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# Wind Power Industry-informational Modelling of Cooperation with Energy System

This paper presents current status and perspectives of use of wind energy in the countries of Europe and the World. The problems connected with modelling and simulation of wind power plant operation and their cooperation with energy systems have been highlighted. The paper contains many statistical data which enabled to assess the opportunities of pure energy production.

Описаны современное состояние и перспективы использования энергии ветра в странах Европы и в мире. Рассмотрены проблемы, связанные с моделированием работы станций, использующих энергию ветра, и их взаимодействие с энергетическими системами. Приведены статистические данные, позволяющие оценить возможности производства экологически чистой энергии.

*K e y   w o r d s: energy, wind, statistics, modelling, energy system.*

**Resources and energy production.** Rapid increase in energy consumption was caused by: technology revolution determined by e. g. invention of steam engine, discovery of electricity, development of automotive industry, development of industry and significant drop in population worldwide. It is estimated that our civilization has used energy corresponding to 500 billion toe while 2/3 has been used in last century. Participation of individual primary energy commodities in general consumption and the forecast of its consumption worldwide is presented in Fig. 1 [1]

Unlike the non-renewable sources of energy such as coal, oil, gas or uranium, whose natural systematic resources shrink dramatically, renewable sources of energy will not change as long as the Solar System exists.

Growing awareness of threats to natural environment from conventional energy industry causes that more and more attention is paid to technologies of production based on renevable and unconventional resources. Potential of these sources is not high, its dissipation is significant and frequently only of local importance and the costs of use are still high and they need active support. Division of primary sources of energy, their natural and technically possible transitions and the form of use is presented in Table 1 [2].

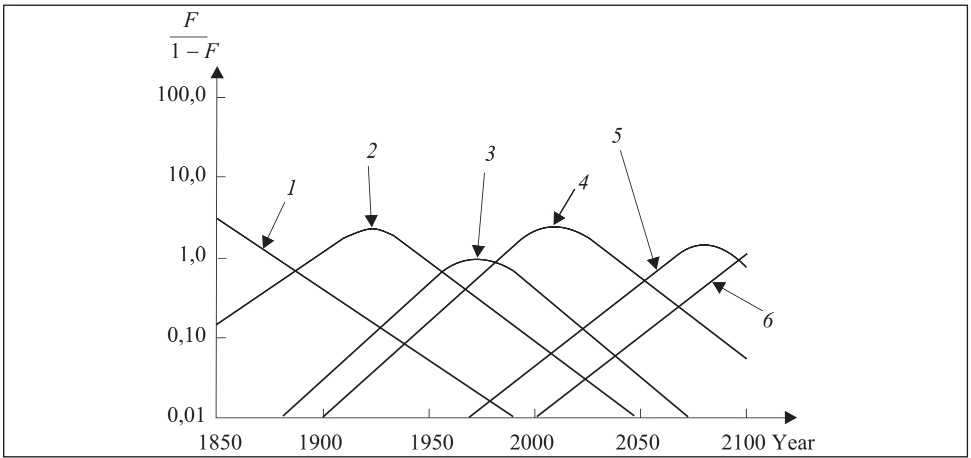


*Fig. 1.* Present state and the forecast for primary energy consumption: *1* — wood; *2* — coal; *3* — oil; *4* — natural gas; *5* — nuclear energy; *6* — solar energy; *F* — participation in energy consumption

*Table 1.* **Division of renewable sources of energy**

| Primary sources of energy | | Natural processes of energy conversion | Technology processes of energy conversion | Form of obtained energy |
|---|---|---|---|---|
| Sun | Water | Evaporation, ice | Water plants | Electricity |
| | Wind | Atomspheric | Water power plants | Heat and electricity |
| | | Wave energy | Wave energy power | Electricity |
| | | Oceanic currents | Ocean energy power | " |
| | Solar radiation | Heating the surface of the Earth and its atmosphere | Ocean heat power plants | " |
| | | | Heat exchanger | Heat energy |
| | | | Solar heat power plants and solar power plants | " " |
| | | Solar radii | Photovoltaic cells and solar power plants | Electricity |
| | | | Photolisis | Fuels |
| | Biomass | Biomass production | Heating and heat power plants | Heat energy and electricity |
| | | | Processing equipment | Fuels |
| Earth | Isotope radioactive decay | Geothermal resources | Heating and geothermal power plants | Heat energy and electricity |
| Moon | Gravity | Water tides | Tidal power plants | Electricity |

Table 2 presents production worldwide and potential and costs of production of 1 kWh from individual sources of renewable energy [2]. Analysis of these data proves that the potential of the sources exceeds by thousand times the production of its energy, which demonstrates the opportunities of production of energy from sun, wind, and geothermal energy.

**Wind energy.** Especially interesting issue is a dynamic of production of electricity from wind, which is presented in Fig. 2 (for last 13 years) [3]. Increase in production is of an exponential nature an in analysed period (1993—2006) production worldwide has increased almost 20 times. The perspectives of further dynamic development and problems connected with opportunities of its use have decided that next part of the considerations will be focused on energy obtained from wind.

Atmospheric air movements in relation to the surface of the Earth is what we call a wind. It is created as a result of uneven distribution of the pressure in the atmosphere. These differences are caused mainly by uneven heating of air mass with solar radii, especially in equatorial zones. The result of this phenomenon are the movements of air in vertical direction, spread into two streams, in upper layers of the atmosphere to the direction of the North Pole and South Pole and, in ground boundary layer in reverse direction. These phenomena are of dynamic nature both on local and global scale and the wind velocity depends on pressure differences in individual zones. The direction and velocity of the wind is also affected by spinning motion of the Earth (Coriolis force) and sea tides. About 1—2 % of solar energy radiation which gets to the surface of the Earth is exchanged for kinetic energy of the wind, which corresponds to the power of about 2700 TW [4].

*Table 2.* **Production of energy and costs of production from renewable resources at 2003**

| Sources of energy | Production worldwide (TWh) | Electricity and heat energy potential worldwide (1000 TWh/year) | Cost of production (1 kWh/Eurocent) |
|---|---|---|---|
| Water | 2631 | 14 | 2 — 8 |
| Bioenergetics | 175 | Less > 77 | 5 — 6 |
| Wind | 75 | 178 | 4 — 12 |
| Geothermal | 50 | 1400 | 2 — 10 |
| Sea | 0,8 | 32 | 8 — 15 |
| Solar collectors | 0,5 | Less > 440 | 12 — 18 |
| Photovoltaics | 2,5 | | 25 — 65 |
| Total of renewable sources | 2934 | Less >2141 | — |

N o t e. Energy consumption worldwide is: electricity 16.700 TWh; primary energy in total 120.000 TWh.

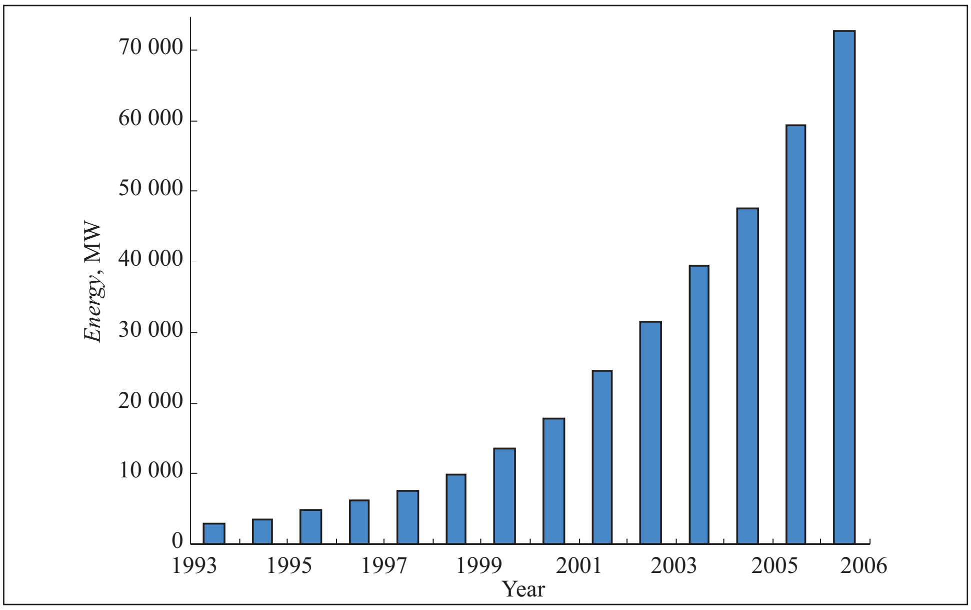


*Fig. 2.* Total wind power installed in the world

Fundamental importance for assessment of wind energy usefulness is its wind velocity annual mean. Wind velocity and the energy which can be obtained from it changes daily, monthly or periodically. Investigations and observations prove favourable correlation between wind velocity and energy demand (usually bigger winds are accompanied by higher energy demand). While considering use of wind it is necessary to know the velocity on the level of wind turbine wheel.

Wind velocity increases with the height $H$ measured from the ground level. $H_G$, below which the gradient wind is assumed ($V_G$) depends on roughness of the Earth surface, unevenness, flora and buildings. On the basis of experiments it is assumed that the distribution of wind velocity as a function of the height is determined by exponent function from the following formula [2]:

$$V_H = V_{10}\left(\frac{H}{10}\right)^{\alpha},$$

where $V_{10}$ — wind velocity at the height of $H = 10$ m over the ground level; $H$ — height (m) over the ground level; $\alpha$ — coefficient dependent on type of terrain and the buildings, determined empirically.

For wind energy sector in Poland, with consideration of physiographic and topographic conditions, a six-grade scale of terrain roughness is suggested. Their characteristics and coefficient is presented in Table 3; while Table 4 presents values of the $\alpha$ exponent as a function of terrain roughness and mean time [2].

Calculation of the velocity out of the height $H = 10$ m with a particular terrain roughness and $\alpha_x$ for the height $H$ and roughness of 0 with coefficient $\alpha_0$ makes the following hold true:

$$V_{H-0} = V_{10-x}\left(\frac{10}{H_{G-x}}\right)^{\alpha_0}\left(\frac{H_{G-x}}{10}\right)^{\alpha_x}.$$

Examples of changes in velocity with the height $H$ are presented in Fig. 3 [2].

Annual average of wind velocity is of fundamental importance for assessment of conditions for building the wind power plants. From practical point of view, the opportunity to use wind power energy is limited by a few conditions:

lowest acceptable value of wind velocity $V_d$, at which wind power plant starts operation;

calculated wind velocity $V_0$, at which the electricity obtains nominal capacity $N_n$;

maximal wind velocity $V_g$, at which the wind power plant is shut down (within the range of wind velocity of $V_0 \leq V \leq V_g$ power plant control system tends to ensure almost continuous capacity equal to the nominal $N_n$ and continuous rotational velocity of the turbine wheel);

within the range of wind velocity $V_d \leq V \leq V_0$ the wind power plant control system maintains continuous rotational velocity of the turbine wheel.

For the assessment of profitability of building of power plant in a particular conditions the amount of produced annual electricity at the annual average wind

*Table 3.* **Characteristics of terrain roughness, classification**

| Roughness class | Height of the gradient wind $H_G$, m | Terrain description |
|---|---|---|
| 0 | 300 | Open plain terrain, on which the unevenness height is lower than 0.5m |
| 1 | 330 | Open flat or insignificantly wavy terrain. Single buildings and trees may occur in large distances from each other |
| 2 | 360 | Flat or wavy terrain with large open spaces. Group of trees or low buildings may occur in significant distances from each other |
| 3 | 400 | Terrain with obstacles i.e. forests, suburbs of bigger cities and small towns, industrial terrains with free development |
| 4 | 440 | Terrain with numerous obstacles located in small distance from each other, i.e. clusters of trees, buildings, distances of e.g. 300 m from the point or observation |
| 5 | 500 | Terrain with numerous large obstacles, very close to each other, forests and centres of big cities |

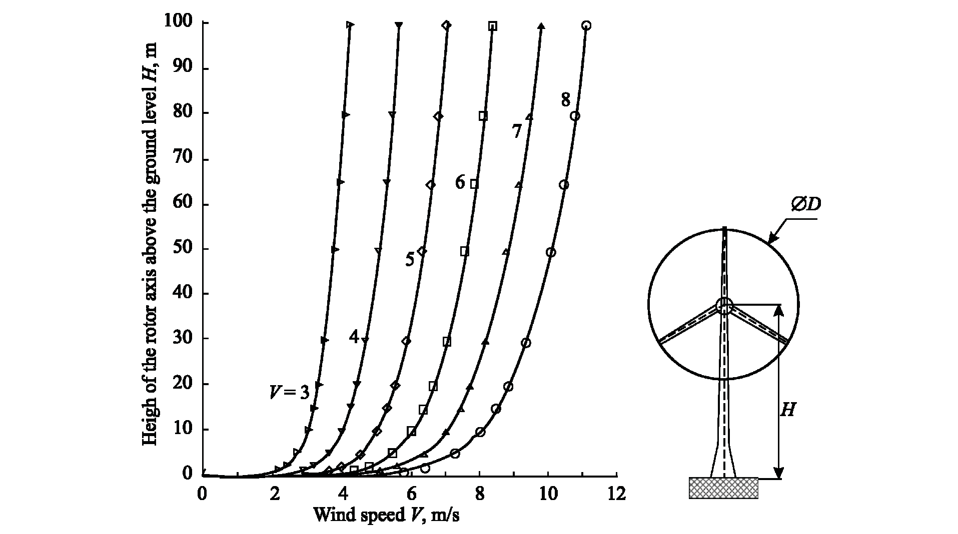


*Fig. 3*. Distribution of wind velocity as a function of *H* height for different values *V* and $\alpha = 0{,}14$ (open terrain)

power is calculated. Considering the conditions i.e. $V_d$, $V_0$, $V_g$ and changeability of generator capacity within the range of wind velocity of $V_d$ and $V_0$, the actual probable amount of the energy over the year can be calculated.

Wind power plant capacity within the range of velocitys $V_d$ and $V_0$ can be calculated using the formula below:

$$N = N_n \sin\left(\frac{\pi}{2}\frac{V\ V_d}{V_0\ V_d}\right),$$

where $V$ — wind velocity for the range of $V_d$ and $V_0$, m/s. This equation can be used for estimations, if the generator characteristics $N = f(V)$ is unknown.

*Table 4.* **Values of α exponent for average times and for the roughness classes** [2]

| Terrain roughness class | Roughness coefficient *K* | Coefficient α for average time | | | |
|---|---|---|---|---|---|
| | | 1 h | 10 min | 2 min | 2 s |
| 0 | 0,005 | 0,150 | 0,130 | 0,115 | 0,075 |
| 1 | 0,007 | 0,165 | 0,140 | 0,120 | 0,075 |
| 2 | 0,010 | 0,190 | 0,155 | 0,125 | 0,080 |
| 3 | 0,015 | 0,220 | 0,170 | 0,135 | 0,080 |
| 4 | 0,025 | 0,270 | 0,200 | 0,150 | 0,085 |
| 5 | 0,050 | 0,350 | 0,245 | 0,175 | 0,085 |

Possible locations of the wind power plants are determined by the annual average wind velocitys prepared in the form of maps.

Such maps can be an initial indication for location. Final choice must be confirmed by long-term (at least 12 months) measurements of wind velocitys in a given point over the ground.

Particularly favourable conditions for wind power plant locations in Poland can be found in seaside regions, at the north and east end and selected areas of central Poland.

Seaside regions of lands are particularly useful, which is confirmed by the European Union practice (Germany, Denmark, Netherlands) as well as worldwide. Final decision on usefulness of a particular region for the wind energy sector should result from economic reasons, it may sometimes be confirmed by social reasons and access to the existing energy infrastructure.

**Development of wind energy industry in Europe and worldwide.** Status of energy based on application of wind energy is presented in Table 5, where presents wind power installed capacity for the past four years (2003—2006) for three continents: Europe, Asia, North America and the countries with highest production is [3]. Installed capacity of wind power plants worldwide at the end

*Table 5.* **Installed capacity in wind power plants worldwide (MW) and dynamics of growth in 2003 — 2006**

| Geographic region | Years | | | | Dynamics of growth in 2003 — 2006, % |
|---|---|---|---|---|---|
| | 2003 | 2004 | 2005 | 2006 | |
| European Union | 28 568 | 34 366 | 40 490 | 48 042 | 68,1 |
| Other European countries | 196 | 253 | 397 | 489 | 149,4 |
| Europe in total | 28 764 | 34 619 | 40 887 | 48 531 | 68,7 |
| USA | 6352 | 6800 | 9149 | 11 603 | 82,6 |
| Canada | 326 | 441 | 684 | 1451 | 345,1 |
| North America in total | 6678 | 7241 | 9833 | 13 054 | 95,4 |
| India | 2120 | 2800 | 4434 | 6053 | 185,5 |
| China | 644 | 740 | 1260 | 1699 | 163,8 |
| Japan | 566 | 700 | 1150 | 1128 | 99,2 |
| Other Asian countries | 19 | 27 | 254 | 324 | 1605,2 |
| Asia in total | 3349 | 4267 | 7098 | 9204 | 174,8 |
| Other countries worldwide | 572 | 880 | 1417 | 1839 | 221,5 |
| Total | 39 363 | 42 007 | 59 235 | 72 628 | 84,5 |

of 2006 exceeded 70.000 MW. For European countries this capacity amounted to almost 50.000 MW while the growth of installed capacity in wind power plants is of exponent nature (see Fig. 2). For the analysed period, the growth of installed capacity in wind power plants in Europe increased by 68,7 % and in EU countries by 68,1 %. Table 6 presents comparison of the participation in this growth in individual countries of EU [3].

*Table 6.* **Installed capacity in wind power plants worldwide (MW) and dynamics of growth in the EU countries in 2003—2006 years**

| № | European Union | Years | | | | Dynamics of growth in 2003—2006, % |
|---|---|---|---|---|---|---|
| | | 2003 | 2004 | 2005 | 2006 | |
| 1 | Germany | 14 609,0 | 16 628,8 | 18 414,9 | 20 621,9 | 41,1 |
| 2 | Spain | 6202,8 | 8263,2 | 10 027,9 | 11 615,1 | 87,2 |
| 3 | Denmark | 3115,0 | 3117,0 | 3128,8 | 3136,6 | 0,7 |
| 4 | Italy | 904,3 | 1261,5 | 1718,3 | 2123,4 | 134,8 |
| 5 | UK | 649,3 | 888,8 | 1332,1 | 1962,9 | 202,4 |
| 6 | Portugal | 295,9 | 520,3 | 1047,0 | 1716,4 | 479,7 |
| 7 | France | 249,0 | 405,5 | 755,6 | 1635,0 | 552,6 |
| 8 | Netherland | 910,0 | 1077,7 | 1224,0 | 1560,0 | 71,4 |
| 9 | Austria | 415,0 | 606,2 | 818,9 | 964,5 | 130,0 |
| 10 | Greece | 375,0 | 465,0 | 573,3 | 746,5 | 98,9 |
| 11 | Ireland | 199,9 | 342,3 | 495,3 | 745,2 | 272,5 |
| 12 | Sweden | 399,0 | 442,0 | 493,0 | 519,0 | 30,0 |
| 13 | Belgium | 66,9 | 92,9 | 158,4 | 193,1 | 188,0 |
| 14 | Poland | 61,2 | 68,1 | 72,0 | 152,6 | 150,8 |
| 15 | Finland | 52,0 | 82,0 | 82,0 | 86,0 | 65,3 |
| 16 | Hungary | 3,3 | 3,3 | 20,5 | 60,9 | 1933,3 |
| 17 | Lithuania | 0,0 | 0,8 | 6,4 | 54,0 | — |
| 18 | Czech Republic | 10,6 | 16,5 | 22,0 | 50,0 | 371,6 |
| 19 | Luxemburg | 21,5 | 35,3 | 35,3 | 35,3 | 66,6 |
| 20 | Estonia | 2,9 | 20,0 | 32,0 | 32,0 | 966,6 |
| 21 | Latvia | 23,0 | 24,0 | 27,0 | 27,0 | 17,3 |
| 22 | Slovakia | 2,6 | 5,1 | 5,3 | 5,1 | 96,0 |
| 23 | Cyprus | 0,0 | 0,0 | 0,0 | 0,0 | — |
| 24 | Malta | 0,0 | 0,0 | 0,0 | 0,0 | — |
| 25 | Slovenia | 0,0 | 0,0 | 0,0 | 0,0 | — |
| EU in total | | 28 568,2 | 34 366,3 | 40 490,0 | 48 042,5 | 68,1 |

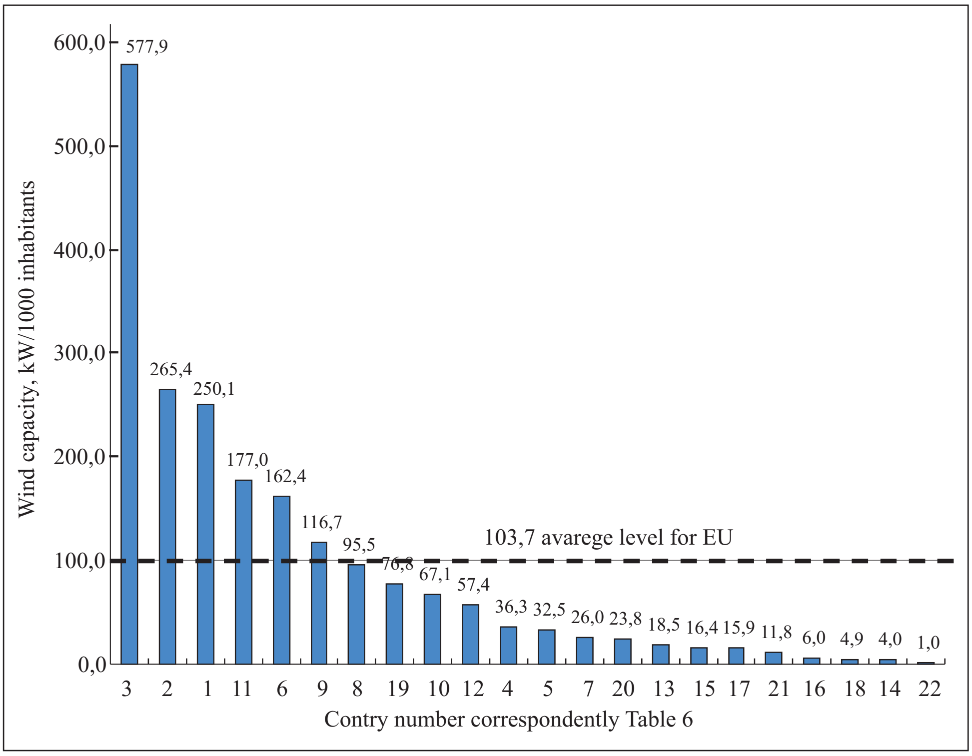


*Fig. 4.* Wind capacity in the Europeans countries in kW/1000 inhabitans

Table 6 shows huge percentage growth in analysed period of time related to the level of capacity in 2003, which varied for individual countries.

This results mainly from EU policy, where the emphasis is put on renewable sources of energy. According to recent arrangements by EU summit (March 2007), the participation of renewable sources of energy in global production should be 20 % in 2020. Thus wind power energy sector, with the financial support, will be the part of energy sector which in incoming years will develop dynamically. More objective factor for assessment of wind energy application is an installed capacity coefficient for individual countries of EU per 1000 inhabitants (Fig. 4) [3].

With the average for EU countries of 103,7 kW/1000 inhabitants the huge disproportion can be observed from 1 kW/1000 inhabitants for Slovakia to 577,9/1000 inhabitants in Denmark. It should be highlighted that different countries have different resources and they are at different level of economic growth (new countries of EU in comparison to old countries of the Fifteen). Economic and civilization downward tendency for some countries is clearly confirmed by

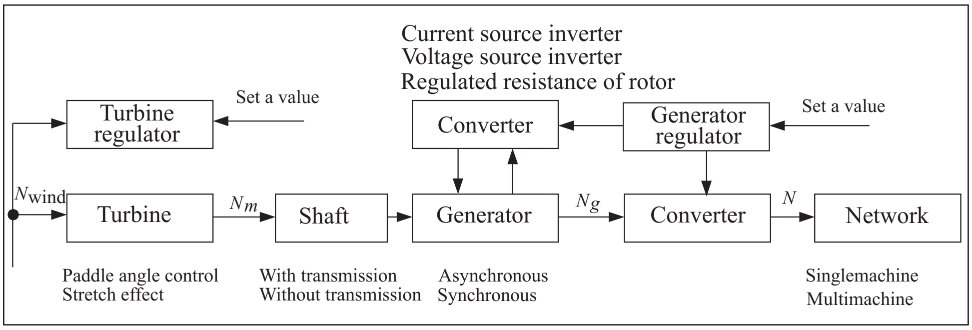


*Fig. 5.* General model of wind power plant

value of indexes (see Fig. 4). High indexes are characteristic for the seaside (Denmark, Spain, Ireland) and highly developed (German) countries, which intensively supported wind energy sector development.

**Wind power plant modelling.** While planning, designing and analysis of the wind power operation in the energy system and its effect on this system the models which more or less reflect the actual state are used. While modelling wind power plants it is necessary to employ particular technical solutions as the components. Generally, wind power plants can be equipped in synchronous or asynchronous generator. The generator can be connected to network directly or by means of power converter. Variety of solutions used in wind energy sector enables the general model of wind power plant (Fig. 5) to be created [5].

Each element requires separate analysis, but particularly interesting is an analysis of wind turbine model and the effect of external and internal factors on cooperation with energy system. Fig. 6 presents flow chart of such a model [6]. Each element presented in Fig. 5 requires to be considered separately. Undoubtedly, the most influential for the turbine operation is a wind velocity as an independent variable. Change in wind velocity are of stochastic nature both in short and long time periods. During analysis and modelling of wind power plants in energy system the changeability of the wind is accepted as a total of harmonics of various frequency from 0.1 to 10 Hz, changes of incremental nature (least possible) and changes of the increasing nature and as a stochastic process. Velocity formula can be formed as following:

$$v(T) = V_0 \left( 1 + \sum_k A_k \sin(\omega_k t) \right) + v_g(t),$$

where $V_0$ — average wind velocity; $A_k$ — amplitude of $k$ harmonic for wind velocity; $\omega_k$ — frequency (pulsation) of $k$ harmonic for wind velocity; $v_g$ — wind gust.

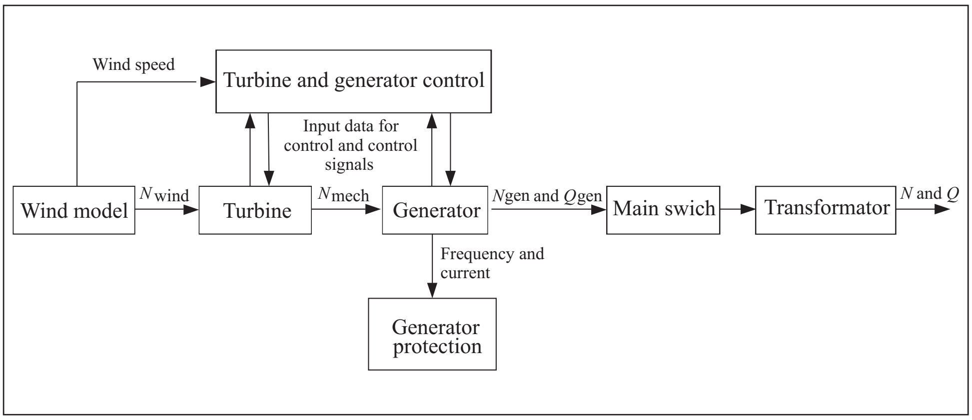


*Fig. 6.* Flow chart of wind power plant

During modelling of wind, the gusts are also considered. For the gusts the following holds true:

$$v_g(t) = \frac{2v_{g\ \max}}{1+e^{4(\sin(\omega_g t)I)}},$$

were $v_{g\ \max}$ — wind gust amplitude; $\omega_g$ — gust frequency ($\omega_g = 2\pi / T_g$).

Amplitude of wind gusts can fluctuate in quite broad limits e. g. up to 10 m/s, and the period may be within $T_g = 10 \div 50$ s.

An example of solutions applied in modeling of wind power plants is preparation of the model which includes [2]: of generator; of turbine; of protective devices; of transformer; of wind.

Using own studies and adapting the algorithms connected with energy system control, the authors carried out simulation tasks of the wind power plants and its control opportunities as well as cooperation with energy system. Fig. 7 presents the example of algorithm for active power control and its essence [6].

**Operation of wind power plants with energy system.** Basically, operation of power plant is determined only by wind conditions i.e. wind velocity and its changeability in time. Thus, taking these conditions into consideration, one can observe four fundamental states of wind power plants:

wind power plant downtime with readiness — resulting from too low wind velocity lower than cutin velocity $V < V_d$;

operation with partial load (not rated) — means operation with maximization of the energy obtained from wind stream in the situation when wind velocity $V$ has the value from the range of $V_d \le V \le V_0$, where $V_0$, is a rated velocity of the wind which corresponds to the rated power of wind power plant;

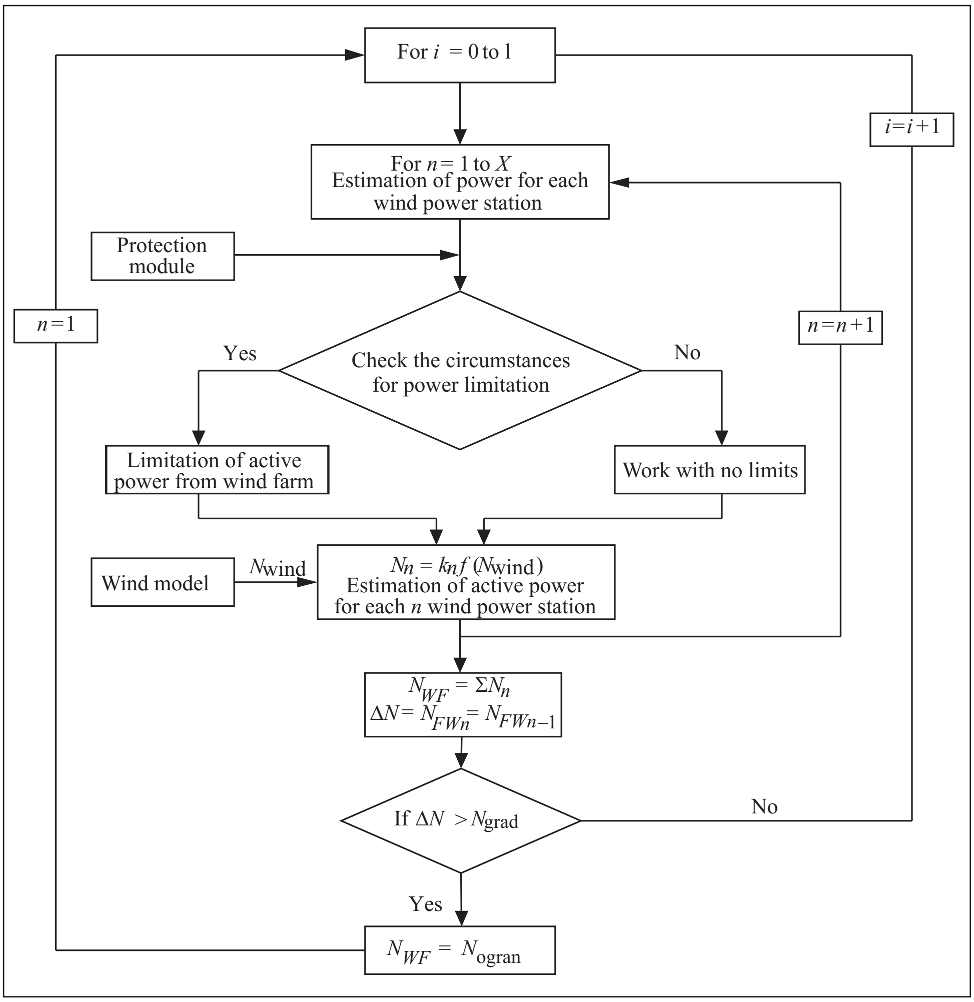


*Fig. 7.* Part of the algorithm for active power control for a wind form: $I$ — total number of steps in simulation resulting from simulation time and integration step; $X$ — number of wind power plants on the discussed wind form

operation with the rated load — means operation with continuous and rated active power, where the wind velocity is higher or equal to rated velocities $V_0 \leq V < V_g$ and lower than cut-out velocity $V_g = 25$ m/s;

power plant downtime with readiness — resulting from too high wind velocity $V \geq V_g$.

The above modes for wind power plant are usually presented in form of characteristics of power plant production $N = f(V)$, i. e. course of obtained power as a function of wind velocity. Normal operation of the power plant is connected with continuous changes in its operation mode and thus with continuous and varied effect on energy system. Wind power operation in energy system, including changeability of effect on the system has both positive and negative nature. Impact of wind power plant on the energy system depends on two fundamental factors, i.e. wind conditions and wind power plant structure.

Fast development of wind energy sector causes continuous increase in rated capacity in individual wind power plants. The capacities of wind farms installed in energy systems are also on the increase. This situation forced the energy system operators to prepare detailed requirements, which include[6]:

active capacity control;

operation of the farm in case of changes in voltage and frequency;

starting the farm's operation and disconnecting from the network;

voltage and passive capacity control;

procedure in case of network disturbance;

quality standards for electricity;

power energy protection automation;

monitoring and telecommunication system;

check tests.

These requirements cause the necessity of appropriate control of farms in normal and disturbance modes of the National Energy System. Many tasks will have to be overtaken by central (group) system of automated control over wind forms which affects the control systems of individual wind power plants.

Solutions applied nowadays by producers, ensuring operation of the equipment in case of disturbances within the range of voltages from 15 to 90 % of rated voltage for the periods of time from 0.6s to 10s.

To sum up, it should be observed that wind power plants have the following advantages:

they do not contaminate the natural environment;

wind energy is free;

they can be build on wastelands (deserts, coasts, rocks);

they ensure new workplaces.

Disadvantages of wind power plants include:

high investment and maintenance costs;

they can lead (German experience of 2003—2004) to destabilization of the energy system of a country;

they pose threat to birds;

«amateur» structures operate quite loudly, e. g. tips of rotor blades with diameter of 22 m, rotating at 1rps move at 250 km/h and its characteristic that they vibrate, which is the source of infrasound.

Development of wind energy does not limit to building next wind power farms in seaside regions, moreover, in a few-years time the economically profitable and socially acceptable location will have vanished. As a result of too large number of aeroenergetic installations in seaside region, the unique landscapes of seaside locations may be obstructed, which consequently may lead to reduction in its tourist and recreation advantages. Thus the strategy of further development of wind energy sector is still to be reoriented in the following directions:

locations of new wind farms in seaside regions; but not on the land but in the sea;

building, as in case of small water energy sector, small wind turbines ensuring decentralized sources of energy for local needs;

using wind energy for purposes other than production of electricity;

building of hybride wind-solar installations as a source of hot water and building heating.

Описано сучасний стан та перспективи використання енергії вітру в країнах Європи і у світі. Розглянуто проблеми, пов'язані з моделюванням роботи станцій, що використовують енергію вітру, та їх взаємодію з енергетичними системами. Наведено статистичні дані, які дозволяют оцінювати можливості виробництва екологічно чистої енергії.

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