Evaluation of efficiency of wind power plants operation in wind conditions of the Northern Black Sea region of Ukraine

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Abstract. The article presents the results of many years' experience of industrial operation of wind power plants (WPPs) of the Ochakiv Wind Park. In the course of the research a parametric model of WPP performance was developed; factors influencing the performance of wind power plants in Ukraine were analysed; modern methods of economic and mathematical modelling were studied and appropriate ones were selected to assess the efficiency of WPP operation in wind conditions of the Northern Black Sea region of Ukraine; an algorithm for solving the problem of efficient operation of WPPs in Ukraine has been developed; grounding on six years' studies of results of the Ochakiv WPP operation in Ukraine unique databases have been created; a model of correlation between the capacity of wind power plant (WPP) FL 2500-100 and wind speed in the Northern Black Sea region of Ukraine was developed; the obtained results were interpreted and conclusions were made based on the parametric model of WPP performance taking into account the specific external factors of the Northern Black Sea region of Ukraine.

1. Problem statement

The development of alternative energy in Ukraine is one of the Government's priorities. In June 2020, The Cabinet of Ministers of Ukraine (the "CMU") signed "Memorandum of understanding on resolution of problematic issues in renewables sector between the Ukrainian state authorities and Renewable Energy Sources (RES) producers and investors". [1]. The Memorandum states that for all WPP owners the tariff was 7.5% reduced. At the same time, the Ukrainian government undertakes to define and approve annual quotas for green energy support and to provide conducting auctions for distributing these quotas. A month later, on 21st July 2020 The Verkhovna Rada of Ukraine adopted the Law "On amendments to certain laws of Ukraine as to enhanced support for the electricity

production from alternative energy sources" [2]. The law stipulates: reduction of sizes of green tariffs for the wind power plants, which were launched into operation by establishing reduction coefficients; implementation of liability for non-balance of actual and accepted (forecasted) electricity production schedules for all WPP producers.

The above mentioned changes will promote the development of balancing capacity sector and create economic incentives to improve the accuracy of forecasting WPP electricity supply schedules. The law also provides a gradual transition from traditional practice of purchasing electricity at stable (fixed) tariffs to flexible pricing, at which the price is determined by the market based on the ratio of the government's demand and WPP producers' supply. That is, the law fixes the pricing based on the reduction auction where the winner is the producer who proposed the lowest price. The introduced changes determine promptness and urgency of studying evaluation of efficiency of wind power plants operation taking into account specific of the Ukrainian economy and consumer needs and wishes.

2. Analysis of recent studies and publications

Numerous publications devoted to studies in aerodynamics contain fragmentary information regarding the expedience of wind energy development in different countries [3], data on the location of wind power plants in specific areas, technical and operational characteristics of certain WPPs.

Most multi-sided description of the world wind energy status is presented in the work of Carlo L. Bottasso (prof. Technical University of Munich) "Wind energy: status, challenges and perspectives" [4]. It was a joint research with participation of scientists P. Bortolotti, S. Cacciola, F. Campagnolo, A. Croce, V. Petrovic, C.E.D. Riboldi, J. Schreiber, J. Wang, the results of which were discussed at the conference HIT Summer School of Energy 2017. However, there is a lack of a comprehensive analysis of efficiency of wind power plants operation in particular areas, taking into account the specific databases and peculiarities of the impact of various environmental factors. Consequently, there appeared a necessity in conducting an inter-branch study.

3. Goals setting

The aim of the article is to present the results of many years' study of industrial operation of wind power plants under the direct guidance of the Director of the Ochakiv Wind Park Volodymyr Podhurenko and develop parametric model of WPP performance taking into account the external factors of the Northern Black Sea region of Ukraine.

The theoretical and methodological background of the research has been formed based on the modern provisions of aerodynamics and simulation modelling, where a special attention is drawn to the analysis of data on industrial operation of two WPP fields of the Ochakiv Wind Park in Ukraine (WPU). During the research general and special scientific methods were used, in particular: statistical analysis - to form a database of a wind power plant operation efficiency for a six-year period; mathematical modelling - to estimate the actual performance of wind power plant FL 2500-100 in the Northern Black Sea region of Ukraine; analysis and synthesis – to create an algorithm for solving the problem of efficient operation of WPPs in Ukraine; induction and deduction - to interpret the conclusions of the study.

4. Findings and discussion

A wind energy flow of any region is characterized by instability over time that causes WPP performance hypersensitivity to the place of its location. Only 10% of violations in calculations make up 30% of violations in production [5]. Therefore, quite a lot of publications are devoted to evaluation of technical indicators of efficient wind power plants operation to supply electricity to both autonomous [6] and electric power grid consumers, especially for the Northern Black Sea region characterized by high potential and most favourable conditions for wind power operation in Ukraine [7].

The study was arranged in seven stages: 1) development of parametric model of WPP performance; 2) analysis of wind power plant performance; 3) study of modern methods of economic and

mathematical modelling and selection of the most appropriate ones for the problem solution; 4) development of algorithm for solving problems of effective WPP performance in Ukraine; 5) summarization of data on WPPs of the Ochakiv Wind Park and the database formation; 6) creation of the model of correlation between the performance of WPP FL 2500-100 and wind speed in the Northern Black Sea region of Ukraine; 7) interpretation of results and formulation of conclusions.

Modern high-power WPPs are complex automated electromechanical systems for converting kinetic energy of moving air masses into electricity with a given specifications, where a significant number of parameters is permanently changing [8]. This system with non-linear properties is schematically presented in Fig. 1.
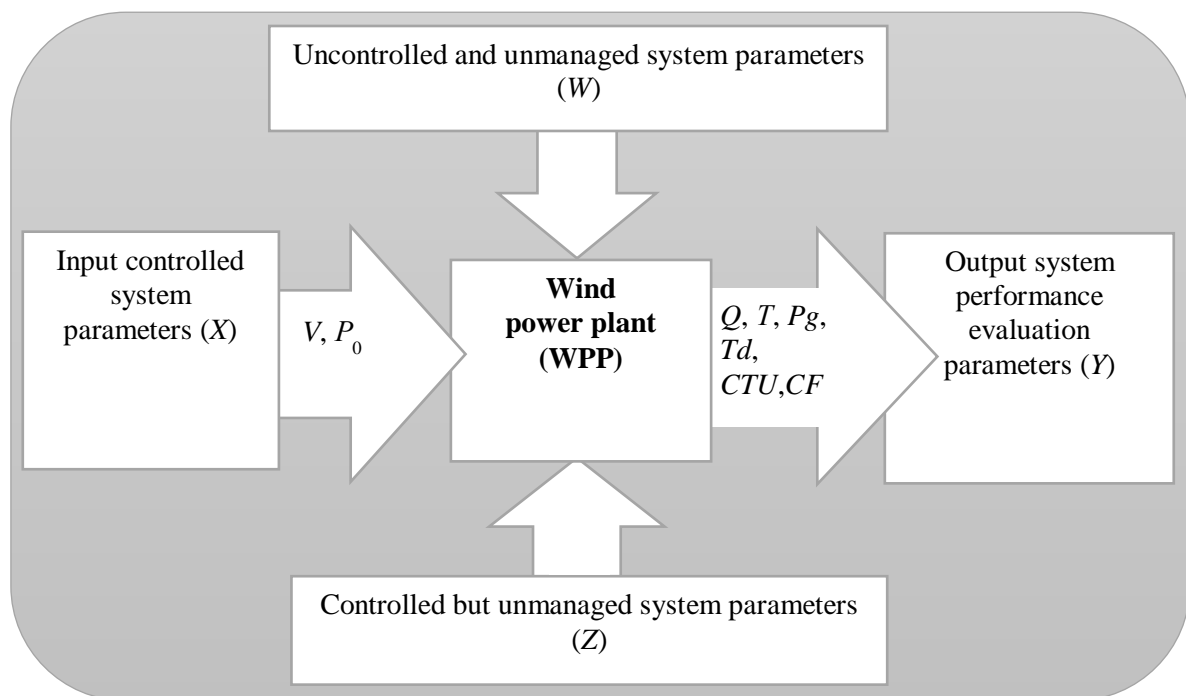
where: V - current wind speed; P_0 – power of generation limiting (with probable imposed restrictions); Q - electricity generation quantity; T - working time for a certain period; Pg - power generation; Td - downtime for various reasons; CTU - coefficient of technical use; CF – capacity factor

Fig. 1. Parametric model of wind power plant (WPP) performance

Output system performance evaluation parameters (Y) being scalars, characterize and quantitatively evaluate the WPP performance efficiency. The group of controlled but unmanaged system parameters (Z) includes the properties of wind power plants, the direct intentional change of which is difficult or impossible. For example, the angle of attack of a wind turbine blade (β), which varies depending on wind speed and effects on changes in power generation capacity. Uncontrolled and unmanaged system parameters (W) include all sorts of effects, which are random and cannot be defined.

This parametric model describes simplified mapping of a complex WPP system in time, where the input (X) and output (Y) parameters are determined and characterized by a probable distribution. Thus, the proposed model is dynamic, deterministic and stochastic. The efficiency of WPP operation in the given wind conditions, is mainly evaluated by the following three criteria: annual electricity generation quantity, capacity utilization factor and cost of electricity produced [9]. In this article the authors focus on the first two criteria. As a generalized technical and economic indicator has been introduced the nominal capacity factor (CF), which allows evaluating the efficiency of WPP operation. Its numerical value characterizes the integrated technical efficiency of WPP operation and

allows to do comparative analysis of technical excellence of different WPPs in specific wind conditions.

Based on a thorough analysis of available scientific works in aerodynamics, which consider the factors influencing the efficiency of WPP operation in Ukraine [10, 11] and the current status of studies related to scientific and applied problems of mathematical and computer modelling of high power WPPs, an algorithm for solving problems of efficient operation of wind power plants in Ukraine has been proposed (Fig. 2).
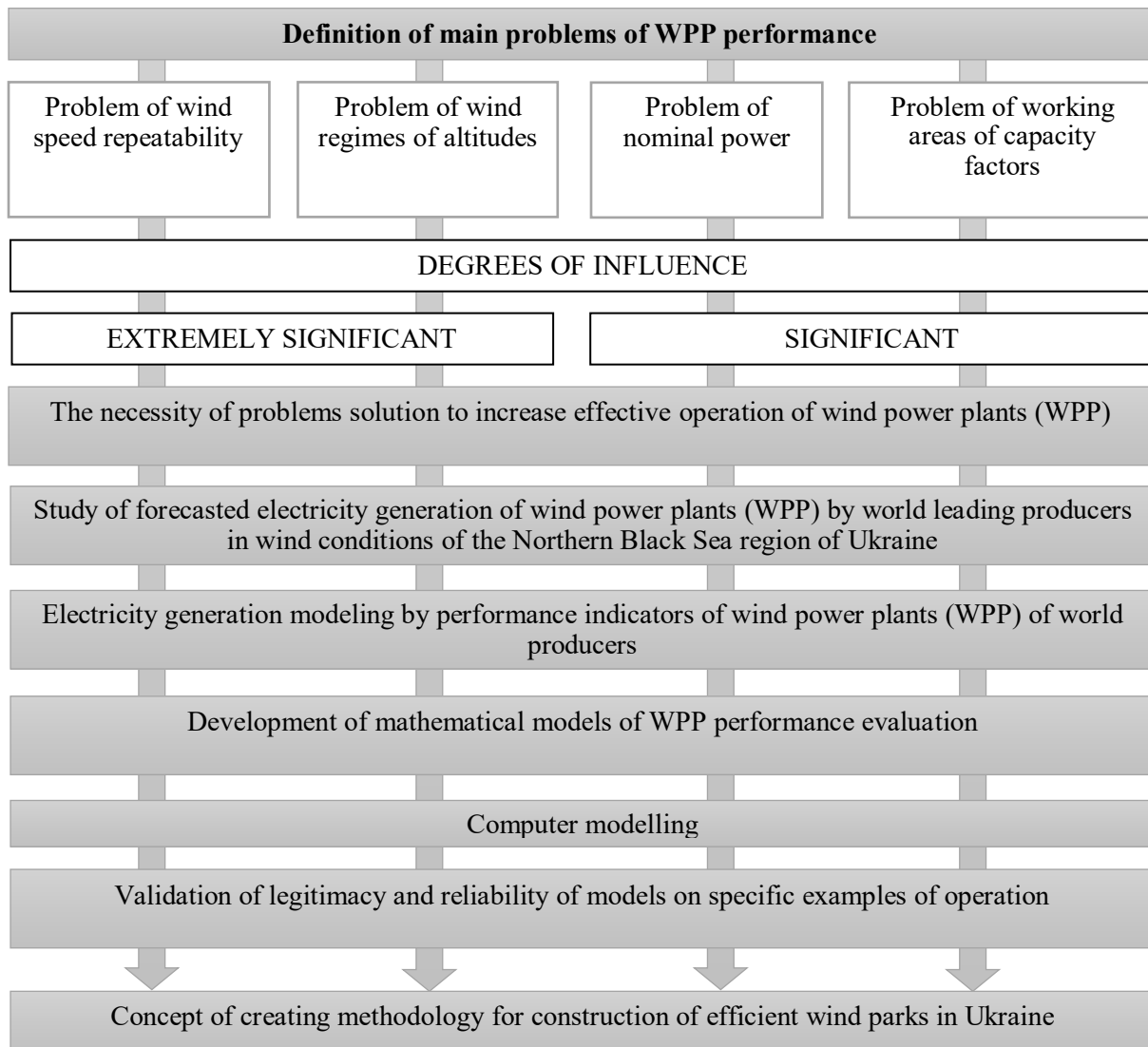
Definition of main problems of WPP performance

Problem of wind speed repeatability	Problem of wind regimes of altitudes	Problem of nominal power	Problem of working areas of capacity factors

DEGREES OF INFLUENCE

EXTREMELY SIGNIFICANT	SIGNIFICANT

The necessity of problems solution to increase effective operation of wind power plants (WPP)

Study of forecasted electricity generation of wind power plants (WPP) by world leading producers in wind conditions of the Northern Black Sea region of Ukraine

Electricity generation modeling by performance indicators of wind power plants (WPP) of world producers

Development of mathematical models of WPP performance evaluation

Computer modelling

Validation of legitimacy and reliability of models on specific examples of operation

Concept of creating methodology for construction of efficient wind parks in Ukraine

Fig. 2. Algorithm for solving the problem of efficient operation of WPPs in Ukraine

The study of problems of efficient operation of WPPs in Ukraine took place on the bases of two fields of the Ochakiv Wind Park located in Mykolaiv region of Ukraine. The effectiveness of six-year industrial operation of WPPs in the Northern Black Sea region allowed proving the efficiency and profitability of wind power plants operation in this area. Many years' sustainable year-round efficient operation of the Ochakiv Wind Park confirms feasibility of industrial construction of WPPs in Ukraine taking into account specific wind conditions in this definite region.

The purpose of this study is establishing actual values of WPP efficient operation indicators, determining correlations and receiving quantitative indicators in terms of the impact of various factors

to determine optimal operating parameters of industrial WPPs. The object of the study is wind power plant FL 2500-100 having the following main parameters: turn-on speed ($V_{turn-on}$) - 3.5 m / s; nominal speed (V_{nom}) - 11.5 m / s; turn-off speed ($V_{turn-off}$) - 25 m / s; rotor diameter - 100 m; rotor coverage area - 7854 m^2; number of blades - 3; rotor rotation frequency - 9.4…16.5 min^{-1}; generator type - asynchronous dual power supply with a phase rotor; nominal generator capacity - 2500 kW; generator rotation frequency - 750…1316 min^{-1}; reducer type - three-stage, planetary-gear; nominal reducer capacity - 2671 kW; gear ratio - 1: 79.2; total weight (blades, hubs, rotor, gondola, tower) ~ 490 tons.

The databases have been formed grounding on the actual daily and monthly indicators recorded by automated commercial electricity metering system (ASKOE) and supervisory control and data acquisition system (SCADA). The proposed model is based on capacity characteristics of WPP FL 2500-100 (Fig. 3).
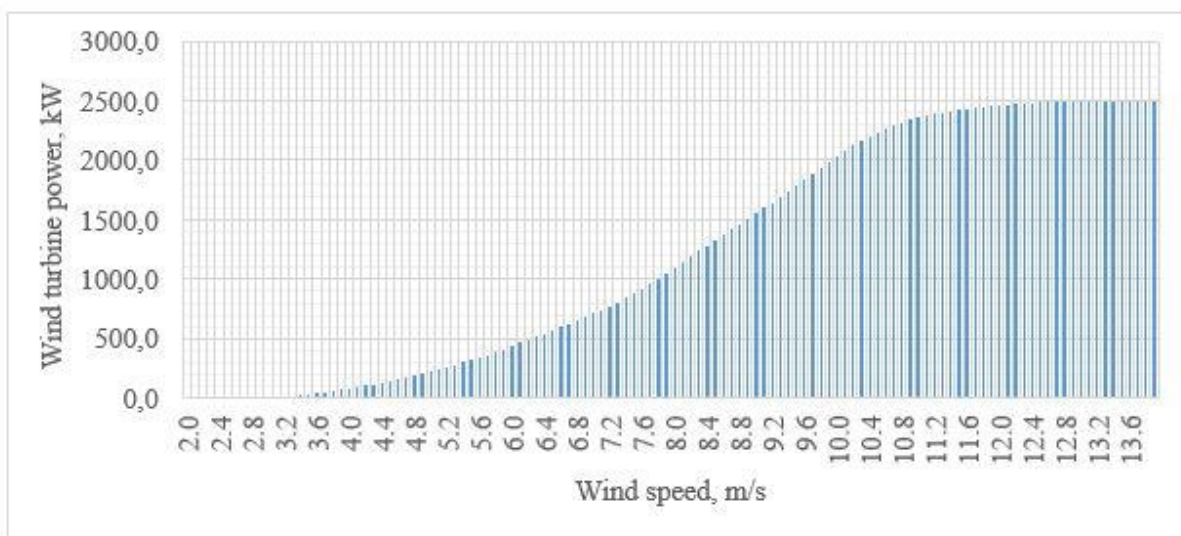

Fig. 3. Capacity characteristics of WPP FL 2500-100

Modelling of capacity characteristic of a wind power plant $P(V)$ can be generally parameterized as a polynomial in k degree by V: $P(V) = a_0 + a_1 V + a_2 V^2 + ... + a_k V^k$, ($k \geq 3$). The latter condition is based on the hypothesis that the average wind power should be proportional to V^2. The real wind power plant is characterized by the threshold value of wind speed $V_0 = V_{on}$, starting from which it generates electricity, and the nominal value of wind speed $V_N = V_{nom}$, when a wind power plant reaches a constant nominal power P_N. (Fig. 4).

Capacity characteristic of a wind power plant has been modelled by grade-5 polynomial for the current wind speed ($R^2 = 0,993$) [12]:

$$P(V) = (-2293,14098 + 1902,83735 \cdot V - 600,37994 \cdot V^2 + 89,10042 \cdot V^3 -$$

$$- 5,65921 \cdot V^4 + 0,12780 \cdot V^5) \cdot \theta(V - V_0) \cdot \theta(V_N - V) + 2500 \cdot \theta(V - V_N). \quad (1)$$

where the stepwise theta functions of Heaviside were used: $\theta(x) = \begin{cases} 1, & 0 \leq x; \\ 0, & x < 0. \end{cases}$

and x – a whole number.

The calculation of annual quantity of electricity generated by WPP FL 2500-100 in the wind conditions of the Northern Black Sea region according to the proposed capacity characteristic model fixed electricity generation quantity $Q = 8925$ MWh with capacity utilization factor 40.8%.
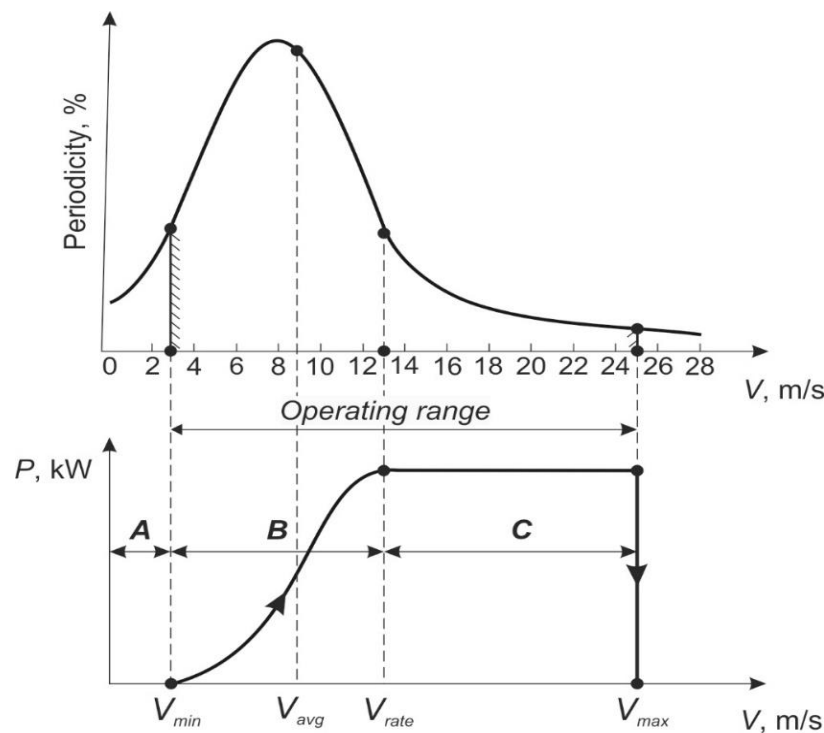
Fig. 4. Typical areas of wind cascade and capacity characteristic of a wind power plant

The obtained results proved the efficient operation of WPPs in the wind conditions of the Northern Black Sea region of Ukraine. The obtained modelled values of electricity generation quantity and capacity utilization factor show the maximum potential effectiveness. However, if real actual values are significantly lower, the proposed model has to be completed with additional analysis for revelation of the causes.

5. Conclusions

Modelling of correlation between the performance of wind power plant (WPP) FL 2500-100 and wind speed in the Northern Black Sea region of Ukraine allowed to confirm the hypothesis of efficient WPP performance in the region's wind conditions. Capacity characteristic of a wind power plant has been modelled by grade-5 polynomial for the current wind speed ($R^2 = 0.993$), which allowed to calculate the annual performance of a wind power plant.

The prospect of further studies is creation of a comprehensive WPP profitability assessment methodology, which will be specially developed for the Northern Black Sea region of Ukraine and will take into account maximum number of controlled and uncontrolled environmental factors. As well, using actual data on industrial operation of the Ochakiv Wind Park, the authors intend to expand this research in terms of revealing factors of impact on WPP operation efficiency and create the updated comprehensive methodology.

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