a reference.

The minimum wind speed for calculations was set to be 2.5 m/s – the minimum wind speed for stable charging from VE series wind turbines [20]. The maximum speed was set to be 20 m/s, at which the VE-2 wind turbine is switched off.

Wind speed data were obtained with some gaps, so before making calculations, lost or missing data were reconstructed.

To preserve the characteristics of probability distribution on the whole data set and in place of gaps, a variation of filling gaps with selection was used [21]. When using this method, the missing values are selected based on the estimation of the data distribution. According to [22], distribution selection has an impact on wind speed probabilities and statistical characteristics of the reconstructed data. Weibull distribution was used for wind speed data, as suggested in [16].

Power at the output of wind turbine is calculated by following equation [23]:

$$P=\frac{1}{2}C_p \cdot \rho \cdot A \cdot v^3, \qquad (21)$$

where v – wind speed, ρ – air density, C_p – power coefficient, $A=DH$, D – diameter of a circle, plotted by the most distant blades from the rotation axis, H – height of the vertical-axis wind turbine.

Parameters of wind flow and wind wheel can be marked as a constant factor f:

$$P_{in}=\frac{1}{2}C_p \cdot \rho \cdot A \cdot v^3 = f \cdot v^3. \qquad (22)$$

Constant factor for the VE-2 wind turbine:

$$f=\frac{P_{in}}{v^3}=\frac{2000}{8^3}=3{,}91. \qquad (23)$$

Constant factor f is nonlinear, because parameters ρ and C_p change with wind speed [24], but for simplifying the calculations it was assumed to be constant.

At an average wind speed of 5,24 m/s average wind turbine:

$$P_{in}=f \cdot v^3 = 3{,}91 \cdot 5{,}24^3 = 562{,}7W. \qquad (24)$$

An individual wind project can achieve an approximate 20% [25] mean absolute error [26] in day-ahead forecasting relative to the installed wind capacity. Wind power prediction error was selected to be 10% for the calculations.

The load power data were taken from the active load power of a private household in Hauts-de-Seine, France [27]. Load power data are given for 47 months with a frequency of 1 minute. 55-day long data were selected from the data set. Average power of the load was $P_{out}=1091{,}6W$.

Since, on average, the load from the data set requires higher power than the average wind power from the data set, the batteries will not be able to provide the load with energy for a long time interval, so a higher value of the coefficient $f_{\max}=f \cdot y$ was chosen for the calculations, and the multiplier y was selected in such a way that the equality was fulfilled: $P_{in}=P_{out}$.

The HZB12-180FA [28] series 6-cell battery from HAZE Battery Company Ltd with a capacity $C_a=202$ Ah during discharge time $\tau=8$ h and a service life of 12 years was selected as the rechargeable battery. Depth of discharge was selected to be 88,6%, allowing discharge to 1.7 V per cell. For this battery Peukert's constant was found to be $k=1{,}11$ when temperature $T=20$ °C.

The processed data inserted into equations (11) and (16) provides the 1st-order difference non-parameterized method, into equations (13) and (16) – provides the 2nd order difference non-parameterized method, into equations (11) and (19) – provides the 1st-order difference parameterized method, into equations – (13) and (19) provides the 2nd-order difference non-parameterized method. As a result, number of batteries can be estimated and compared when using different methods.

III. Results and discussion

Parameterized and non-parameterized methods using 1st and 2nd order differences provide estimation of minimum number of batteries in an energy storage system that can provide energy at required discharge duration with the specified parameters.

Fig. 1 shows the number of batteries as a function of wind energy and load energy. Plot 1 (blue-green) is based on the 1st order difference non-parameterized method,

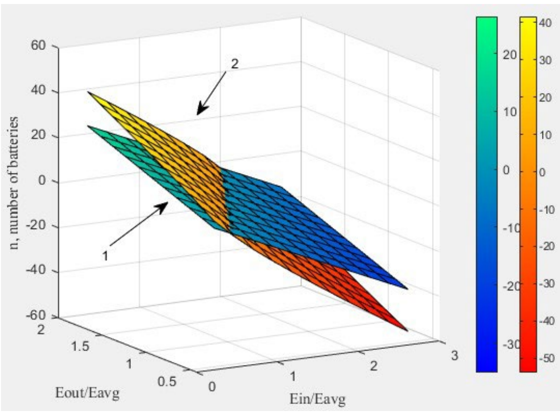

Fig. 1 The number of batteries as a function of wind energy and load energy, with taking into account the impact of power fluctuations (plot 2) and without (plot 1)

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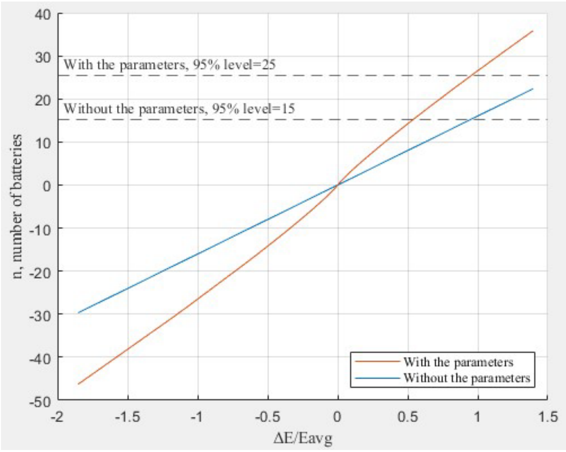

Fig. 2 The number of batteries as a function of the difference between the wind power energy and the load energy, with taking into account the impact of power fluctuations (red curve) and without (blue curve)

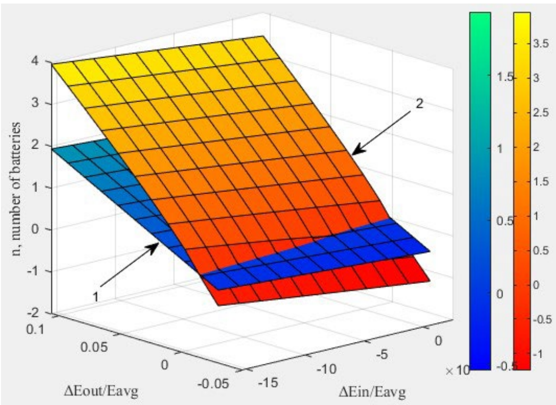

Fig. 3 The number of batteries as a function of the difference between the theoretical and the empirical wind power and load energy, with taking into account the impact of power fluctuations (plot 2) and without (plot 1)

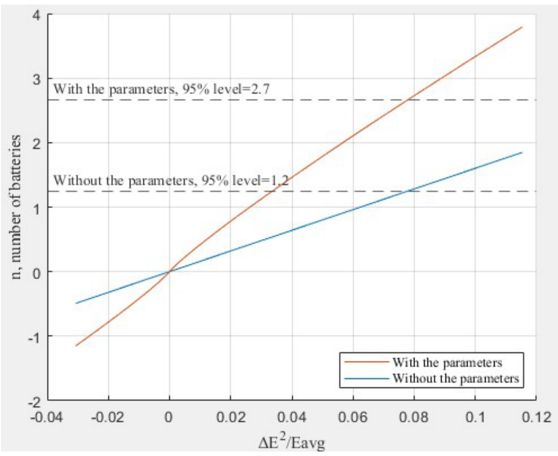

Fig. 4 The number of batteries as a function of the difference between the theoretical and the empirical energy value of the wind turbine and load, with taking into account the impact of power fluctuations (red curve) and without (blue curve)

and plot 2 (yellow-red) is based on the 1st order difference parameterized method. To plot them, wind energy and load energy were divided into 10 equal intervals from the minimum value according to the empirical dataset to the maximum one with 1 value in each interval, and then the required number of batteries was calculated for all the possible pairs of the wind and load energies. In the figure, the energy is normalized relative to the average energy value over all time intervals t .

Fig. 2 shows the number of batteries as a function of the difference between the wind power generation and the load consumption for different time intervals t , normalized to the average energy value for all the time intervals. The curves were plotted using the 1st-order difference non-parameterized method (blue curve) and parameterized method (red curve). The number of batteries that will theoretically provide the load with energy with 95% level of confidence is shown, represented as 95% percentile [29] [30].

The increase in the required number of batteries when using the parameterized method compared to the non-parameterized method is due to the fact that with an increase in discharge current and discharge time, the Peukert's coefficient causes a nonlinear effect, reducing the amount of possible energy to be extracted and thus increasing the required number of batteries to be able to store the required amount of energy.

Fig. 3 shows the number of batteries as a function of the difference between the theoretical and the empirical wind power generation and the load consumption. Plot 1 (blue-green) is based on the 1st-order difference non-parameterized method, and plot 2 (yellow-red) is based on the 1st-order difference parameterized method. To plot them, the energy differences were divided into 10 equal intervals from the minimum value according to the empirical dataset to the maximum one with 1 value in each interval, and then the required number of batteries was calculated for all possible pairs of the wind and load energies.

Fig. 4 shows the number of batteries as a function of the difference between the theoretical and the empirical wind power generation and the load consumption for different time intervals, the average energy value for all the time intervals. The number of batteries that will theoretically provide the energy load with 95% level of confidence is shown. The curves were plotted using the 1st-order difference non-parameterized method (blue curve) and non-parameterized method (red curve).

Fig. 2 and Fig. 4 can be divided into 4 quadrants with the center in plots intersection point. 1st quadrant, located top-right relatively to the intersection point, represents time intervals with energy shortage that is expected to be covered by installing batteries, 3rd quadrant represents time intervals with free energy that is expected to be either stored in batteries or transferred

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to an external grid. Plot asymmetry on Fig. 2 and Fig. 4 can be explained by statistical nature of wind power and load power.

Based on the 1st quadrant of the figures, it can be seen that using the 2nd order difference method (Fig. 4) requires installation of fewer batteries (2.7 compared to 25) than using the 1st order difference method (Fig. 2) for the same wind energy and load energy data when using the appropriate storage control algorithm.

If there is an external grid and the distribution of input data is such that the amount of free energy is greater than the amount of energy required to balance energy and meet the needs of the load, it is possible to install batteries based on the 3rd quadrant of the figures, with the external grid acting as an additional storage device or as an additional load customer.

When compared to other researches related to energy storage sizing, sources [15] [31] [32] don't define how to choose required battery discharge duration depending on power data, and don't take into account Peukert's effect.

The paper shows the impact of wind power and load power fluctuations on energy storage sizing, consisting of batteries of equal capacity. Taking into account the statistical nature of the wind power is done by using the 1st order difference parameterized method allows to refine the value of the number of batteries by 67% on the reviewed dataset compared to the non-parameterized method. In the case of the 2nd order difference method, according to the refinement, 125% more batteries should be installed. The use of the 2nd order difference method compared to the 1st order difference method can significantly reduce the required number of batteries when using the appropriate energy storage control algorithm, even with the parameterized method. The calculation methodology is shown on the example of lead-acid batteries of the HZB12-180FA series manufactured by HAZE Battery Company Ltd and data of wind speed from Phu Yen Province, Vietnam and load power from a private house in Hauts-de-Seine, France.

Further research may include analyzing state of charge of the batteries depending on their number, profitability of installing batteries according to the free energy amount and selling excess energy to the grid.

References

[1] Enerdata, "World Energy & Climate Statistics – Yearbook 2023," 2023. [Online]. Available: https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html. [Accessed 02 10 2023].

[2] V. S. Biletskyi, V. M. Orlovskyi, B. I. Dmytrenko and A. M. Pokhylko, Osnovy naftohazovoi spravy (Basics About the Oil and Gas Industry), Kyiv: PoltNTU Khalikov R. Kh., 2017, p. 312.

[3] H. Ritchie, M. Roser and P. Rosado, "Energy," 2022. [Online]. Available: https://ourworldindata.org/electricity-mix. [Accessed 02 10 2023].

[4] "BESS 101: Revolutionizing the Energy Landscape with Battery Energy Storage Systems," 2023. [Online]. Available: https://www.acebattery.com/blogs/what-is-engery-storage-system. [Accessed 03 11 2023].

[5] H. Fathima and K. Palanisamy, "Optimized Sizing, Selection, and Economic Analysis of Battery Energy Storage for Grid-Connected Wind-PV Hybrid System," Model. Simul. Eng., vol. 2015, pp. 1-16, 2015. **DOI:** 10.1155/2015/713530

[6] A. L. Bukar, C. W. Tan and K. Y. Lau, "Optimal sizing of an autonomous photovoltaic/wind/battery/diesel generator microgrid using grasshopper optimization algorithm," Sol. Energy, vol. 188, p. 685–696, August 2019. **DOI:** 10.1016/j.solener.2019.06.050

[7] M. K. Yaremenko, K. S. Klen and V. Y. Zhuikov, "Influence of Wind Speed Forecasting Error on the Choice of the Number of Balancing System Batteries," Microsystems, Electron. Acoust., vol. 6, no. 3, December 2021. **DOI:** 10.20535/2523-4455.mea.237245

[8] K. S. Klen, M. K. Yaremenko and V. Y. Zhuikov, "The influence of the wind speed prediction error on the size of the storage controlled operation zone in the system with the wind generator," Proceedings of the Institute of Electrodynamics of the National Academy of Sciences of Ukraine, vol. 57, pp. 35-41, 2020. **DOI:** 10.15407/publishing2020.57.035

[9] SmartGauge Electronics, "Peukert's Equation," 2008. [Online]. Available: http://www.smartgauge.co.uk/peukert2.html. [Accessed 31 10 2023].

[10] R. Mouangue, M. Kazet, A. Kuitche and J. M. Ndjaka, "Influence of the Determination Methods of K and C Parameters on the Ability of Weibull Distribution to Suitably Estimate Wind Potential and Electric Energy," International Journal of Renewable Energy Development, vol. 3, no. 2, pp. 145-154, 2014. **DOI:** 10.14710/ijred.3.2.145-154

[11] J. Wang, J. Hu and K. Ma, "Wind speed probability distribution estimation and wind energy assessment," Renewable and Sustainable Energy Reviews, no. 60, pp. 881-899, July 2016. **DOI:** 10.1016/j.rser.2016.01.057

[12] Z. H. Hulio, W. Jiang and S. Rehman, "Technical and economic assessment of wind power potential of Nooriabad, Pakistan," Energ Sustain Soc, vol. 7, no. 35, 2017. **DOI:** 10.1186/s13705-017-0137-9

[13] S.-H. Cha, "Comprehensive Survey on Distance/Similarity Measures between Probability Density Functions," INTERNATIONAL JOURNAL OF MATHEMATICAL MODELS AND METHODS IN APPLIED SCIENCES, vol. 1, no. 4, 2007.
URL: http://www.fisica.edu.uy/~cris/teaching/Cha_pdf_distances_2007.pdf

[14] R. L. Burden and J. D. Faires, Numerical Analysis, 7 ed., Brooks/Cole, 2000. **ISBN:** 978-0-534-38216-2
URL: https://archive.org/details/numericalanalysi0000burd

[15] Asian Development Bank, "Handbook On Battery Energy Storage System," 12 2018. [Online]. Available: https://www.adb.org/sites/default/files/publication/479891/handbook-battery-energy-storage-system.pdf. [Accessed 31 10 2023].

DOI: 10.20535/2523-4455.mea.290932

[16] Ministry of Industry and Trade, General Directorate of Energy, "Final report of wind measurement – GIZ/MoIT Wind Energy Project," 2013. [Online]. Available: http://gizenergy.org.vn/media/app/media/Publications/Windata/Annual Report/Xuan Hoa - Phu Yen/GIZ_Report Xuan Hoa-Year 2013 - EN.pdf.

[17] M. G. de Klerk and W. C. Venter, "Power calculation accuracy as a function of wind data resolution," Journal of Energy in Southern Africa, vol. 28, no. 2, pp. 71-84, 2017. **DOI:** 10.17159/2413-3051/2017/v28i2a1656

[18] C. I. Protogeropoulos, Autonomous wind / solar power systems with battery storage, Cardiff, Wales: University of Wales College, 1992. **URL:** https://www.osti.gov/etdeweb/biblio/557283

[19] A. Dai and C. Deser, "Diurnal and semidiurnal variations in global surface wind and divergence fields," Geophys. Res., vol. 104, no. D24, p. 31109–31125, 1999. **DOI:** 10.1029/1999JD900927

[20] "Specifications of wind turbine VE-2," [Online]. Available: http://altenergo.biz/wp-content/uploads/2016/07/VE-2.pdf.

[21] "Fill gaps using autoregressive modeling - MATLAB fillgaps," [Online]. Available: https://www.mathworks.com/help/signal/ref/fillgaps.html.

[22] M. K. Yaremenko and K. S. Klen, "The Effect of Wind Speed Change on the Payback Period of Batteries," Kyiv, Ukraine, 2022. **DOI:** 10.1109/ELNANO54667.2022.9927066

[23] G. Li, D. Wang, X. Liu and P. Zhao, "Research on wind turbine power performance based on the operation Data," 2019. **DOI:** 10.1051/e3sconf/201913602002

[24] K. A. Abed and A. A. El-Mallah, "Capacity factor of wind turbines," Energy, vol. 22, no. 5, pp. 487-491, 1997. **DOI:** 10.1016/S0360-5442(96)00146-6

[25] M. Milligan, K. Porter, E. DeMeo, P. Denholm, H. Holttinen, B. Kirby, N. Miller, A. Mills, M. O'Malley, M. Schuerger and L. Soder, "Wind Power Myths Debunked," IEEE Power and Energy, vol. 7, no. 6, pp. 89-99, 2009. **DOI:** 10.1109/MPE.2009.934268

[26] C. J. Willmott and K. Matsuura, "Advantages of the mean absolute error (MAE) over the root mean square error (RMSE) in assessing average model performance," Climate Research, vol. 30, no. 1, pp. 79-82, 2005. **DOI:** 10.3354/cr030079

[27] G. Hebrail and A. Berard, "Individual household electric power consumption," UCI Machine Learning Repository, 2012. **DOI:** 10.24432/C58K54

[28] Blue Box Batteries Ltd, "HAZE HZB12-180FA Battery," [Online]. Available: https://www.blueboxbatteries.co.uk/brands/haze/hzb-front-access/hzb12-180fa-battery. [Accessed 31 10 2023].

[29] E. Langford, «Quartiles in Elementary Statistics,» Journal of Statistics Education, vol. 14, no. 3, 2006. **DOI:** 10.1080/10691898.2006.11910589

[30] The MathWorks, Inc., "Percentiles of data set," [Online]. Available: https://www.mathworks.com/help/matlab/ref/prctile.html. [Accessed 31 10 2023].

[31] A. Oudalov, R. Cherkaoui and A. Béguin, "Sizing and Optimal Operation of Battery Energy Storage System for Peak Shaving Application," 2007. **DOI:** 10.1109/PCT.2007.4538388

[32] A. Ashabi, M. M. Peiravi, P. Nikpendar, S. N. Salehi and F. Jaryani, "Optimal Sizing of Battery Energy Storage System in Commercial Buildings Utilizing Techno-economic Analysis," International Journal of Engineering, Transactions B: Applications, vol. 35, no. 08, pp. 1662-1673, 2022. **DOI:** 10.5829/ije.2022.35.08b.22

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Вплив зміни потужності вітру та потужності навантаження на ємність системи балансування

М. К. Яременко[f], 0000-0001-8782-1642
К. С. Клен[s], 0000-0002-6674-8332
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського» 00syn5v21
Київ, Україна

Анотація—**У дослідженні представлено метод врахування впливу потужності вітроустановки та потужності навантаження на розмір накопичувача енергії, який складається з акумуляторів однакової ємності, для балансування енергії в системах розподіленої генерації з вітроустановками. Для врахування впливу розраховується різниця між енергією вітру та навантаження залежно від закону розподілу потужності вітру та навантаження. Було представлено 2 методи розрахунку різниці енергій: метод різниці 1-го порядку та метод різниці 2-го порядку. При використанні методу різниці 1-го порядку використовується різниця між згенерованою енергією вітру та енергією, отриманою навантаженням протягом обраного інтервалу часу. При використанні методу різниці 2-го порядку використовується різниця між теоретичним і фактичним значенням енергії протягом обраного інтервалу часу. Різниця енергії потім використовується для знаходження часу, необхідного для того, щоб навантаження отримало недостатню кількість енергії. При використанні великого інтервалу часу він розбивається на менші інтервали, для кожного з них розрахунок відбувається окремо, формуючи вибірку значень, а остаточне значення вибирається з вибірки виходячи з бажаного довірчого інтервалу. Виконано порівняння 4 методів розрахунку розміру накопичувача енергії, заданого певною кількістю акумуляторів: параметризований та непараметризований метод різниці 1-го порядку з урахуванням та без урахування параметрів відповідно, та метод різниці 2-го порядку, також параметризований і непараметризований, де параметрами є: струм розряду, необхідна тривалість розряду, глибина розряду, ємність акумулятора, коефіцієнт Пейкерта, час розряду при повністю зарядженому акумуляторі, температура навколишнього середовища і похибка прогнозування потужності вітру. У якості прикладу розрахунку було взято та оброблено дані швидкості вітру з провінції Фуєн у В'єтнамі, з яких потім було пораховано потужність вітру, та дані потужності навантаження з приватного домогосподарства у О-де-Сені у Франції, та свинцево-кислотний акумулятор HZB12-180FA. Оскільки дані швидкості вітру мають добові варіації, розмір кожного інтервалу часу було обрано рівним добі. З вибірки даних кількості акумуляторів було обрано значення, що рівне 95% перцентилю. Було показано, що використання параметризованого методу у порівнянні з непараметризованим призводить до збільшення необхідної кількості акумуляторів, що пояснюється уточненням значення необхідної кількості акумуляторів у зв'язку з впливом перерахованих параметрів. А використання методу різниць 2-го порядку у порівнянні з методом різниць 1-го порядку може значно зменшити необхідну кількість акумуляторів при використанні відповідного алгоритму керування системою балансування, навіть якщо метод є параметризованим. Подальші дослідження можуть бути спрямовані на аналіз стану заряду акумуляторів залежно від їх кількості, рентабельність встановлення акумуляторів відповідно до кількості вільної енергії та продаж надлишку енергії у зовнішню мережу.**

Ключові слова — система зберігання енергії; акумулятор; енергоємність; вітер; навантаження; прогнозне балансування енергії