БЪЛГАРСКА АКАДЕМИЯ НА НАУКИТЕ • BULGARIAN ACADEMY OF SCIENCES

ПРОБЛЕМИ НА ТЕХНИЧЕСКАТА КИБЕРНЕТИКА И РОБОТИКАТА, **65**
PROBLEMS OF ENGINEERING CYBERNETICS AND ROBOTICS, **65**

София • 2012 • Sofia

Models of Wind Potential Prediction

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Abstract: *The paper makes a survey of the methods for wind potential prediction. It discusses the systems and their elements used to make reliable prognosis of the wind power. The problem becomes still more actual with the application of wind energy as a kind of renewable energy instead of different conventional sources. The result of the number of innovations discussed, the better knowledge of the processes in the wind farm network will make the energy usage more efficient.*

Keywords: *Renewable energy sources, wind potential prognosis, models of the wind power.*

1. Introduction

The necessity for diversification of the energy generation, which arises from safety requirements, unsteady prices of the fuel and climate changes, leads to the development of non-conventional sources (wind, small hydroelectric stations, solar, tide, geothermal resources, etc.) or the so called renewable energy in the entire world. The advanced countries have already accepted renewable energy as a key tool to decrease bad emissions in the environment, as well as to achieve energy independence, to diminish the import of oil, gas and coals.

Wind electric power is a new class of energy, different from the conventional types. It sets a lot of new problems concerning its generation, as well as its inclusion in the existing networks.

The energetic potential of the wind is indeed remarkable. About 1-2% of the solar energy falling on earth is turned into wind energy. For comparison, the energy absorbed by plants through photo synthesis and transformed into bio mass is only 0.02-0.03%, almost hundred times smaller. Modern civilization, often considered quite lavish, consumes about 0.005-0.006% of this energy [1]. According to the estimation in [2] the actual energy consumption could be satisfied by wind power generation at height up to 80 m on 20% of the sites, with average annual wind rate above 6.9 m/s.

At the end of 2007 the installed wind power in the world is 93.8 GW, 61 GW being in Europe. For more than a decade the production of wind energy in the world is doubled every three years, thus reaching 242.10^{12} Wh from the installed power of 121 GW in 2008 [3]. In 2009 the growth of wind power generation continues. Ten GW new capacities are deployed in USA, and 2.459 GW – in Spain. In Europe the network includes about 8 offshore wind farms with 199 generators and total power of 577 MW. Despite of the rapid development, the share of the wind energy in the total power consumption remains quite low, about 0.3% [4].

The world resources of easily obtained wind power is evaluated at 1500 GW, with annual production of 3.10^{12} kWh, that makes 500 kWh per an inhabitant of the already over 6 milliard world population [5, 6].

The main technology for wind energy generation is based on the well known old wind wheel. Its improvement during the last decades has moved this technology to its limit capacities – deriving energy up to 50 % from the ground wind layer at height up to 180 m. The generation is limited by Betz law, and the diameter of the wheel (propeller) – by the mechanic strength of the materials used.

Another technology is using the kite mechanism [4]. It enables energy generation at height of 200-800 m, where the wind speed is higher and not so dependent on the ground surface. The kite itself has a simple construction, small weight, but requires complex control. This technology allows the construction of energy parks with greater energy density, the site remaining free for other activities. However, this technology is not operative up to the moment. It is theoretically grounded, experimentally confirmed on a small scale, but due to its promising possibilities, it will be soon developed and operatively used.

2. Models, predicting the wind potential

2.1. General information

The reliable prognosis of the wind power is an essential component for the successful integration of the Wind Turbine Generators (WTG) in the available electrical power line, especially when the wind energy takes a significant part in the total energy. The system for wind prognosis is an apriori condition to construct a WTG farm [7].

The real life control of the network requires prognostication with different horizon. The direct control of WTG needs prognosis up to 1 min. The network operative control requires prognosis covering several hours up to 2-3 days. The long term prognoses are used for economic analyses – estimation of the obtained energy, planned repairs, initial design of WTG farms, dynamics of the energy produced [8-10].

The prediction process uses time series; data about the wind picture in the near or distant environment; physical models applied for weather forecast. The prognoses and the operative control of the electrical power generated by wind, are the subject of many research projects [11-14].

The prognoses are given as averaged indicators for different time intervals – minutes, hours, days, and so on. The prognostication with time series uses the following models:

- AutoRegressive (AR),
- AutoRegressive with Moving Average (ARMA);
- AutoRegressive Integrated with Moving Average (ARIMA);
- neural networks;
- adaptive networks based on fuzzy logic;
- adaptive networks using radial basic functions.

These approaches use the necessary data collected for a given place, without any investigation of the near environment. However, the necessary quantity of data is too large (of the order of ten thousands) and must be acquired for long intervals – 1-2 or more years. Considerable influence is noted of the data even from the preceding 12 years [13].

The methods using data from the close environment offer efficient short time prediction. They apply [11, 13]:

- recurrent neural models,
- fuzzy models,
- space correlation.

The necessary data in these approaches are not numerous and they refer to short time intervals, but the places must be several.

2.2. Digital modeling of the wind potential

The digital modeling of the direction and speed of the wind, of the wind flow density at different points of the relief, as well as at different levels above the earth surface is accomplished by spatial interpolation of the wind direction and speed, experimentally observed and acquired in the meteorological station close to the place considered. The data about the site characteristics of the area, the presence of obstacles and the surface unevenness are also accounted. In this way the suitability of a given site for wind usage as a power source is evaluated. Herein the main prerequisites will be discussed, that form the base of the methododogy leading to solution of the problem of evaluating different wind features and flow parameters from the viewpoint of its use for energy generation.

2.2.1. Basic elements [11, 15, 16], Fig. 1

2.2.1.1. Unevenness of the site. The unevenness of the site defines the general influence of the surface and the obstacles, causing slowing up of the wind rate close to the earth surface. The site unevenness is characterized by the unevenness parameter Z_0. Formally Z_0 is the height at which the average wind speed becomes zero, if the wind profile in height is logarithmic.

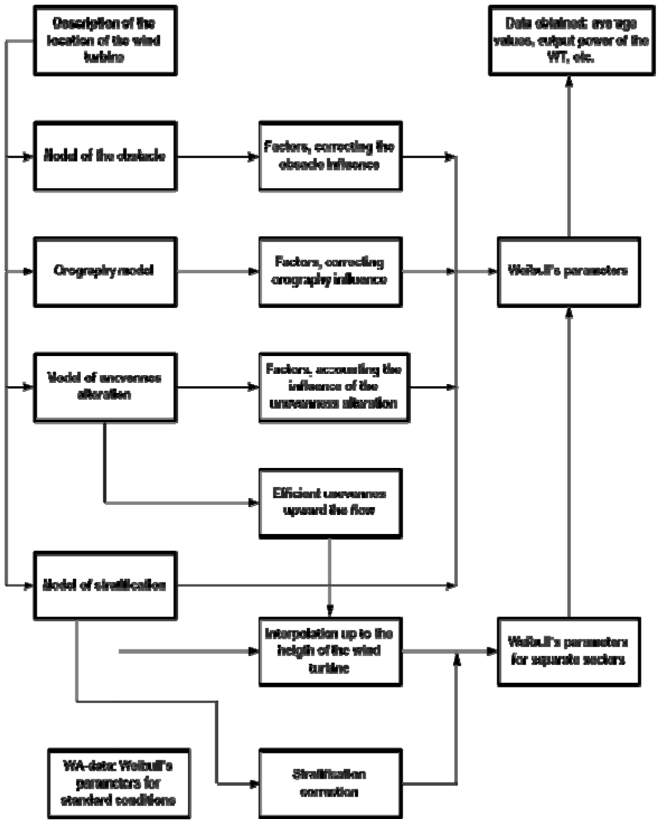

Fig. 1. Scheme of a model for digital modeling of the ground wind

The unevenness of certain surface is determined by the size and location of the uneven elements. The geometric and physical characteristics of different elements of roughness also play an important part. Every element of unevenness is characterized by its height *h*, the area of the section against the wind *S* and the permeability *P*.

For the purpose of modeling each type of landscape is assigned a given unevenness class. The unevenness influence decreases with increase of the height above the terrain. In the final results the unevenness is obtained in a digital form as percents of influence given in tables.

2.2.1.2. Influence of the obstacles. The obstacles cause strong disturbance in the wind field, spreading vertically up to three times of *h* (the obstacle height) and horizontally along the flow 30-40 times of *h*. Whether an obstacle will ensure a shelter of a given place depends on the following parameters: distance of the obstacle up to the place studied; height of the obstacle; height of the point considered; length of the obstacle; permeability of the obstacle, given in Table 1.

Table 1. Permeability of different obstacles

Type of the obstacle	Permeability
Solid barriers (walls)	0.0
Very solid obstacles	0.35
Thick obstacles	0.35-0,50
Open obstacles	>0.50

Since the actual obstacles have a finite length L, this leads to decrease of the shelter size, due to waves mixing in this direction. That is why a correction is introduced in the expression for the shelter. With height increase above the terrain the obstacle influence decreases. In the final results the obstacles influence is reflected as percents for each azimuth sector.

In the twelve 30-degrees sectors used in the analysis (or eight 45-degrees sectors), the relative decrease of the wind speed is given by the expressions:

$$R_2 = (1 + 0.2x/L) - 1 \text{ for } L/x > 0.3$$

or

$$R_2 = 2x/L \text{ for } L/x \le 0.3.$$

2.2.1.3. Orography influence. The basic elements of orography are its elements (hills, peaks, slopes, plains, mountain chains, etc.) leading to additional effects that intensify the wind close to the peaks, and in the plains and around the low peaks slopes decrease the wind power. The flow deformation depends also on their spatial orientation with respect to the dominating wind. The relative alteration of the speed above the earth surface is defined as

$$dS = (U_2 - U_1)/ U_1,$$

where U_1 and U_2 are rates of the wind on the hill and on the terrain in front the hill along the direction of the wind flow.

With the increase of the height above the terrain the orography influence decreases depending on the geometric size of the element.

In the final results this influence is given as percents for every azimuth sector and deviation in degrees with respect to the main direction.

2.2.2. Statistic grounds of modeling

The density of the wind energy ($\overline{E}$) is calculated with the help of the expression

$$\overline{E} = \overline{(1/2)\rho U^3} = (1/2)T\int_0^T \rho U^3(t)dt = (1/2)\rho\overline{U}^3,$$

where ρ = const is the air density; U – speed of the wind; T – time interval.

Since the data of the wind speed have random character, statistic approach is used for its description. The statistics from the averaging can be ordered in tables with respect to the frequencies of observation of a given speed or in order to use a more compact presentation – the statistic distribution of Weibull in the case.

The two-parameter statistic distribution of Weibull has the following mathematic record for the frequency of observation of the wind speed:

$$f(U) = k / A(U / A)^{k-1} \exp(-(U / A)^k,$$

where $f(U)$ is the frequency of observation of the speed U.

The two parameters of Weibull are the parameter A, m/s, and the measureless parameter k, called parameter of the shape.

The energy production is expressed by the integral

$$P = \int \Pr(u)\, P(u)\, du,$$

where Pr (u) is the distribution density, $P(u)$ – the power curve.

The upper equation can be reduced to

$$P = \int (k/A)\, (u/A)^{k-1} \exp(-(u/A)^k\, P(u) du,$$

where A and k are parameters of Weibull's function.

2.2.3. Scheme of a model for digital modeling of the ground wind (Fig. 1)

The programs for digital modeling enable the removal of topography influence from the measured data and analysis of the frequency distribution. The data correction can be accomplished separately for every measurement or realizing an appropriate transformation of the frequency distribution. Herein the problem is solved by the second approach.

2.2.3.1. A model of unevenness alteration. The logarithmic profile of the wind is used only in cases of comparatively homogeneous surface. If this condition is not satisfied, it will give deviations and the assigning of only one unevenness parameter will be impossible. The efficient parameter of unevenness can be obtained in different ways depending on the height of observation. The average alteration of the ground surface unevenness and the speed of the ground wind depend on the surface conditions only referring to the distance along the flow of unevenness change.

2.2.3.2. Model of the obstacle. The friction of the ground surface is caused by the obstacles resistance. Their common influence is modeled by the unevenness parameter. The wind profile is usually disturbed close to an obstacle found at a distance, comparable with its height H. The purpose of the model used in the paper is to correct the data with respect to the influence of single obstacles that are located far one from another, so that the complications, caused by waves' mixture, are avoided.

2.2.3.3. Model of orography. The influence of orography on wind is expressed in alteration of its speed and direction. The purpose of the orography model is to remove this influence from the wind data. BZ model of Troen is applied in order to compute the disturbances in the wind speed, induced by orographic features, such as single hills or a complex terrain. The basis of the model is the theory of Jackson and Hunt for a flow around a low hill. The equations for movement of a neutral flow are initial and it is assumed that the alterations of the flow, caused by a complex site, can be regarded as disturbances of the main status of the wind – the logarithmic profile. The information that must be entered in the program is the terrain height for every point of the network.

2.2.3.4. Model of stratification. The alteration of the logarithmic profile of the wind speed depending on stratification is often neglected when evaluating the wind statistics. This model treats different wind profiles as small disturbances of the basic neutral status. A simplified procedure is used, which requires the introduction of the ground flow of heat in the form of an average value and mean square deviation.

2.2.3.5. Integrating model for analysis. This model is comprised by the models described in the former chapters. On the basis of the data from wind observations, the description of the unevenness of the surrounding terrain, the obstacles and orography, the local climate is computed in the form of parameters of Weibull's distribution, referring to standard conditions.

2.2.3.6. Applied model of the program. The applied model enables the computing of the speed distribution for a given place on the basis of the local wind climate. The procedure is closest to the inverse one of the analyzing model. The correcting factors for the obstacle, the alteration in unevenness and orography are computed exactly as in the analyzing model, but here data for the obstacles, unevenness and orography of the place considered are used. Logarithmic interpolation is applied for height and roughness, different from the standard ones. The values of unevenness for each sector are computed in the model of unevenness alteration. The correcting factors are applied for the A-parameters of each sector, preserving the table values of k. At the end, correction of the stratification is done in the way described in the model for stratification. The model computes the sector parameters of Weibull and the sector frequency for a selected regional climate for given height above the terrain and for data of the terrain unevenness, obstacles and orographic phenomena.

2.2.3.7. Specialized data bases for modeling. The following specialized data bases are used in modeling:

- Data base of the direction and speed of the wind;
- Data base of the orography;
- Data base of the obstacles;
- Data base of the unevenness of the covering surface.

2.2.4. Main results from digital modeling

After determining the parameters of Weibull's function, herein denoted as A and k parameters for different degrees of unevenness, different heights above the terrain and different directions, the so called atlas of the wind at a given place is created, which aids the solution of the following problems:

• determining the degree of influence of the obstacles, the unevenness and orography on the direction and speed of the wind;

• spatial interpolation and extrapolation of the direction and speed of the wind for the place considered (directions of the dominating wind, speed of the wind, etc.);

• determining the flow density at an arbitrary point on the relief;

• determining the quantity of electric energy from a certain type of a turbine with given parameters (power, height of the generator axis above the terrain, diameter of the vanes, etc.);

• determining the spatial orientation of the wind farm;

• selecting a generator with optimal parameters for the place studied, and others;

• other parameters.

3. Models of the wind potential

3.1. ARMA model for one-day prognosis of the potential and direction of the wind

In [18] one-day prognosis of the speed and direction of the wind is discussed, using ARMA model and determining the coefficients according to the method of least squares. Data from the last year, two or three previous years are used for the prediction – Fig. 2.

The data are acquired every 15 min and averaged every hour. For a prognosing horizon of *n* hours, *n* successive data are used (the authors use *n* = 48 and 72) for the current time and for the same hours, days and months in every one of the preceding years. When only one past year is used, the prediction with horizon of *i* hours is according to the expression:

$$\hat{Y}(n+i) = a + bx(n+i) \ \forall i = 1, 2, ..., n$$

as $A = \begin{vmatrix} a \\ b \end{vmatrix} = \left| \Gamma^{\mathrm{T}}.\Gamma \right|^{-1} \Gamma^{\mathrm{T}} Y,$

$$\Gamma^{\mathrm{T}} = \begin{vmatrix} 1 & \dots & 1 \\ x(1) & \dots & x(n) \end{vmatrix},$$

$$Y^{\mathrm{T}} = \left| y(1), y(2), ..., y(n) \right|,$$

In an extended form

$$A = \begin{vmatrix} a \\ b \end{vmatrix} = \frac{1}{\det \Gamma^{\mathrm{T}}.\Gamma} \begin{vmatrix} \sum_{j=1}^{n} x^2(j).\sum_{j=1}^{n} y(j) - \sum_{j=1}^{n} x(j) \sum x(j) y(j) \\ n\sum_{j=1}^{n} x(j) y(j) - \sum x(j) y(j) \end{vmatrix}.$$

Y is the vector of the observed *n* data for the previous year and $X^{\mathrm{T}} = \left| x(1)x(2)...x(n) \right|$ – the vector of the last actual *n* data.

For two preceding years the prediction with horizon of *i* hours is done according to the expression:

$$\hat{Y}(n+i) = a + b_1 x_2(n+i) + b_2 x_1(n+i) \ \ \forall i = 1, 2, ..., n,$$

where x_2 are the actual parameters of the wind for the last year, and x_1 – the wind parameters for the last but one.

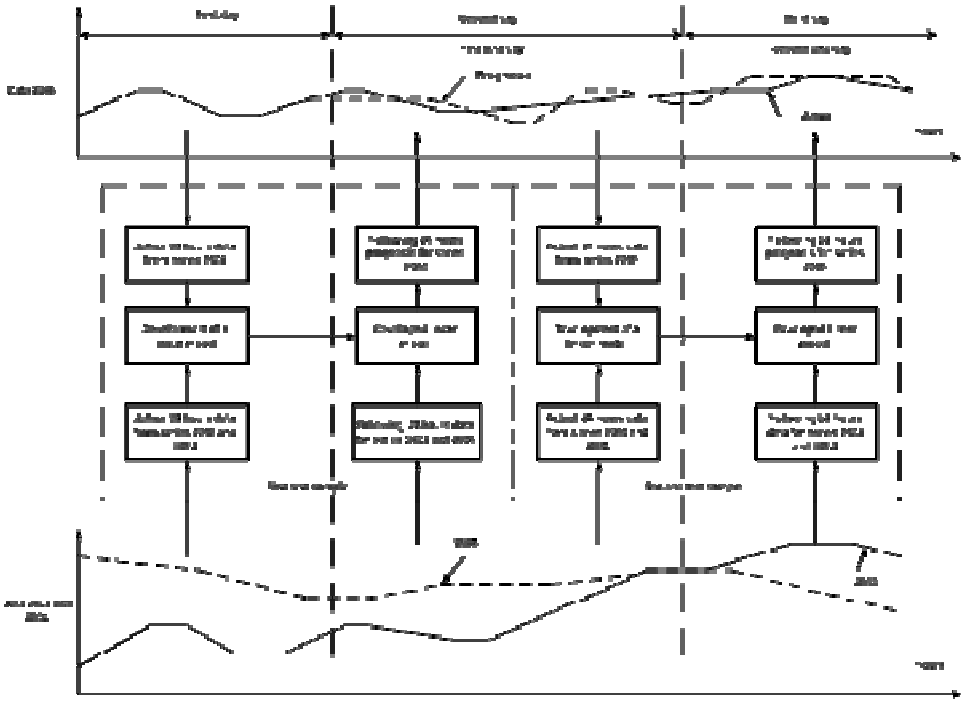

Fig. 2. Two-years model for prediction one day ahead (n = 24) of the speed and direction of the wind

The parameters a, b_1 and b_2 are parameters of the model determined by the expressions:

$$A = \begin{vmatrix} a \\ b_1 \\ b_2 \end{vmatrix} = \left| \Gamma^{\mathrm{T}} . \Gamma \right|^{-1} \Gamma^{\mathrm{T}} Y,$$

$$\Gamma^{\mathrm{T}} = \begin{vmatrix} 1 & \dots & 1 \\ x_2(1) & \dots & x_2(n) \\ x_1(1) & \dots & x_1(n) \end{vmatrix}.$$

The speed and direction of the wind are determined separately with the help of these expressions; they are not correlated.

It is shown that the probability of the prognosis is increased with the increase of the depth (the number of previous years) of the prediction time, and also with the decrease of the horizon. Fig. 3 shows as illustration the semi- and the full day prognoses for the wind speed, obtained by the authors.

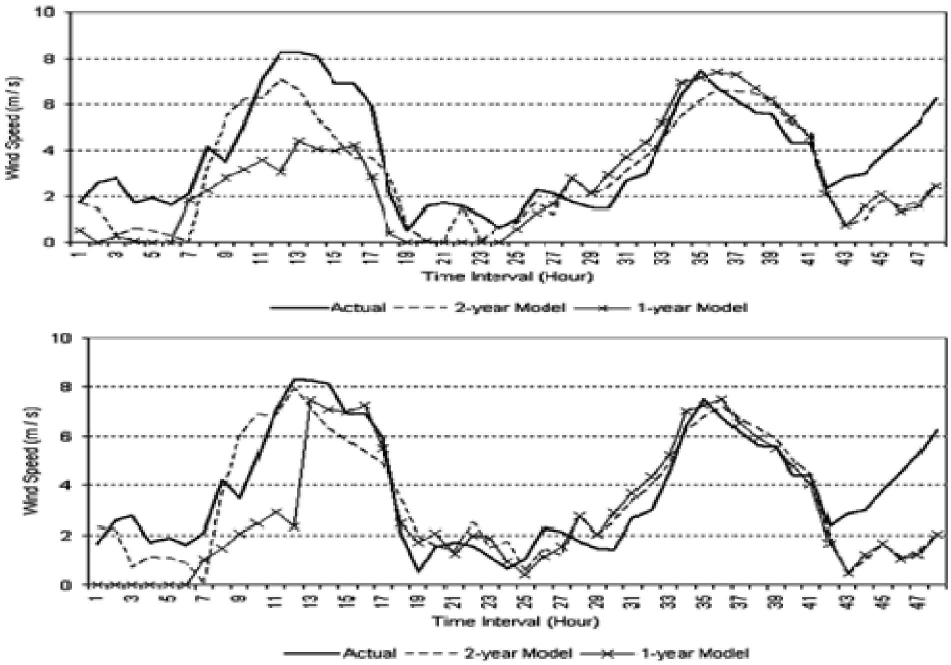

Fig. 3. Semi-day and full day prognosis of the wind speed

The authors have also obtained comparable results about the wind direction. One interesting experimental result is that the prognosis is more precise for the summer months in comparison to the winter ones. The high degree of influence of the data from the preceding several years is also surprising.

3.2. Fuzzy model for prediction of the wind potential using spatial correlation

3.2.1. Introduction

The quick changes of the wind strength could cause significant problems in economy and reliability, especially in areas with widespread wind power generation (on the Greek island of Crete it can reach from 20 up to 40 %). The prediction of the wind power, together with load prognosis, enables planned connection or turn off of the wind turbines or conventional generators, achieving in this way low operative reserve and optimal cost.

A fuzzy model is proposed for prediction of the wind speed and the energy yielded in a wind farm. The model is learned using a scheme based on a genetic algorithm. Data about the speed and direction of the wind are used, measured in neighbouring areas located at about 30 km from the wind turbine. Simulation results are shown for two applied cases, which enable prognosis of the wind speed from 30 min up to 3 hours ahead. It is demonstrated that the applied model achieves adequate solution of the problem, showing considerable improvement in comparison with the constant model.

3.2.2. Problem formulation

Two sites are considered – A (oriented along the wind direction) and B (opposite the wind), located in the wind flow. At sufficient height above the earth we can accept that there is a field of even speed of the wind. This is valid for the limit layer, where the winds are caused by global pressure gradients and remain uninfluenced by the heat transmission and the terrain characteristics.

3.2.3. Fuzzy system of inference

Fuzzy logic is a research area, based on the principles of approximate propositions and computing intelligence. It differs from the solutions with the help of classic sets, logics and exact Boolean values (true and false). Instead, it uses fuzzy linguistic variables (for example small, average, big) and continuous interval of true values within the interval [0, 1]. The fuzzy models are used in cases when the system is hardly modeled accurately (but there is an imprecise model) or when there is uncertainty in the problem formulation.

The typical fuzzy system consists of the following main parts:

- a base of rules, containing a given number of IF-THEN rules;
- a block, making the decision, which accomplishes the operations on the rules;
- interface for fuzzification, which transforms the non-fuzzy (crisp) inputs into fuzzy sets, processed by the block for propositions;
- interface for defuzzyfication, which transforms the fuzzy inference, providing non-fuzzy (quantifiable) output.

3.2.4. Fuzzy model for wind prediction

The design of a fuzzy model for the separate cases is accomplished in the following sequence:

- selection of successive inputs;
- selection of premises inputs;
- defining the model structure.

4. Conclusion

Nowadays numerous methods and technical tools are developed which make the energy system less dependent and sufficiently stable with respect to variability and uncertainty of the generation and consumption. In the advanced countries, where the wind energy is used for more than a decade, the possibility for 20-30% share of the wind power is quite real. This is the result of a number of innovations, better knowledge of the processes in the network and in WTG, some of them being:

- Better prediction of the wind field and of the loads.
- Increased flexibility of the control of the network and its components – generators, consumers, accumulators of electric power (gas under pressure, electric

accumulators). This includes rapid alteration of the generated power, decreased lower limit of the power, in which the generator remains stable, quick service;

- Introduction of more sophisticated methods of control. The use of vector control increases the speed of reaction towards occurring changes. The transition to doubly fed WTG with variable speed and full conversion enables maximal deriving of the wind energy, easy control of the relation active/reactive power.

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Модели предсказания ветрового потенциала

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(Р е з ю м е)

В работе представлен анализ методов предсказания ветрового потенциала. Обсуждаются системы и их элементы, которые позволяют получение надеждного прогноза ветровой силы. Проблемма становится еще более актуальной с применением энергии ветровых генераторов вместо конвенциональных источников. Дискутируются инновации, которые дают лучшее познание процессов ветровой сети, что сделает енергию более эффективной.