Igor Razzhivin[1], Aleksey Suvorov[1], Mikhail Andreev[1], Alisher Askarov[1]

National Research Tomsk Polytechnic University, Russia (1)

doi:10.15199/48.2021.03.11

Development of Automatic Pitch Angle Control Mathematical Model for Type-4 Wind Turbines Specialized Hybrid Processor

Abstract. *The goal of this paper is to synthesize the intelligent pitch angle control system under variable wind conditions for the specialized processor that reproduces the operating modes of type-4 wind turbines in real time in the specialized software-hardware hybrid simulation tool. The control schemes using main strategies of a conventional control and an intelligent control with a fuzzy logic have been discussed. The strategy based on a combined pitch control system was adopted. As a result, the authors designed and implemented a comprehensive mathematical model for pitch angle control of wind turbines. The RTDS hardware-software tool was used as a reference for model validation. The results showed a fairly good similarity, therefore, the developed model can be applied to control the pitch angle in a hybrid model of type-4 wind turbines for wind power plants simulating in the large-scale electric power system.*

Streszczenie. *Przedstawiono system sterowania kątą turbiny wiatrowej w czasie rzeczywistym. Do sterowania wykorzystano elementy logiki rozmytej. Wykorzystano oprogramowanie i sprzęt. Przeprowadzono symulacje dla różnych prędkości turbiny wiatrowej, (**System sterowania kątem w turbinie wiatrowej typu-4 z wykorzystanie specjalizowanego procesora hybrydowego**)*

Keyword: wind turbine, pitch angle control, hybrid simulation.
Słowa kluczowe: turbina wiatrowa, sterowanie kąta, procesor hybrydowy.

Introduction

The use of renewable energy sources (RES) helps to cover the increasing electricity consumption in many developed countries. Among the different types of RESs, the largest pace of integration relates to wind power generation. The wind energy is considered one of the very fast growing and most competitive green energy being applied worldwide, especially in Europe, USA, Canada, Middle East, and Africa [1]. The main difficulty in wind energy using is the inconstancy of its speed and, therefore, its power generation in time. The wind has not only a long-term and seasonal variability, but also changes its activity during the day (instantaneous speed pulsations and wind gusts). As level of wind energy integration into modern electric power systems (EPS) increases, the impact of wind turbine installations (WT) on frequency and voltage stability becomes more and more significant [2, 3].

Over the past decade, the variable speed WTs (type 3 and 4) have become the most common installed units. The type 3 and 4 wind turbines make it possible to achieve the optimal output power in a wide range of wind speed by the rotational speed regulation in response to changes in the input wind speed. Moreover, a back-to-back voltage source converter (BTB VSC) usage in their topology allows reducing the coupling of the EPS and generator frequencies. The type-4 WTs with a permanent magnet synchronous generators (PMSG), which are connected to the grid via a BTB VSC, are the most perspective ones due to their advantages such as: (1) a higher efficiency, (2) a good power capability and a low maintenance due to less mechanical components and etc. [4, 5]. To extract the maximum efficiency, more optimal adaptive and automatic control systems (ACS) for WTs are being developed, which provide the continuous control in various wind conditions and are able to adapt to changes in the state of the object and input disturbances. Obviously, an ACS of BTB VSC is the main one in the type-4 WTs, but it cannot provide the full control of WT in highly changing wind conditions. Therefore, a modern ACS of WT require the necessary installation of the pitch angle control system [6]. The pitch angle control system in type-4 WT makes it possible to ensure its normal operation at a wind speed above the rated value (for a particular WT), and to protect the blades from damage during squally wind by their stopping [7]. The tuning of the pitch angle control system has a several different approaches.

Review of existing control systems

The pitch angle control system provides the change of blade' angle of attack (β) in accordance with wind speed (V_W) [8]. When the wind speed changes, the pitch angle control system enables smoothly starting and emergency stopping of the wind wheel, which, in turn, allows the WT to operate with a power close to the rated value at different wind speed. The regulation can be divided into three main modes [9].

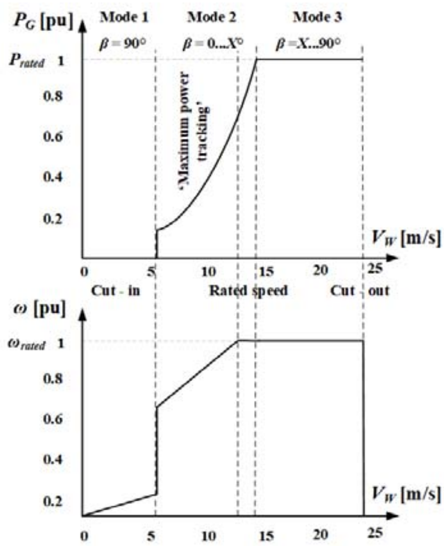


Fig. 1. The operation modes of WT: X is the limit value of β for Mode 2

Mode 1: The mode includes the range from WT standstill to startup. The control strategy consists of wind speed tracking: it is determined initial wind speed to WT startup. After that, the pitch angle control system begins the execution of operations required to WT startup.

Mode 2: In this mode, the power optimization mode is carried out, consisting of the maximum power generation. The power optimization can only be done by finding the pitch angle that corresponds to the optimal power coefficient $C_P(\beta,V_W)$ at a given wind speed. In the mode 2 there are two principles of WT operation can be used: rotating the nacelle in the horizontal plane (yaw regulation) and changing the rotating generator torque (maximum power point tracking). The goal in this mode is to extract the maximum wind energy utilization rate.

Mode 3: This mode relates to the range of wind speed values more than rated. The pitch angle control system should limit a wind energy utilization rate to prevent overshooting the electrical and mechanical loads of the generator. In this mode, the type-4 WT maintains a constant value of rotor speed and rated power via changing the pitch angle.

The limits of the pitch angle values are set according to particular WT standard values or according to the power characteristics of WT – the power curves which dependence on the tip speed ratio (Z) and β: the control system sends a signal to the pitch servo, the regulation takes place according to the given control laws. The value of β can be configured as a reference signal depending on the input parameters, which may be as follows (Fig. 2):

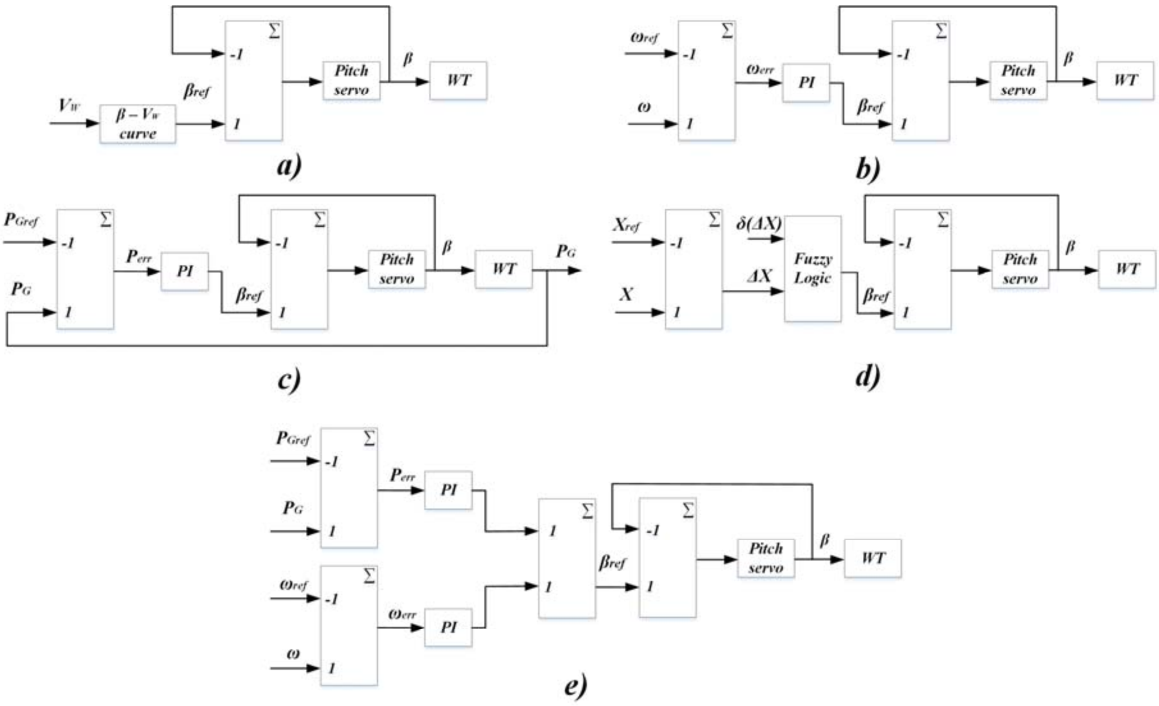


Fig. 2. The different variants of the pitch angle control systems implementation

1) Wind speed V_W, as shown in Fig. 2a. Theoretically, the reference value of pitch angle (β_{ref}) can be obtained from the curve $\beta(V_W)$. This control strategy is simple, as the wind speed is directly measured, and regulates the generator output power at its rated value. However, this approach has a significant limitation since anemometers are installed on the nacelle behind the blades, therefore, it is not possible to measure wind speed correctly [10].

2) Rotor speed ω, as shown in Fig. 2b. The measured rotor speed is compared with its reference. Then the error signal is sent to a PI controller and provides a value of β_{ref}. The rotor speed control is used in pitch angle controller to enhance the transient stability [11].

3) Generator power P_G, as shown in Fig. 2c. The error signal of the generator power is sent to a PI controller. The PI controller provides a β_{ref}. The non-linear variation of the pitch angle in case of high wind speed implies the necessity of a non-linear control. This approach has a limitation related to a high sensitivity of aerodynamic torque to wind speed close to the rated and with high turbulence component. Such control system regulates the generator output power at its rated value, as in the first control strategy [12].

4) Fuzzy logic based controllers. The rule-based fuzzy logic controllers are useful when the system dynamic is not well known or when system contains significant non-linearities, such as wind speed with a stochastic nature and a turbulence component. Fuzzy logic controllers are shown in Fig. 2d. Moreover, the fuzzy logic block can be applied to all of the above examples, and the input signal can be wind speed, rotor speed or generator power [13].

5) The combined control systems (Fig. 2e) in which the generator power and rotor speed is compared with their references. Such systems have designed to maintain the generator output power at its rated value in case of wind speed more than rated and to ensure the transient stability during the network faults [14, 15].

As seen from the above, the considered approaches to the pitch angle control are aimed at generator power regulation and high power efficiency ensuring taking into account a stochastic nature of wind speed. In addition, the pitch angle controller is also used to stabilize the operation of WT in case of transient faults. The comparison of different strategies via simulation in [16] showed that the pitch angle control strategy with generator power as a controlling variable has a rapid pitch angle respond to the wind speed variation and minimum power oscillations. The response of the control strategy with rotor speed has a squared error to β changing. The ACSs based on the fuzzy logic control have relatively complex algorithms and require certain competencies in their implementation [17].

Therefore, in this paper, a combined control strategy (Fig. 2e) was adopted. In [10-17], various control algorithms were tested in small test EPS models. However, it is recommended to test the algorithms in large-scale EPS models for a correct decision on the use of one or another algorithm and a comprehensive assessment of the implemented system' operation under various conditions. The known specificity and complexity of the modern EPS exclude the possibility of receiving all necessary information, in particular during the disturbances, via physical modeling, so a mathematical modeling is the main method for testing algorithms in large-scale EPS [18, 19].

Implementation of ACS for specialized processor of type-4 WT

The accuracy and efficiency of EPS mathematical modeling are determined by the following main factors: the completeness and detailing of applied mathematical models in simulation tools, which perform the solution of a mathematical model of the considered EPS with the guaranteed and acceptable accuracy.

For a reliable analysis of the control and regulation systems of WT, comprehensive models of each element and a large-scale EPS model as a whole are required because the mutual impact of individual elements or their small groups on the EPS' states can be lost in small test and very limited EPS schemes. However, the existing simulation tools do not fully allow this resulting in a discrepancy between the modeling data and the real ones [20]. Therefore, the authors propose to use their own development a specialized software-hardware hybrid simulation tool – Hybrid Real-Time Power System Simulator (HRTSim) [21]. The HRTSim is a real-time multiprocessor system consisting of a set of specialized processors (SPs), which simulate all main equipment of the simulated EPS. The hybrid approach assumes continuous and mutual simulating on digital, analog, and physical levels. Thus, the HRTSim is proposed to be used as an effective tool for solving the mentioned problem. This article describes the implementation of a pitch angle control system. Further, this system is applied in the hybrid SP of type-4 WT model (SP WT). The main principles of design and implementation of a hybrid SP described in [22] on the example of HVDC link, a similar approach has been used for the creation of SP WT.

The implementation of the WT mathematical model and its control system was performed in the digital level of the SP WT on ARM-based AT91SAM7X256 microcontroller. The assembler language was used for programming that allowed to speed up the simulation process. The developed system of the pitch angle control for HRTSim is shown in Fig. 3.

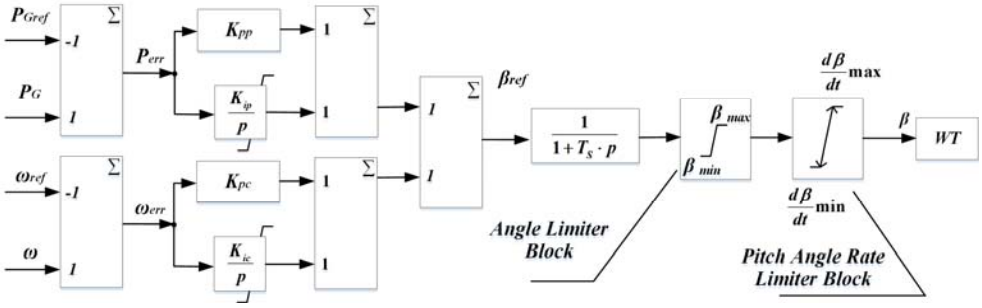


Fig. 3. The model of pitch angle control system for HRTSim: K_{PP} and K_{PC} are proportional gains of PI-controller, K_{IP} and K_{IC} are integral gains of PI-controller, P_{Gref} and ω_{ref} are rated power and rated shaft speed of WT respectively, ω is the current shaft speed of WT, T_S is a servo motor time constant

The Angle Limiter block limits the minimum and maximum value of pitch angle and the Pitch Angle Rate Limiter block limits the rate of change of pitch angle. The maximum rate of change of pitch angle is usually in the range from 2 to 10 degrees per second.

Realization and test studies of the implemented ACS

Testing of the developed ACS model for SP WT has been carried out by the comparison with the simulation results in RTDS. The experimental studies have been carried out on a model of WKA-60 wind turbine [23]. Figure 4 shows the resulting pitch angle control system tests with a step change in wind speed.

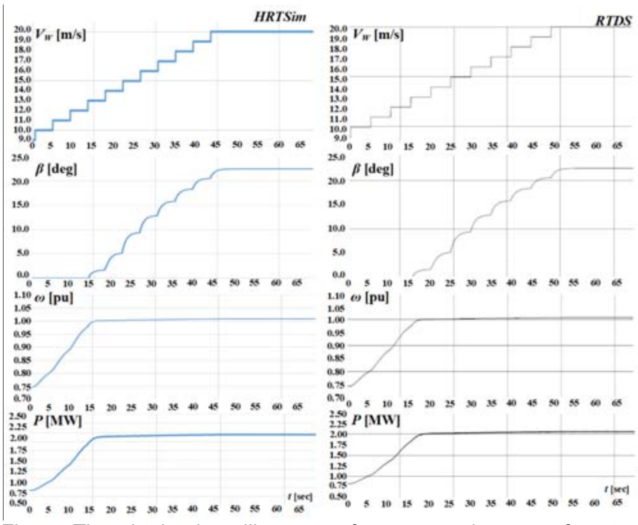


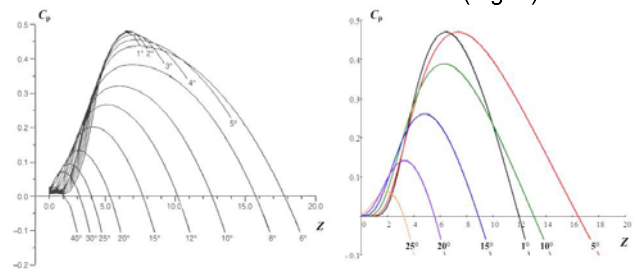
Fig. 4. The obtained oscillograms of processes in case of a step change in wind speed

As seen in Fig. 4, the oscillograms of the developed model are identical to the RTDS oscillograms, the maximum relative error is less than 1% throughout the process. With a step-up increase of the wind speed above 10.5 m/s, the pitch angle begins to change. In addition, the results of power generation and rotational speed stabilization above the rated wind speed are also shown, which indicate the correct operation of the model.

The characteristic curves $C_P(Z,\beta)$ of the modeled WT was approximated by the least squares method [9]:

$$C_P(Z,\beta) = C_1\left(C_2 - C_3\beta - C_4\beta^2 - C_5\right)e^{-C_6(Z,\beta)} \quad (1)$$

The WT characteristics $C_P(Z,\beta)$ have been also implemented in the microcontroller, the approximation of which showed a high degree of the coincidence with the standard characteristics of the WKA-60 WT (Fig. 5).



a) b)

Fig. 5. $C_P(Z,\beta)$ characteristics of WKA-60 WT obtained (a) from direct measurement and (b) via simulation

The oscillograms shown in Fig. 5 coincide quite well for the modeled WT, the maximum efficiency is achieved at a pitch angle from 1 to 5 degrees and the optimal tip speed ratio is approximately equal from 6 to 10.

Figure 6 shows the oscillograms of the pitch angle depending on the wind speed in case of a dynamic wind model implementation in HRTSim.

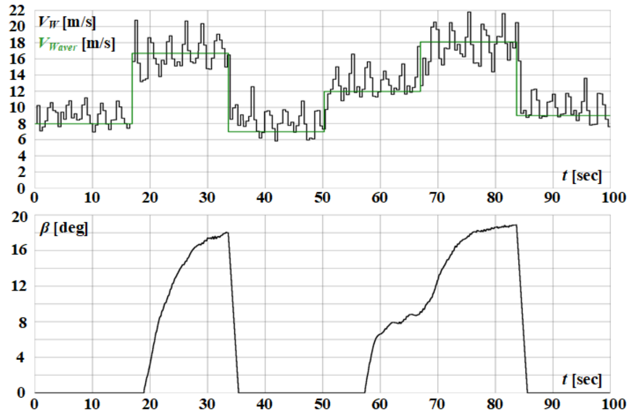


Fig. 6. The pitch angle changing in case of a dynamic wind model: V_{Waver} is an average value of wind speed

The oscillogram of pitch angle changing with a dynamic change in the wind speed reflects the efficiency of the pitch angle control system, when V_{Waver} changes from 8 to 16 m/s (above rated value), the pitch angle control system starts to operate, after that, when V_{Waver} decreasing, the β returns to the initial value. It is also seen from the oscillogram that the dynamic component of the wind does not affect the pitch angle control system, which corresponds to the real operating conditions of the WT, when, due to the inertia of WT, the short-term (turbulent) wind gusts do not affect the transients.

Conclusion

The paper considered the main strategies for controlling the pitch angle of a WT with a variable rotational speed. The authors have developed and programmed a digital model of the pitch angle control system intended for a hybrid model of the type-4 WT used in HRTSim. Test results have shown a high degree of coincidence with similar tests, which carried out via RTDS. The model of the pitch angle control system in SP WT makes it possible to receive a more accurate response of WT as a whole in transient states and in case of sudden wind loading changes. In the same way, any required control systems (relay protection, automation, control system of BTB VSC) can be implemented in microcontroller of SP WT.

Acknowledgment

The work was supported by Ministry of Science and Higher Education of Russian Federation under the governmental grant “Science” № FSWW-2020-0017.

Authors*: senior lecturer of Division for Power and Electrical Engineering, Igor Razzhivin, Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, Russia, E-mail: lionrash@tpu.ru; senior lecturer of Division for Power and Electrical Engineering, Aleksey Suvorov, Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, Russia, E-mail: suvorovaa@tpu.ru; associate professor of Division for Power and Electrical Engineering, Mikhail Andreev, Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, Russia, E-mail: andreevmv@tpu.ru; PhD student of Division for Power and Electrical Engineering, Alisher Askarov, Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, Russia, E-mail: aba7@tpu.ru.*

REFERENCES

[1] Renewables 2020 Global Status Report GSR // Access mode: https://www.ren21.net/reports/global-status-report/.
[2] V. Akhmatov, “Analysis of dynamic behavior of electric power systems with large amount of wind power,” Ph.D. dissertation, Dept. Elect. Eng., Tech. Univ. Denmark, Kgs. Lyngby, Denmark, Apr. 2003.
[3] Y. Zhang, Z. Chen, W. Hu, and M. Cheng, “Flicker mitigation by individual pitch control of variable speed wind turbines with DFIG,” IEEE Trans. Energy Convers., vol. 29, no. 1, pp. 20–28, Mar. 2014.
[4] Ackermann, T. Wind Power in Power Systems, John Wiley & Sons, Ltd, Chichester, 2012, p. 1088
[5] Renewable Energy Sources: Theoretical Basisyou, technology, technical characteristics, economy / ed. Stychinsky, N.I. Voropai. Magdeburg: MAFO, 2010 p. 223.
[6] IEC 61400-27-1:2015 Wind turbines - Part 27-1: Electrical simulation models - Wind turbines
[7] Dong-Choon Lee, Tan Luong Van, and Thanh Hai Nguyen, “Advanced Pitch Angle Control Based on Fuzzy Logic for Variable-Speed Wind Turbine Systems,” IEEE Trans.,Energy Conversion, № 30, no. 2, p. 578–587, June 2015
[8] J. F. Manwell, J. McGowan, A. Rogers. ‘Wind energy explained: theory design and applications’. John Wiley & Sons; 2002 p. 705.
[9] Siegfried Heier, Wind energy conversion systems, book, John Wiley & Sons Inc., New York, 1998.
[10] Munteanu, I., Bratcu, A.I., Cutululis, N.-A., Ceanga, E. Optimal control of wind energy systems – Towards a global approach. – Springer: Verlag London, 2007. p. 286.
[11] Michalke G, Hansen AD, Hartkopf T. Control strategy of a variable speed wind turbine with multipole permanent magnet synchronous generator. Proceedings of the European Wind Energy Conference EWEC, Milan, Italy, 7–10 May 2007
[12] R. Sakamoto et al., "Output power leveling of wind turbine generator for all operating regions by pitch angle control," IEEE Power Engineering Society General Meeting, 2005, San Francisco, CA, 2005, pp. 45-52 Vol. 1, doi: 10.1109/PES.2005.1489543.)
[13] Benguergour I., Allaoui T., Kouadria A. M., Denai M., Optimization and Adaptive Control of Wind water Pumping System based on fuzzy RST and genetic RST, *Przegląd Elektrotechniczny*, Vol. 96, No. 2, 2020, pp. 193-199.
[14] Anderson P.M., Bose A., Stability simulation of wind turbine systems, IEEE Trans. Power Appar. Syst., 1983, PAS-102, (12), pp. 3791–3795.
[15] Gajewski P., Pieńkowski K., Direct torque control and direct power control of wind turbine system with PMSG, Przegląd Elektrotechniczny, R. 92, no.10, 2016, pp 249-253
[16] Different Conventional Strategies of Pitch Angle Control for Variable Speed Wind Turbines 15th international conference on Sciences and Techniques of Automatic control & computer engineering - STA'2014, Hammamet, Tunisia, December 21-23, 2014
[17] Hagras H., Wagner C. (2012) Towards the wide spread use of type-2 fuzzy logic systems in real world applications. IEEE Computational Intelligence Magazine 7: 14–24
[18] B. A. Carreras, D. E. Newman, I. Dobson. Does size matter? Chaos, vol. 24 (2), 2014, Art. ID 023104
[19] Suvorov, A., Gusev, A., Ruban, N., Andreev, M., Askarov, A., & Stavitsky, S. (2019). The Hybrid Real-Time Dispatcher Training Simulator: Basic Approach, Software-Hardware Structure and Case Study, *International Journal of Emerging Electric Power Systems*, *20*(1), 20180165. doi: https://doi.org/10.1515/ijeeps-2018-0165
[20] Suvorov, A., Gusev, A., Andreev, M. et al. The novel approach for electric power system simulation tools validation. Electr Eng 101, 457–466 (2019). https://doi.org/10.1007/s00202-019-00795-9.
[21] Suvorov, A., Gusev, A., Ruban, N., Andreev, M., Askarov, A., Ufa, R., Razzhivin, I., Kievets, A., & Bay, J. (2019). Potential Application of HRTSim for Comprehensive Simulation of Large-Scale Power Systems with Distributed Generation, *International Journal of Emerging Electric Power Systems*, *20*(5), 20190075. doi: https://doi.org/10.1515/ijeeps-2019-0075
[22] Ufa, R., Andreev, M., Ruban, N. et al. The hybrid model of VSC HVDC. Electr Eng 101, 11–18 (2019). https://doi.org/10.1007/s00202-018-00752-y
[23] IEA Wind Energy Annual Report 1992 // Access mode: https://community.ieawind.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=c87f90ec-b818-0e7c-ad9d-b48bcb0f624a&forceDialog=0