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RESEARCH OF WIND POWER INTEGRATION INTO THE POWER SYSTEM AND POWER BALANCING

Summary of Doctoral Dissertation
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INTRODUCTION

The rapid development of wind power plants (WPP) in Lithuania and the world creates new challenges for controlling electrical power system (EPS) operating conditions. These are related to the precise prediction of WPP power, to assure the sufficient reserve power for power-change balancing, to augmentation of electrical network power flow transmission capacity, reliability and security of overall electrical power system.

In order to ensure the reliable and safe operating of the electrical power system and the effective use of renewable wind energy, there is a lack of reliable wind power plant operating parameters and characteristics that would allow for maximum integration into the electricity system and not cause additional problems in the energy system routine control.

Therefore, it is relevant to establish the energy and power local balancing models of the wind farms (WF) that enable to ensure meeting the needs of local heat and electricity consumers and to establish power balancing of local combined heat and power plants, wind power plants, solar power plants, powers of boiler houses, heat pumps and capacities of the energy storage devices.

Established small power systems (SPS) enable to perform local balancing of energy and power, to reduce power flows of electrical networks and to increase the reliability and security of the electrical power system operation.

It is important to forecast exactly the gross output of wind farm and the total consumption for planning and organization operating conditions of the small power system.

Therefore it is important to improve forecast models of the wind farm gross output to enable more successful planning of the wind power plant operation, to reduce considerably power balancing reserves of the electrical power system, to improve the conditions of wind farms participation in the electricity market.

Objective of the work

Development of energy and power balancing models for electrical generating stations with intermittent power operating mode, which enable to evaluate electrical and heating needs of local consumers and to ascertain equipment parameters of the small electrical power systems.

Tasks of the work

1. To specify the methodology of the statistical parameters analysis of wind farms operating at changeable powers, to identify changing power averages, standard deviations and correlation coefficients; and to evaluate the influence of wind direction and geographical location of wind power plants on power generated by a wind farm.
2. To develop wind power plants’ energy and power balancing methodology and models in the small electrical power system.

3. Development of the statistical gross output forecast model for wind farm and analysis of its accuracy.

Methodology and instruments of the work

Statistical analysis of wind power plant gross output change and research of energy and power balancing is performed by use the quantitative and qualitative data of the wind-farm and load power change, as well as wind and atmosphere forecast with time marks. Making and research of the wind power plant energy and power balancing models according to electricity and heat demand is performed by use of Energy PRO software package and the program Power Factory 14. Determination of unknown estimates for forecast model sample regression equation coefficients is carried out by use the software package SPSS.

Scientific novelty of the work

1. The formation technique of secure and independently operating small electrical power systems is proposed for balancing of wind farm energy and power in accordance with the demands of local electricity and heat consumers without reducing the transfer capability of electrical transmission network.
2. The statistical regression technique for prediction of the wind farm gross output is supplemented by mathematical models enabling to evaluate more detail factors influencing the gross output of the wind farm and to increase the prediction accuracy.

Practical value of the work

1. The scientific research performed shows that proposed technique and models enable to determine the gross outputs of rebalanced wind farms that may be supplementary integrated into the electrical power system and to establish the gross outputs of new wind power plants.
2. The proposed statistical regression model for forecast the gross output of the wind farm provides more precisely the power of wind farms.

Defensive propositions of the dissertation

1. The research methodology of power changes in a wind farm allows to identify more precisely parameters necessary for energy and power balancing, management and regulation.
2. The developed methodology and models of the wind power plants energy and power balance in the small electrical power system allows the determination of the balancing opportunities of wind power plant powers.
3. The developed statistical regression wind power plant power forecasting model enables a more accurate forecast the gross output of the wind farm.

Approval of the work

The thesis material has been published in 5 scientific publications (articles), which were printed in international databases within scientific publications. Of which, 2 articles were printed in a publication by the scientific information institute database “ISI Web of Science”, which has a citation index and 3 articles in other international database publications. Currently, there is one article sent for publication. The thesis material has been presented in 3 international scientific conferences, 1 of which was organised abroad.

Structure of the dissertation

The dissertation is composed of the introduction, 3 chapters, main conclusions and a works cited list. The length of the thesis is 92 pages, including 61 images, 10 tables and 74 titles of consulted works.

1. WIND FARM BALANCING POWER AND FORECASTING METHODOLOGIES AND MODELS REVIEW

1.1. Statistical evaluation of the wind plant electric power and energy parameters

The relevance of evaluation of gross output variation parameters is related to the intense development of the wind power plants. The gross output of the wind power plants is intermittent and unmanaged and depends only on the stochastic change of the wind speed. It is inconsistent with the load changes of the electrical power system (fig. 1.1).

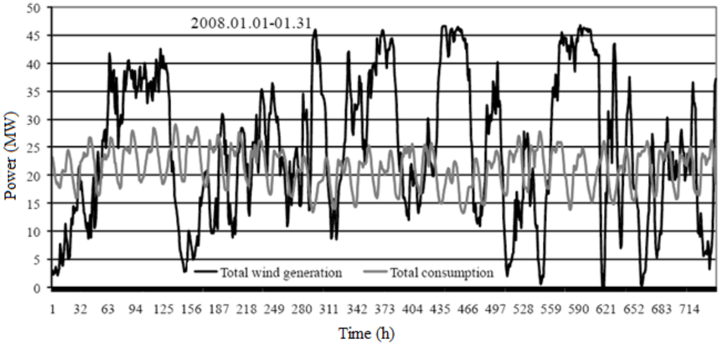


Fig. 1.1 Benaičiai wind farm and local load hourly power changes. (Deksnys, Staniulis, 2009)

It can be seen from average wind farm power changes at different averaging interval in the relative values of distributions (fig. 1.2) and (fig. 1.3) that the average hourly wind power developments are more important than secondal.

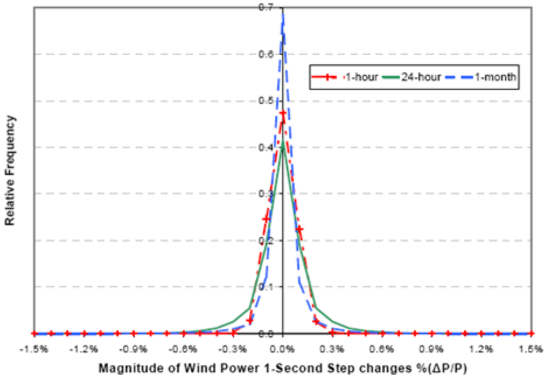


Fig. 1.2 Distribution of 1-second step change values (Wan, 2009)

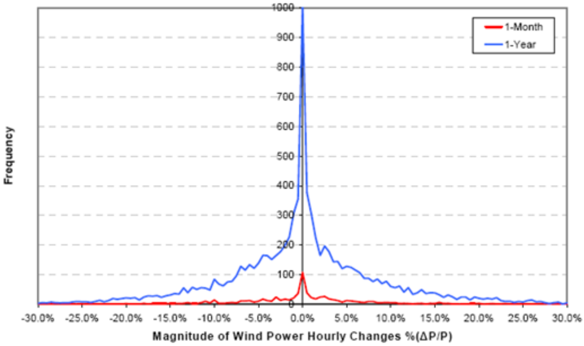


Fig. 1.3 Distribution of hourly step change values (Wan, 2009)

It can be seen from a performed statistical analysis of the wind farm power change data, that the correlation between the wind farm gross outputs decreases with increasing distances between wind farms, and, vice versa, the correlation increases when the duration of power change interval increases (Ernst, 2005).

The information submitted shows that wind farm gross output changing parameters depend on the averaging time of the load changes and the wind farm location. Construction and operation costs decrease when the wind power plants are placed near to each other, thus forming a wind farm. The total gross output of these farms is restricted to land acquisition opportunities, as well as by the transfer capability of the existing electrical transmission network. Lithuanian wind farms are being built as close to the beach in the area of stronger winds, a few dozen kilometers away from each other. (Andriuškevičius et al., 2004). Such location of wind farms increases their joint gross output changes, so in order to determine their impact on the Lithuanian electrical power system it is necessary to obtain more comprehensive analysis of wind power plant gross capacity data and possibly more accurate evaluation of power variation.

It should be noted that given in the literature the wind farm power variation parameter studies were carried out without taking into account the prevailing wind directions and their potential impact on wind power variation.

1.2. Wind power plant capacity balancing in electrical power system

Wind power plant capacity balancing models. Dynamic balancing capacity control model created by Suwannarat et al (2007) for the central power regulation by electrical transmission system operators is presented in fig. 1.4. It consists of a wind farm and the balancing traditional thermal and gas-turbine power plants.

The main purpose of the automatic generation control system (AGC) for balancing capacity model is to maintain stable established electric power frequency value while allocating generating capacities of generating facilities participating in the operation of the system taking into account generation control error identified (GCE).

The problem is written as follows:

$$GCE = -\Delta P_{\text{Gen}} - \frac{\Delta f}{R}; \tag{1.1}$$

$$\Delta P_{\text{Gen}} = \Delta P_{\text{thermal}} - \Delta P_{\text{wind}}; \tag{1.2}$$

$$\Delta P_{\text{thermal}} = \sum_{i=1}^{n} P_{\text{thermal}} - \Delta P_{\text{thermal}}^{\text{schedule}}; \tag{1.3}$$

$$\Delta P_{\text{wind}} = \sum_{i=1}^{n} P_{\text{wind}} - \Delta P_{\text{wind}}^{\text{schedule}}; \tag{1.4}$$

$$\Delta P_{\text{set}} = K * GCE + \frac{1}{T} \int GCE; \tag{1.5}$$

where ΔP_{Gen}, $\Delta P_{\text{thermal}}$, ΔP_{wind} are the deviation of total power generation, thermal power and wind power from the planned power respectively, Δf is the frequency deviation in the system, 1/R is total frequency bias, ΔPset is the correcting power set-point for all the selected units, K is the proportionality factor (gain), T is the integration time constant.

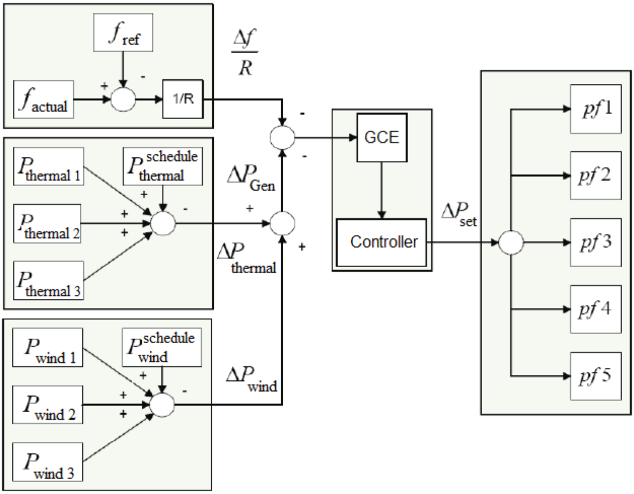


Fig. 1.4 AGV model of balancing system (Suwannarat et al., 2007)

The authors specify that the results given by use the balancing capacity model created indicate that balancing of wind power plant capacities is performed better, and this reduces the flows in transmission lines and allows more precise identification of the development possibilities of wind power plants.

Dynamic balancing power control model presented in the paper of authors (Gelažanskas et al. 2015) comprises such essential generating sources as thermal and hydro power plants able to balance electrical power systems (power generated by use of renewable energy sources and load variations) and energy accumulation systems. The balancing sources such as thermal power plant, hydro power plant, and energy accumulation system, are controlled using different initial signal variation components (the variation between actual and planned wind power plant capacities and load capacities). For this purpose, the model uses filters next in front of the thermal and hydro power plants – "TPP low- pass filter" and "HPP low-pass filter". The structure of dynamic balancing capacity control model is presented in fig. 1.5.

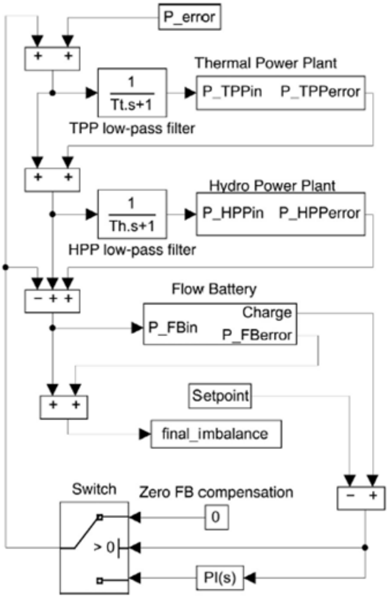


Fig. 1.5 Model of the balanced system (Gelažanskas et al. 2015)

In the balancing system model, the variations of actual and planned system loads or the system saldo is balanced by thermal power plant, hydro power plant, and power accumulation system.

$$P_{\text{error}} = P_{\text{act}} - P_{\text{f}}\,; \tag{1.6}$$

where P_{error} is the initial error, P_{act} is actual power and P_{f} is forecasted power.

Unbalanced power is recorded in a section "non-balance". If parameters of power plants, power accumulation system, and filters are selected correctly, and regulatory reserve power is enough, the capacity difference obtained in a model is equal to zero.

In a model, proportional integral controller "PI(s)" is used for maintaining suitable charge level of energy accumulation system.

Dynamic model control signal of thermal power plant is the following:

$$P_{\mathrm{TPPin}} = (P_{\mathrm{Delta}} + P_{\mathrm{PI}}) \cdot \frac{1}{T_{\mathrm{TPPI}} s + 1}; \tag{1.7}$$

where P_{Delta} is the difference between actual and forecasted wind power (MW), P_{PI} is the power for maintaining ESS charge level (MW), T_{TPP} is the time constant of the TPP filter (s).

Dynamic model control signal of hydro power plant (task) is determined according to:

$$P_{\mathrm{HPPin}} = (P_{\mathrm{Delta}} + P_{\mathrm{PI}} - P_{\mathrm{TPPout}}) \cdot \frac{1}{T_{\mathrm{HPP}} s + 1}; \tag{1.8}$$

where *P*TPPout is the output of TPP (MW), *T*HPP is the time constant of the HPP filter (s).

Dynamic model control signal of energy accumulation system (task) is determined by:

$$P_{\mathrm{ESSin}} = P_{\mathrm{Delta}} - P_{\mathrm{TPPout}} - P_{\mathrm{HPPout}} - P_{\mathrm{PI}}; \tag{1.9}$$

where P_{ESSin} is the output of HPP (MW).

In the balanced system model of Gelažanskas et al (2015), the capacity installed in energy accumulation systems for ensuring the balance in a wind power plant makes 24.8 % of wind power plant installed capacity while EPS is operating in an “island” mode and 6.3 % of wind power plant installed capacity while the plant is operating in the entire system.

Aiming to define the development possibilities of wind power plants in Denmark, electrical power system authors Sorknæs et al. (2014) presented the capacity balancing model according to the demand of thermal power and electricity, and the research of the existing state, as well as future state was performed. By using the program Energy PRO for the model diagram given in fig. 1.6 operating condition matching of combined heat and

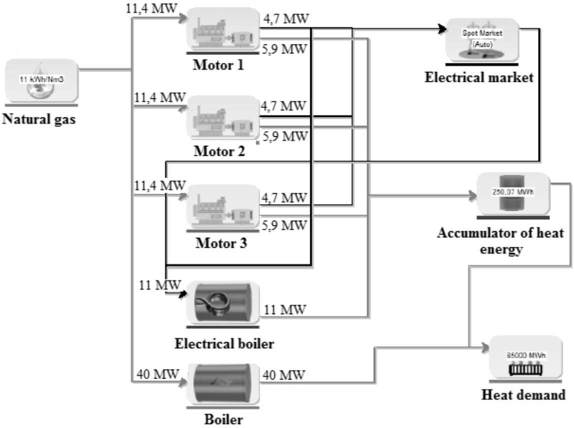


Fig. 1.6 Capacity balancing model diagram according to the demand of heat and electricity (Sorknæs et al. 2014)

power plants, gaseous and electrical boiler houses was modelled under operation circumstances corresponding to variable electrical energy price established by electricity market, including the additional function to participate in electricity balancing market.

The use of combined heat and power plants for wind power plant capacity balancing requires the matching of the heat and electricity generation modes, the problem be solved by employing of heat accumulators (Yang et al. 2015, Kuhi–Thalfeldt 2009, Lund, et al. 2012, Sorknæs et al. 2014) It was provided in the presented model the exchange of natural gas by biogas, and possibility of heat pumps, accumulator charging stations and hydrogen using for balancing of power plants burning the renewable energy resources. It was emphasized that use of heat pumps for capacity balancing of power plants operating on the basis of renewable energy resources according to heat demand of individual householders or centralised heat systems extends the possibilities of wind power plant capacity balancing (Chen et al. 2015). Power balancing was studied in all given research works for the part of common electrical power system, i.e. without creating the small power system which should disconnect in the case of electrical power system failure, thus increasing the reliability of energy supply to consumers (Lu et all. 2006, Hammons 2007).

1.3. Wind farm power prediction systems and models

According to initial data used, WF power prediction models are classified as time series models and numerical weather prediction models (fig. 1.7). Time series models use direct wind speed or WF power measurement data, which then are analysed by time series models to predict the WF power for few hours forward. Long-term predictions are based on the numerical weather prediction models that are more precise than time series models.

A time series model is simple and the prediction error for short time periods (few minutes or hours) might be relatively small, not exceeding several percent, since the atmosphere processes are slow enough. For longer periods, preciseness rapidly decreases and errors might reach even few tens percent.

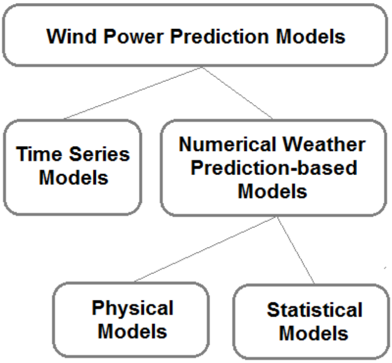


Fig. 1.7 Types of wind farm power prediction models (Marčiukaitis 2007)

Numerical weather prediction models are classified as physical and statistical models (fig.1.7). In physical models, local wind speed in wind farm’s territory is evaluated according to data of numerical weather prediction model and recalculated for the wind farm power prediction. Statistical models calculate WF power prediction according to numerical weather prediction and WF's power measurement data (Marčiukaitis, 2007; Foley, et al., 2012).

WF power prediction using *physical models* is rather imprecise even for one wind power plant. Preciseness of this model in the case of a wind farm decreases even more, since it is complicated to at least more precisely calculate the wind speed in height of wind turbine axis or average wind speed for all plants of a wind farm. It has been identified that the wind speed might be completely different in regards to each wind power plant. Therefore, aiming to decrease system errors of physical models and increase preciseness of power prediction, wind direction is taken into account.

Statistical models are based on inter-relation set between wind farm power measurements and relevant numeric weather predictions. Over time, parameters of such relationship change due to changing weather conditions, wind fluctuations, WF characteristic changes, changes of plants present in the territory of WF, and artificial obstacles. Therefore parameters of statistical relationship are constantly recalculated. In statistical models, the relationship between numerical weather prediction and wind farm power measurement data can set by adaptive regression or artificial neural network methods (Costa, et al. 2008; Gomes, Castro, 2012; Sideratos, Hatziargyriou, 2007). Statistical models possess one evident advantage above physical models: the impact of relief, obstacles, atmosphere stability, and other factors, is constantly checked and assessed by statistical relationship parameters. Prognoses based on statistical models are linked to certain wind farm locality, therefore their system errors automatically decrease. Moreover, statistical models analyse past data and subsequently mistakes can be avoided. Their main shortcoming is the requirement to have measurement data for long enough periods in order to set a statistical model and calculate regression coefficients. Therefore, for newly constructed wind farms such models cannot be used at the beginning of the performance.

Prediction models are assessed according to their precision. Precision of physical and statistical wind prediction models is influenced by accuracy of numerical weather prediction results. Relative average error of wind farm power prediction models depends on prediction period and reaches about 8% of installed power for 24 hours, 8–12% for 36 hours, and 16% for 48 hours. (Costa, A., et al. 2008; Junga, Broadwater, 2014). Since 2012, forward prediction for 24 hours of power generated by all wind farms in Lithuania is performed using physical program model *AIOLOS* developed by Swedish company *VITEC*. Its preciseness is 11% in regards to the average power generated by WFs (Baranauskas, Ažubalis, 2014). It shows high enough preciseness of physical model, since the error has been calculated in regards to the average gross output, but not the installed one. However, it should be noted that lower power predicting errors of the WFs located in larger region appear due to the so-called spatial alignment effect and autocorrelation of errors compared to the prediction errors in separate WFs (Gasset, et al., 2012; Birgiolas, Katinas, 2006).

WF power prediction models have their advantages and disadvantages; however all of them are not precise enough. Therefore, in our research work, the more precise statistical regression model is suggested for wind farm power prediction which assesses wind speed and direction, atmospheric pressure and temperature, systematic errors of wind and atmosphere prediction, location of wind power plants in the territory of wind farm, natural and artificial obstacles, roughness of the earth surface, and permanent variation of them.

In the situation of increasing number of wind power plants, changeable and only partially predicted capacity of them and generation of electricity, electrical power systems experience some problems encumbering the assurance of a permanent balance between the energy generation and consumption in the system, power exchange and marketing of electricity between neighbouring countries. Therefore it is necessary to have available operative power reserves in the electrical power system to ensure the reliable operation of the system. As a result of our research work aiming to overcome the given problems the technique of wind power plant parameters study is established. This technique enables to determine more precisely average values of changeable powers of different duration in the wind farms, standard deviations of average power changes and coefficients of correlation. Results of the study evaluate not only wind speed, but also the direction and the wind power plant location in the farm. There are two proposed models of the small electrical power system enabling to study the possibilities of balancing the gross outputs and energy in wind power plants according to consumer heat and electricity demand. The use of these models enables to determine integrated capacities of wind farms in the small electrical power system and necessary for balancing capacities of combined heat and power plants, capacities of boiler houses and heat pumps, of heat energy accumulators and balanced capacities of solar power plants. The proposed model of wind power plant power balancing is used to study the possibilities to control the short time power deviations and variations of frequency in the small electrical power system. Scientific research of the author proves the possibility of integration the wind power plant capacities into electrical power system and possibility to increase the energy security of the system without reducing the transfer capability of the electrical transmission network.

2. WIND PLANTS ENERGY AND POWER BALANCING AND FORECASTING METHODOLOGY

2.1. Definition of wind power plant parameters

Rapid distribution of renewable wind power plants call increased attention in the safe and realiable operation of the energy system. Also, aiming to safely and possibly more efficiently use renewable wind power, it is neccesary to have reliable wind farm operation indicators and characteristics that would the maximum preciseness evaluate power generated by such plants and create more precise prospective schedules of WF power. For this purpose, WF power variations and their standard deviations, calculated during three different averaging time periods (30 s, 15 min and 1 h), are the main parameters analysed allowing to evaluate variations of power generated, while the averaging time periods selected are relevant for the regulation of active power and system balancing.

For the analysis of the results and the setting of significance intervals, power variation groups are defined.

Aiming to more precisely evaluate WF power variations, the power dependence on wind direction and speed is defined. Therefore power variations and other parameters analysed shall be calculated taking into account wind direction – K:

$$K \in \{\mathrm{N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, NNW}\}.$$

The power variation taking into account wind direction can be calculated as follows:

$$\Delta P_{K,i} = P_{K,i+1} - P_{K,i}; \tag{2.1}$$

where $P_{K,i}$ and $P_{K,i+1}$ – adjacent power values under the same wind direction.

Average value of wind farm power changes can be determined by the formula

$$\overline{\Delta P_K} = \frac{1}{n}\sum_{i=1}^{n} \Delta P_{K,i}; \tag{2.2}$$

where $\Delta P_{K,}$ is power changes due to wind direction, n is the number of power change values.

Standard deviation of gross output changes due to wind direction may be evaluated from the formula

$$\sigma_K = \sqrt{\sum_{i=1}^{n} \frac{1}{n-1}\left(\Delta P_{K,i} - \overline{\Delta P_K}\right)^2} \tag{2.3}$$

Correlation coefficients of two WF variations taking into account wind direction can be defined by the formula:

$$r_{K,12} = \frac{\sum_{i=1}^{n}(\Delta P_{K,1,i})(\Delta P_{K,2,i})}{\sqrt{\sum_{i=1}^{n}(\Delta P_{K,1,i})^2}\sqrt{\sum_{i=1}^{n}(\Delta P_{K,2,i})^2}}; \qquad (2.4)$$

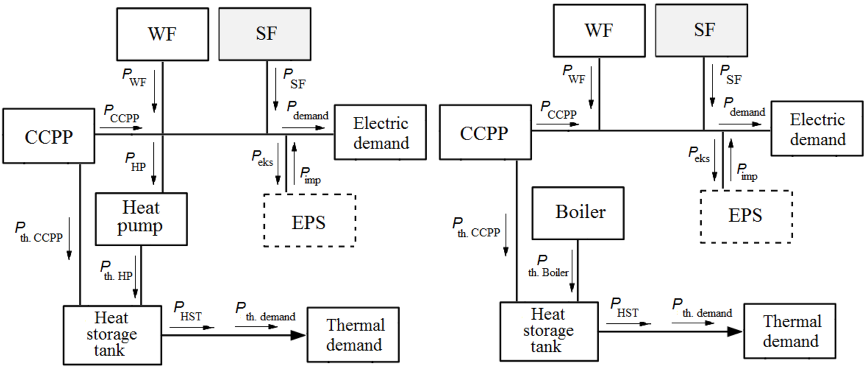
where $\Delta P_{K,1i}$ and $\Delta P_{K,2i}$ are the i-th changes in power generation of the first and the second farms, respectively.

Aiming to identify the influence of wind direction on WF power variation, average power variation arrays taking into account wind direction shall be made.

2.2. Balancing of wind power plant capacity

Balancing model of wind power plant capacity. Two models of the small power system are proposed. Models are devoted to study possibilities of balancing the energy generated by wind power plants in accordance with heat and electricity consumers demand, to determine powers and other technical characteristics of balancing equipment, and to analyse operation conditions in the electrical power system. Models consist of wind farms, combined cycle power plant based on burning of natural gas or biogas, accumulator of heat energy and boiler house (fig. 2.1a) or heat pump using the heat of the earth depth (fig. 2.1b). It is stated by detailed research that in warm periods when the heat demand is reduced and operation conditions of combined heat and power plant are changed small power system encounters with the deficit of electrical energy. Using the electricity accumulators for reducing the lack of energy in the system is inexpedient and ineffective, therefore models are supplemented by solar farms (SF). In the proposed models (fig. 2.1), combined heat and power plant which balances the energy of wind power plants, operates according to electrical load schedule, therefore the generation of heat is independent from the demand. If the excess heat energy is produced it is stored in heat energy accumulator and later when heat lack appears it is supplied to the consumer according to heat demand.

In the second model (fig. 2.1b) additional heat energy is produced by heat pumps instead of a boiler house. If the wind farm generates the excess energy and electricity demand is small, heat pumps produce heat energy and supply it to the consumers, and the excess heat is given away to the heat accumulator. Heat energy stored in accumulators is later supplied to the consumer according to heat demand. If consumers' heats demand increases, heat produced by the pump is reduced, and heat demand is satisfied by combined cycle power plant.



a) b)

Fig. 2.1 Wind plant power balancing models: a) with CCPP and a boiler house, b) with CCPP and a heat pump

Based on the conditions described and WF capacity balancing workflows presented (fig. 2.1), the following equations of balancing SPS hourly capacities are made.

Hourly power balances of WF power balancing model involving CCPP and a boiler are expressed by the equations:

$$P_{\text{demand..}}+P_{\text{eks}}=P_{\text{WF}}+P_{\text{SF}}+P_{\text{CCPP}}+P_{\text{imp;}} \tag{2.5}$$

$$P_{\text{th. demand.}}=P_{\text{th. CCPP}}+P_{\text{Boiler}}+P_{\text{HST}}. \tag{2.6}$$

Hourly capacity balances of WF power balancing model involving CCPP and a heat pump are the following:

$$P_{\text{demand}}+P_{\text{eks}}+P_{\text{HP}}=P_{\text{WF}}+P_{\text{SF}}+P_{\text{CCPP}}+P_{\text{imp;}} \tag{2.7}$$

$$P_{\text{th. demand.}}=P_{\text{th,CCPP}}+P_{\text{th. HP}}+P_{\text{HST}}. \tag{2.8}$$

In both cases the minimisation of the objective function shall be performed:

$$\min\,(P_{\text{eks,}},\ P_{\text{imp}});\tag{2.9}$$

where $P_{\text{demand.}}$ Is an average hourly power of the demand for electricity; P_{eks} is an average hourly power of electricity export to EPS; P_{WF} is an average hourly power of a wind farm; P_{SF} is an average hourly power of a solar farm; P_{CCPP} is an average hourly electric power of a combined cycle power plant; P_{imp} is an average hourly power of electricity import from EPS; $P_{\text{th. demand}}$ is an average hourly of the demand for heat; $P_{\text{th. CCPP}}$ is an average hourly heat of a combined cycle power plant; P_{Boiler} is an average heat of a boiler; P_{HST} is an average hourly of a heat storage tank; P_{HP} is an average electric capacity of a heat pump; and $P_{th. HP}$ is an average hourly heat of a heat pump.

Using balancing models created and knowing actual hourly schedules of electricity and heat consumers for one year as well as meteorological data on wind speed and direction, weather temperature, and solar radiation of the same period of time, it is possible to balance WF capacities. For this purpose it is necessary to define the characteristic of all elements of models created.

2.3. Balancing of wind plant capacities

A mathematical model of the small electrical power system (SEPS) is made for defining the wind power plants with changeable power balancing possibilities. The model consists of the wind farm (WF), combined cycle power plant (CCPP), heat pump (HP), electricity accumulator (EA) and electricity customers (EC) (fig. 2.2). Small solar power plants are not included into the model for complexity and expensiveness of power control.

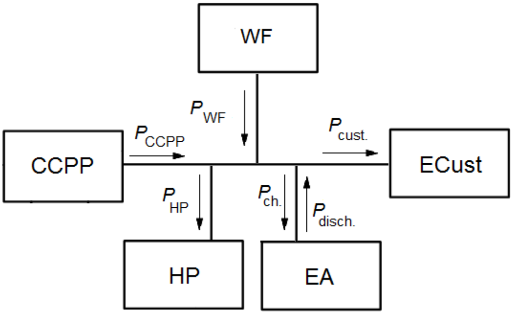


Fig. 2.2 Flow diagram for the model of the wind farm power balancing

A mathematical model of SEPS power balancing is constructed of separate system elements, equivalent diagrams of power circuits and control modules described by algebraic and differential equations. Functional compatibility of SEPS mathematical modules and initial conditions of variables are determined by equations of power balances by evaluation of active and reactive power loss:

$$\begin{cases} P_{WF} + P_{CCPP} \pm P_{EA} - P_{HP} - P_{ECust} - \Sigma P_{\Delta} = 0 \\ Q_{WF} \pm Q_{CCPP} \pm Q_{EA} - Q_{HP} - Q_{ECust} - \Sigma Q_{\Delta} = 0 \end{cases}; \qquad (2.10)$$

where P_{WF}, Q_{WF} is active and reactive power of wind farms, P_{CCPP}, Q_{CCPP} is active and reactive power of combined cycle power plant, P_{EA}, Q_{EA} is active and reactive power of electricity accumulator, P_{HP}, Q_{HP} is active and reactive power of a heat pump, $P_{\mathrm{ECust.}}$, Q_{ECust} is active and reactive power of consumers, $\sum P_{\Delta}$, $\sum Q_{\Delta}$ is sum of losses of active and reactive powers.

Power control mathematical models are constructed for asynchronous motor of heat pump (AM), for synchronous generator (SG) of gas turbine and for electricity accumulator to ensure the maintenance of gross output and total consumption balance in the wind power plants.

The mathematical vector model control method is adapted for the heat pump motor control. Vector components of control model are determined from the analysis of the current and voltage circuit structures. Phase locked loop is applied for synchronisation of stator circuit in accordance with the power system thus ensuring a reliable parameter evaluation at small system parameters swing and harmonics. The current of AM rotor is proportional to the driving torque. In this case, the current is used to control of the active and reactive power. Therefore, for the chosen mode of operation, regulator of rotation speed depends on the parameters of the rotor current and voltage as well as on the value of electromagnetic driving torque. The function 2 s duration prescribed parameter range. The balance depends on the rated active power of the motor and on the control range. Asynchronous motor power control system is able to change the active power with the rapidity of microseconds by changing of the circuit current and voltage vectors (Deksnys, Triškauskas, 2013). The change of voltage and current vectors depends on control range related to electromagnetic driving torque and mechanical braking torque that form the electrical angles between the voltage and current vectors. Interaction of these angles sustains the balance of active power in the provided range.

Mathematical model of combined cycle power plant synchronous generator driven by gas turbine power circuit mathematical model. The power circuit mathematical model of CCPP gas turbine synchronous generator is constructed of rotor and stator equivalent circuits (Shenbo, Tang 2006). Exitation winding of rotating rotor power circuit generates magnetic flux Ψ_{fd}, therefore it is useful to tranform the mathematical model to Park *d*-*q* coordinate system (Kulkarni, Thosar, 2013; Liwei Wang, Hermann, Dommel, 2007). Real and image vector components are separated to use in exitation control system model.

Mathematical model of electricity accumulator is devoted to balance short-time (≤ 2 s duration) power change of the small electrical power system. For this purpose a mathematical model of electricity accumulator is constructed. Equivalent capacitor $\mathbf{C}_{\mathrm{ea}}$ is connected via bipole transistors of direct current DC/DC converters to DC/AC converter direct-current circuit of heat pump wound-rotor asynchronous motor.

By using the given elements of the system, the power balancing model of overall small electrical power system is constructed and can be used to determine the wind farm power balancing possibilities (fig. 2.3).

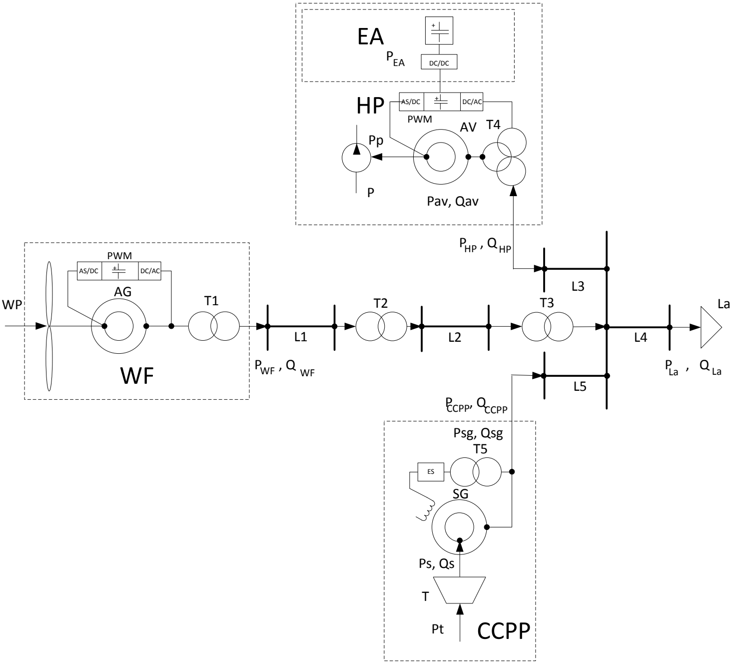


Fig. 2.3 Principal workflow of minor energy system modelled

Active power balance in the electrical power system is determined from the equality of all generator gross output and total consumption of the system. Initial conditions are established under the assumption that values of voltage U_0 and frequency f_0 are rated ones. According to that assumption, the active power change of the small electrical power system in the vicinity of initial values is the sum of partial derivatives:

$$\left|\frac{\partial P_C(U,f)}{\partial U}\right|_0 \Delta U + \left|\frac{\partial P_C(U,f)}{\partial f}\right|_0 \Delta f = \Delta P_G; \qquad (2.11)$$

where P_C is consumer power; ΔU is the change of voltage in the system; Δf is the change of frequency in the system; ΔP_G is the change of gross output.

Power balance equation may be written by use the power changes of the system elements:

$$\left|\frac{\partial P_C(U,f)}{\partial U}\right|_0 \Delta U + \left|\frac{\partial P_C(U,f)}{\partial f}\right|_0 \Delta f = \Delta P_{bal.} + \Delta P_{EA} + \Delta P_{HP} + \Delta P_{CCPP}; \qquad (2.12)$$

where $\Delta P_{\mathrm{bal.}}$ is the change of balancing power; ΔP_{EA} is the change of electricity accumulator active power; ΔP_{HP} is the change of heat pump asynchronous motor active power; ΔP_{CCPP} is the change of CCPP synchronous generator active power.

2.4. Wind farm power statistical regression prediction methodology

Power forecasting possibilities shall be investigated because of the need to predict in advance the gross output of wind farm which is used for operation management of power plants in small electrical power systems and for distribution of consumer loads. Aiming to predict wind farm power, it is necessary to identify the dependence between the gross output of the farm and wind speed, air density, and wind direction, to evaluate the location of plants in the farm, wind and weather parameter prediction discrepancies, the impact of changing external factors, other quantitative and qualitative factors, and to aim for advanced power prediction preciseness. The task will be solved with the help of the multiple regression model (Chatterjee, Simonoff, 2013). For multiple linear stochastic dependence, random change of independent variables defines the change of a dependent variable with certain random error:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_m X_m + \varepsilon; \qquad (2.13)$$

where X_j is independent variables of regression function; β_j is unknown coefficients of regression function of researched population data; and ε is random error.

Having calculated values of the coefficients β_j by the method of least squares, the regression equation can be used for setting the estimate of variable Y with certain preciseness. Assume that variable Y_i was observed for n times $Y_1, Y_2, \ldots, Y_n$ and the independent variable X_j was observed for n times too $X_{1j}, X_{2j}, \ldots, X_{nj}$ (where $j = 1, 2, \ldots, m$). Then multiple linear regression model of analysis can be expressed by matrix equation:

$$\boldsymbol{Y} = \boldsymbol{X} \cdot \boldsymbol{\beta} + \boldsymbol{\varepsilon}; \qquad (2.14)$$

where $\boldsymbol{Y}$ is $(n\times1)$ dependent variable measurement vector; $\boldsymbol{X}$ is $n\times(m+1)$ independent variable measurement matrix; $\boldsymbol{\beta}$ is $(m+1)$ measurement regression equation coefficient vector; and $\boldsymbol{\varepsilon}$ is $(n\times1)$ measurement random error vector.

The expanded matrix can be expressed as follows:

$$\begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix} = \begin{bmatrix} 1 & X_{11} & X_{12} & \cdots & X_{1m} \\ 1 & X_{21} & X_{22} & \cdots & X_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & X_{n1} & X_{n2} & \cdots & X_{nm} \end{bmatrix} \cdot \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_m \end{bmatrix} + \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \vdots \\ \varepsilon_n \end{bmatrix}. \tag{2.15}$$

In multiple linear regression analysis model, variables Y, X_1, X_2 ,..., X_m are quantitative, measured in interval and relative scales, or dichotomous, in m quantity. Linear regression analysis model can be applied, if data meet certain conditions. The main parts of the assumptions for regression analysis are the requirements to random errors ε_i, which show the difference between the observational Y_i value and the value obtained from the regression equation created. These assumptions of linear regression analysis are as follows (Čekanavičius, Murauskas, 2004; McClave, James, 2006; Gaur, Ajai S 2007):

1. Random errors ε_i are normally distributed.
2. Averages of all ε_i are equal to zero, $E\varepsilon_i = 0$.
3. Dispersions of all ε_i are equal (homoscedasticity assumption), $D\varepsilon_i=\sigma^2$.
4. There are no data exclusions.

It has been identified that gross output of the wind farm essentially depends on two quantitative independent variables: air density (ρ) and wind speed (v), and one qualitative variable – wind direction (K). Thus, for the solution of wind farm power prediction task formed, it is relevant to apply regression analysis model for each wind direction:

$$K \in \{\text{N, NNE, NE, ENE, E, ESE , SE, SSE, S, SSW, SW, WSW, W, WNW, NW, NNW}\}\cdot$$

Therefore (2.13) the expression can be simplified and worked out as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon; \tag{2.16}$$

The dependence of gross output generated by certain wind farm and its coefficients upon wind speed and air density based on multiple linear regression analysis model and the expression (2.16) obtained should be calculated. For this purpose hourly prediction data of atmosphere pressure (p_o), temperature (ϑ), wind speed (v), and wind direction (K) were received from Lithuanian Hydrometeorological Service. Statistical hourly data of gross output generated (P) by Benaičiai WF were received from Šventoji Hydrometeorological station. Activity data of four periods in 2009 were used for the establishment of wind farm power dependence and expression of (2.16) coefficients. Hourly data of atmosphere air pressure and temperature were recalculated to the relative air density ρ according to formula:

$$\rho = \frac{p_o}{R\vartheta}; \tag{2.17}$$

where p_o is air density (hPa), ϑ is temperature (K), and R is specific gas constant (287 $JK^{-1}kg^{-1}$).

Since the characteristics of power and the dependence of gross output P upon the product of air density ρ and wind speed v are not linear in changing part of the characteristics, various transformations were applied aiming to obtain linear stochastic dependence. It was determined that the most suitable transformation of WF gross output P dependence upon $\rho \cdot v$ into linear dependence is:

$$Y = \mathrm{Ln}(P), \ X_1 = \frac{1}{\rho \cdot v}. \tag{2.18}$$

The expression (2.18) shows that two independent variables can be replaced by one variable of their product. After assessing two independent variables ρ and v as one variable ρv, multiple linear regression analysis expression applied for the solution of the task becomes linear regression analysis equation of one variable:

$$\mathrm{Ln}(P) = \beta_0 + \beta_1 \frac{1}{\rho v} + \varepsilon; \tag{2.19}$$

where β_0, β_1 are unknown regression equation coefficients of identified wind directions.

The mentioned changes do not affect to the dependence of WF gross output on the product of atmosphere air density and wind speed distribution points. Aiming to identify values of unknown regression (2.19) equation coefficients β_o and β_1, linear regression analysis model was researched using a SPSS (McClave, James, 2006). The correspondence of set regression function obtained to the data was verified using regression model suitability indicators: standard regression error and certainty index. It has been identified that the empirical function duly corresponds to theoretical function. WF power prediction linear regression function (2.19) regression certainty coefficients (*R. Squared)* calculated – $r^2 \in$ [0.961 ÷ 0.988] approximate to unit for all wind directions researched (Table 2.1). Therefore they are correct. The regression function obtained explains the average distribution of values from 96.1% to 98.8% ln P by linear regression in regards to the independent variable $1/\rho v$.

Standard regression errors (*Std. error off the estimate*), changing in the interval from 0.084 to 0.166 and diminishing to zero were calculated. Linear regression equation suitability indicators set for the prevailing wind direction are delivered in Table 2.1. Errors were compared each to other, and the best function with the minor errors was identified in this way. It was identified that the regression function obtained meets the assumptions of residual errors' normal distribution, absence of exceptions, and data homoscedasticity. After the assessment of the correspondence hypothesis and Kolmogorov-Smirnov criterion estimates it is possible to conclude that standardized residual distributions are standard and normal; the hypothesis was not rejected for all wind directions, since ($p \in$ [0.442; 0.988;] and meets the of Kolmogorov Smirnov condition $p > 0.05$.

Table 2.1 Linear regression equation's suitability indicators for prevailing wind direction

Wind Direction, *K*	**R Squared, *r^2***	**Std. Error off the Estimate**	**Kolmogorov-Smirnov criterion, *p***
S	0,988	0,093	0,628
SSW	0,972	0,133	0,880
SW	0,952	0,166	0,570
WSW	0,978	0,134	0,442
W	0,961	0,165	0,712
Not taken into account	0,964	0,154	0,642

The assumption of homoscedasticity, or the quality of conditional dispersions is the requirement that the distribution of residuals shall be the same with each fixed X_{1j} estimate or each fixed prediction estimate $\hat{Y}_i$, i.e. the closer the estimates distribute around X_1 or $\hat{Y}$ axis, the better regression function describes the data analysed. The regression model is sensitive to the violation of this assumption. In the case researched, the distribution of standard residuals was constant.

The influence of the independent variable $1/\rho v$ on changes of dependent variable P was verified using zero hypothesis H_0: $\beta_1=0$, which was rejected in favour of the alternative hypothesis H_a: $\beta_1 \neq 0$. It confirms the existence of linear dependence between $1/\rho v$ and P and the significance of all sample and population regression equation coefficients, since significance level is $p<0.001$ (Table 2.2).

Estimates b of all regression equations' coefficients β and standard residuals, Student statistics, significance levels, and confidence intervals were identified for all wind directions. The above-mentioned coefficients and parameters are given in Table 2.2 only for the prevailing wind direction.

Table 2.2 Coefficients and assumption parameters of linear regression equation for prevailing wind direction

Wind Direction *K*	**Coefficient of regression equation β_j**			**Student's statistics**	**Significance Level *p***	**95 % Confidence interval for β_j**	
	Estimate b_j	**Value**	**Std. Error**			**Lower boundary**	**Upper boundary**
S	b_0	3,958	0,036	110,192	0,000	3,886	4,029
	b_1	-22,258	0,294	-75,712	0,000	-22,845	-21,671
SSW	b_0	4,024	0,050	80,706	0,000	3,925	4,124
	b_1	-22,602	0,404	-55,907	0,000	-23,405	-21,799
SW	b_0	4,320	0,068	63,823	0,000	4,186	4,454
	b_1	-24,859	0,556	-44,747	0,000	-25,961	-23,757
WSW	b_0	4,282	0,039	108,602	0,000	4,204	4,361
	b_1	-24,051	0,321	-74,928	0,000	-24,686	-23,416
W	b_0	4,263	0,084	50,792	0,000	4,096	4,431
	b_1	-24,124	0,599	-40,276	0,000	-25,320	-22,928
Not taken into account	b_0	4,123	0,055	89,751	0,000	3,812	4,434
	b_1	-23,347	0,465	-61,981	0,000	-25,451	-21,242

It can be stated on the basis of the analytical results assessed that the linear regression assumptions are met and the linear regression analysis function can be used in practice. Therefore the WF power for wind direction set can be identified using the following linear regression equation:

$$\mathrm{Ln}(\hat{P}) = b_0 + b_1 \frac{1}{\rho v}. \tag{2.20}$$

Having applied the backward transformation the following exponential regression equation for the prediction of WF power is obtained:

$$\hat{P} = e^{b_0 + b_1 \frac{1}{\rho v}}. \tag{2.21}$$

The results of linear regression analysis show that linear regression equation (2.21) meets the assumptions of linear regression and can be used for the prediction of WF power from minimal to the installed power. Expression (2.21) can be transformed to the simpler one and comfortable to use form:

$$P = C \cdot e^{-\frac{b}{\rho v}}; \tag{2.22}$$

where C is a coefficient equal to the dimension e^{b_0} , b is a coefficient equal to b_1.

Values of WF prediction formula coefficient *C* and *b* for prevailing wind directions are presented in Table 2.3.

Table 2.3. Power prediction expression coefficients

Wind direction	**WSW**	**W**	**SW**	**SSW**	**S**	**Not taken into account**
C	72,385	71,023	75,189	55,924	52,353	61,744
b	24,051	24,124	24,859	22,602	22,258	23,347

It is determined by the research that dependence of the average WF power on wind direction significant and can reach considerably high differences from the average power under increasing estimates of the product of air density and wind speed. If the product ρv reaches the estimate of 17 kg/m^3 m/s the difference from the average power can reach about 5 MW and be equal to about 30% of farm's installed power. It means that the assessment of wind direction and the prediction of WF power is not only relevant, it is necessary.

Power prediction expressions' (2.22) dependence upon the product of air density and wind speed, in standard atmosphere (p_o = 1013,25 hPa; ϑ=15 °C; density ρ =1,225 kg/m^3; g=9,81 m/s^2) in Benaičiai WF with generators of V100-2,75 type is given in Figure 2.3. Benaičiai WF power characteristics (fig. 2.4) visually show the influence of wind direction and allow approximate prediction of gross output generated by the farm under the atmosphere parameters predicted.

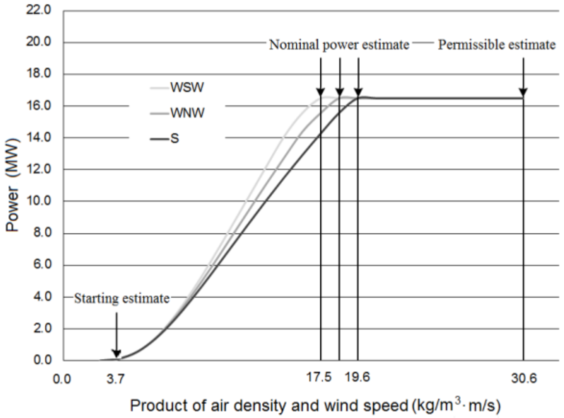


Fig. 2.4 Dependencies of Benaičiai wind farm power on the values of ρv under standard atmosphere conditions

Significant differences of Benaičiai WF power for various directions are influenced by the location of plants and natural or artificial obstacles causing turbulent air movements.

All in all it can be stated that statistical regression WF power prediction model evaluates wind speed and direction, atmosphere parameters, their prediction system errors, plant location within the farm, natural and artificial obstacles, ground roughness, permanent parameter variation and allow more precise prediction of wind farm power.

2.5. Main results of the chapter

1. Technique of the wind farm parameter research constructed enables to analyse wind power plants power change parameters and to determine parameter values necessary for power balancing and control in electrical power systems.
2. Wind farm energy and power balancing technique and models established according to consumer electricity and heat demand contribute to determine technical parameters of the small electrical power system components and possibilities of their independent operation.
3. Statistical regression wind farm power prediction technique and model are developed. Main their advantage is estimation of wind speed and direction, parameters of atmosphere, systematic errors of their prediction, location of plants in the farm, natural and artificial obstacles, the roughness of earth surface and permanent variation of these parameters.

3. WIND FARM ENERGY AND POWER BALANCING AND FORESIGHT STUDY

3.1. Statistical analysis of wind farm power variation

Characteristics of the investigated object. For the application of wind farm capacity and power balancing and planning methodology created, it is necessary to identify characteristics and parameters of WF generating capacities. The following wind farms operating in Lithuania were selected as the object of the investigation: *Benaičiai* (with the installed capacity of 16.5 MW), *Sūdėnai* (14 MW) and *Vėjas I* (30 MW) WFs built in the Western part of Lithuania, in the seaside area of the Baltic Sea (fig.3.1.). The distance between WFs *Benaičiai* and *Vėjas I* (Rūdaičiai village) is 18 km, and between WFs *Sūdėnai* and *Benaičiai* – 3 km.

Fig. 3.1. Deployment of *Sūdėnai*, *Benaičiai* and *Vėjas I* (Rūdaičiai village) wind farms.

For the purpose of research, measured data of maximum changes in power generation over the following time periods of the year 2009 and measured loads of Lithuanian power system over the same time periods were selected:

I measurement period 28/03/2009–04/04/2009 (7 days);
II measurement period 25/04/2009–07/05/2009 (12 days);
III measurement period 16/05/2009–28/05/2009 (12 days);
IV measurement period 16/07/2009–22/07/2009 (6 days).

For the purpose of investigation of power generation dependence on wind speed and direction, parameters of wind speed and direction have been measured at the territory of *Benaičiai* WF at height of wind turbines of wind power plants; data has been averaged for the 10-min time steps.

Lithuanian power system loads and power generation by WFs within selected periods of time were calculated for 1-s time steps with the exception of *Sūdėnai* WF – its power generation was calculated for 1-min. time step. Measurement data on 1-s step changes allow to investigate power generation process of wind power plants by changing time intervals of power generation averaging.

Investigation of variation in wind power generation. For the purpose of investigation of WF generation process and its influence on the electric power system, 30-s and 15-min step changes in average power generation were selected, as they are necessary for activation of primary and secondary reserves of power generation, as well as for frequency and power generation control (Ažubalis, 2011). Hourly variations in power generation were also investigated.

Hourly capacity variations of wind farms analysed and local loads during selected periods are presented in fig. 3.2.

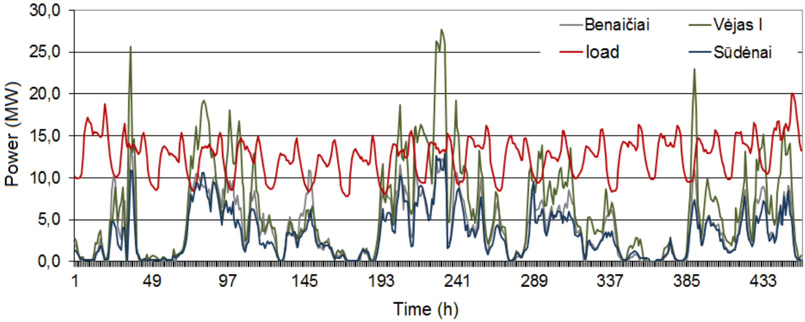


Fig. 3.2. Hourly capacity variations of wind farms in *Vėjas I*, *Benaičiai*, *Sūdėnai* and loads

It can be seen from analysis of the results given that an absolute value of standard deviation (σ) for the 15-min average power changes in the wind farm Vėjas 1 is 1,25 MW, and it is 2,05 MW in all wind farms investigated. However, the overall relative standard deviation in all plants is less than standard deviations of power changes in separate farms and is equal to 3,39 % (Table 3.1).

Maximum increasing change in Vėjas 1 is 13,0 MW, and the decreasing one is 11,3 MW. Maximum increasing change in all plants is 18,8 MW, and the decreasing one is 22,4 MW. It can be seen from the given data that 3 σ confidence interval 6,15 MW doesn’t exceeds the 1/3 of maximum power change, therefore such value of confidence interval may be insufficient for analysis of wind power plant operating modes.

Table 3.1 lentelė. Gross output change parameters in wind farms

Wind farm	Installed capacity MW	Intervalo of power averaging											
		30 s duration						15 min duration					
		Standard deviation		Maximum power change				Standard deviation		Maximum power change			
				+ ΔP		– ΔP				+ ΔP		– ΔP	
		MW	%	MW	%	MW	%	MW	%	MW	%	MW	%
Vėjas I	30	0,46	1,53	5,27	17,6	4,11	13,7	1,25	4,20	13,0	43,3	11,3	37,7
Benaičiai	16.5	0,39	2,36	4,26	25,8	4,63	28,1	0,81	4,48	5,11	30,0	9,75	59,1
Sūdėnai	14	–	–	–	–	–	–	0,74	5,29	6,34	45,3	6,67	47,6
Total	60,5	0,61	1,31	5,80	9,59	5,29	8,74	2,05	3,39	18,8	31,1	22,4	37,0

Influence of wind speed and direction on generated power. For the purpose of determining the dependence of wind power generation on wind direction and speed, measurements were taken in the area of *Benaičiai* WF at the height of wind turbines (80 m) of wind power generation units. Based on these findings, a wind rose was made depicting wind time step and wind direction (fig. 3.3). It was found that in Lithuania, at the seaside, winds predominantly occur in Western (W) – Southern (S) sector with the average wind speed of 6.3–8.1 m/s. The most stable wind in this sector was found to be of WSW direction, with the average wind speed of 7.6 m/s. Although sufficiently strong but short time winds of E and ESE directions may also occur, with the average wind speed reaching of 8,3 m/s.

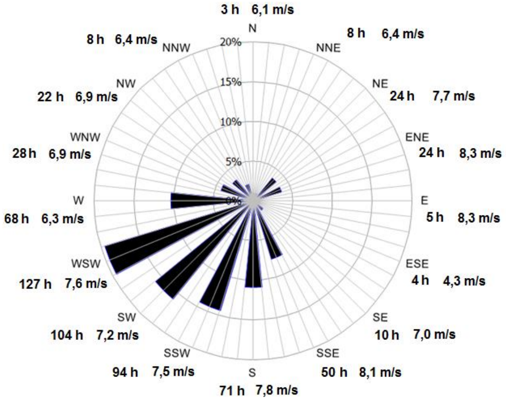


Fig. 3.3. Wind rose based on time.

To find the effect of wind direction on power generation by *Benaičiai* WF arrays of 10 min changes in average power generation were made with respect to wind directions (averages for 10 min time intervals), and diagrams were made enabling to determine maximum power difference between the predominant wind directions.

The obtained curves of power generation by WFs (fig. 3.4) were approximated by the 5th degree polynomials that are jointly expressed as follows

$$P = a + b_1 v + b_2 v^2 + b_3 v^3 + b_4 v^4 + b_5 v^5; \tag{3.1}$$

where P is the power of WF; v is the wind speed; a and b are statistical parameters of the function.

The obtained average wind speeds for 10 min time intervals ranged from 3,5 m/s to 12 m/s.

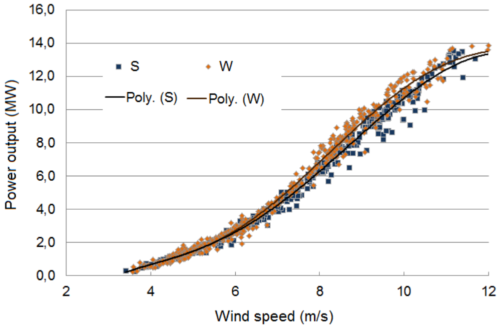


Fig. 3.4. Curves of Benaičiai WF gross output

Values of gross powers beyond the limits of such wind speeds were not included in the data arrays, since the wind farm operation is unstable under minimum and maximum wind speed, and it can distort the results due to the locality of wind, technical and operating-mode reasons, and unplanned disconnections.

Analysis of research findings show that wind directions had influence on the amount of WF gross output by at all wind directions under research, and maximum power generation difference was found to exist between Western (W) and Southern (S) wind directions. Under the same wind speed, the minimum difference of power generation was found to exist at 5 m/s wind speed. Furthermore, with increasing wind speed power generation difference increases too, and at 9 m/s wind speed reaches 4.1% of the installed capacity (see fig. 3.4. and Table 3.1). Afterwards, a decrease in power generation difference could have been determined by the volume of statistical data.

Table 3.2. Values of power generation by *Benaičiai* WF at W and S wind directions

Wind directions	Parameters	Wind speed				
	V, m/s	7,0	8,0	9,0	10,0	11,0
W	*P*, MW	4,6	6,8	9,2	11,3	2,7
S	*P*, MW	4,2	6,3	8,5	10,7	2,4
	Δ P, %	1,9	3,3	4,1	3,5	1,9

In order for the forecasts of variation in WF power generation to be more precise, theoretical curves suggested by producers should be recalculated based on the findings of statistical observations while taking into consideration wind directions.

Measured wind speed values and calculations allow to determine minimum distances between WFs for which a research of influence of power generation variation is purposeful using the following formula:

$$\ell_{\text{park}} = t_{\text{P}} \cdot v_{\text{W}}; \tag{3.2}$$

where t_{P} – time step of wind power generation averaging; v_{W} – wind speed.

In this particular case, under selected 15-min time step of wind power generation averaging, the minimum distance between WFs has to be at least 3,6 – 12,6 km. Consequently, it is worth examining interdependencies of changes in wind power generation by the wind farms that are more distanced from each to other, i.e., WFs *Vėjas I–Benaičiai* and *Vėjas I–Sūdėnai*.

Research results (Table 3.3) show that wind direction has a sufficiently significant effect on WF power generation changes, and both correlation and standard deviations of wind power generation variation achieve highest values at perpendicular wind direction to WF deployment line (wind direction W), and lowest values – at wind blowing in a direction of WF deployment line (wind direction S). In the case of WFs *Vėjas I – Benaičiai*, the lowest correlation coefficient is 0,11, the highest – 0,51, and in the case of WFs *Vėjas I – Sūdėnai* – 0,07 and 0,45, respectively. The lowest standard deviations of WF power generation variations examined under the same wind directions were found to be 3,01 % and 2,95 %, and the highest – 4,95 % and 4,77 %, respectively. Relative standard deviations of variations of total power generation of two WFs were found to be lower than those of variations of total power generation of each WF individually at almost all wind directions (Table 3.3).

Table 3.3 Parameters of WF wind power generation changes based on wind directions

Wind power plants	Parameters	Wind directions								
		NE	**ENE**	**SSE**	**S**	**SSW**	**SW**	**WSW**	**W**	**WNW**
Vėjas I Benaičiai	$\boldsymbol{r_{12}}$	0,33	0,27	0,23	0,11	0,24	0,20	0,29	0,51	0,20
	***σ*, %**	4,30	2,80	3,44	3,01	4,52	4,30	4,09	4,95	3,22
Vėjas I Sūdėnai	$\boldsymbol{r_{12}}$	0,32	0,31	0,15	0,07	0,13	0,13	0,36	0,45	0,35
	***σ*, %**	3,64	2,95	4,09	2,95	4,55	4,32	4,32	4,77	3,18
Vėjas I	***σ*, %**	4,33	3,33	4,33	2,66	5,33	5,33	4,66	5,00	3,33
Benaičiai	***σ*, %**	7,27	5,45	4,24	6,06	6,06	5,45	5,45	6,66	4,84
Sūdėnai	***σ*, %**	5,00	5,71	7,14	5,00	7,14	5,71	5,71	6,42	4,29

Relative standard deviations of 15-min step changes in average power generation for each WF individually are also dependent on wind direction, and vary in a quite large range (Table 3.3) as well as the fact that they are different from relative standard deviations calculated without taking into consideration wind directions. Calculations of power system regimes and determination of the effect from wind farms and range of their power generation variations as well as operating power reserves require assessment of the effect determined by wind direction and geographical deployment of wind farms.

3.2. Wind power plant energy balance research

Wind power plant balancing research is performed according to the WF energy balance model outlined in Chapter 2, using the most applicable (Connolly, et al., 2010) Energy PRO software package. Wind power plant alternating power balance capabilities can be determined using the SPS structure schemes shown in figures 2.1 a), b). The year-long wind speed, solar radiation and hourly air temperature data needed for park-generated power calculations were obtained from the Lithuanian Hydrometeorological Service. The heat and electricity consumer needs are selected realistically: heating for city region that has about 11 thousand inhabitants and centralised heating. The heating need is composed of 48 930 MWh for heating, 8 000 MWh for hot water, 7 940 MWh – for heat loss in the pipelines that change due to surrounding temperature. The total heating need is 64 870 MWh. The consumer electricity need, modelled according to the first structure scheme, comprises 91 301.5 MWh (Table 3.3) and 100 775.1 MWh according to the second scheme (Table 3.4). This increase in energy need is determined by the used surplus electric energy of the heat pump during wind power plant balancing.

During the period of modelling, in order to avoid equipment release stop settings, combined cycle for the plant and heat pump during balancing, the lowest possible generated and used power is set to be equal 1 MW.

Using the iterative energy balance calculations based on the first energy balance model (fig. 2.1 a) and ensuring local consumer electricity and heat needs (fig. 3.5), it is determined that combined cycle power plant of 20 MW electrical power and 20 MW heat power is to be installed in small power system as well as boiler house of 18 MW capacity and heat accumulator of 50,1 MW (Table 3.4). Moreover it is appropriate to install the 10 MW solar power farm for reducing the summer electricity lack. In such a case wind-farm 6 MW power may be balanced in the small power system without transmission the energy to electrical power system.

Analyses of the research results show that local consumer electricity and heat energy demand in the small EPS is balanced during the heating season (fig. 3.5), and during the warm season demand of the heat is satisfied, but electric power balance is not achieved (fig. 3.5). During this season deficient electrical energy is imported to consumers from electrical power system on normal operation conditions.

In the case of emergency operation and independent small electrical power system and usual EPS deficient part of electric energy is compensated by gas turbo-generator which forced operation reduces the efficiency of combined cycle power plant but helps to balance the power generation and the consumer electricity demand. Results of research show that it is necessary to use the heat accumulator at all the year with the aim to achieve the heat balance (fig. 3.5).

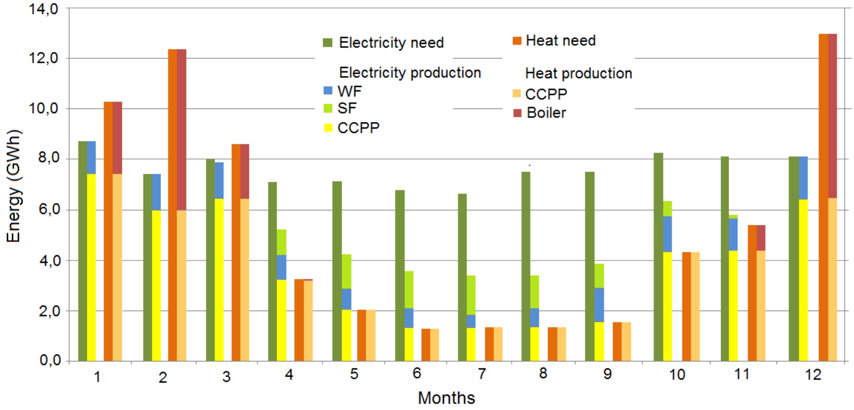


Fig. 3.5 Results of electric and thermal energy balancing (Model with CCPP and boiler house)

Table 3.4 WF energy balancing by CCPP and boiler technical parameters determined

Parameter	Need	CCPP	BH	HA	SF	**WF**
Power, MW	–	$20_e+20_š$	18	–	10	**6**
Electricity, MWh	91 301,5	45 793,3		–	8 556,4	**13 641,5**
Heat, MWh	64 870,0	45 793,3	19 076,7	50,1	–	–

It is determined from WF energy balancing results with help of the first model that WF balancing according to heat demand efficiency index is 0,092 MW_e/GWh_h, heat and electric power expansion index for distributed generation combined cycle power plants is 0,308 MW/GWh_h, boiler house power expansion index is 0,722 MW_h/GWh_h and solar farm power expansion index is 0,154 MW_e/GWh_h.

Results of the iterative power balancing according to local consumers heat and electricity demand by use the second power balancing model (fig. 2.1b) show that it is necessary to install in the SPS the combined cycle power plant of 20MW electrical power and 20 MW heat power, 6 MW electrical load, 18 MW heat pump with mean heat efficiency COP=3 and 50,1 MWh heat capacity accumulator (Table 3.5). Besides, it is established that it may prove useful to install 13 MW solar power farm for reducing electricity shortage in summer. Then 16 MW wind farm power shall be balanced in the small electrical power system without transmission of electricity to electrical power system (Table 3.5).

It can be seen from result analyses that consumption and generation of electricity related to small power system is balanced in winter season, but in summer electricity balance is not achieved (fig. 3.6). In this case, during normal operation conditions, the lacking part of electricity is imported from electrical power system. If small power system and usual EPS operates separately during emergency conditions this part of electricity is compensated by turbo-generator which operation reduces the efficiency of combined cycle power plant, but electricity generation and consumers demand is in balance state. Results of research show that it is necessary to use the heat accumulator at all the year with the aim to achieve the heat balance (fig. 3.6).

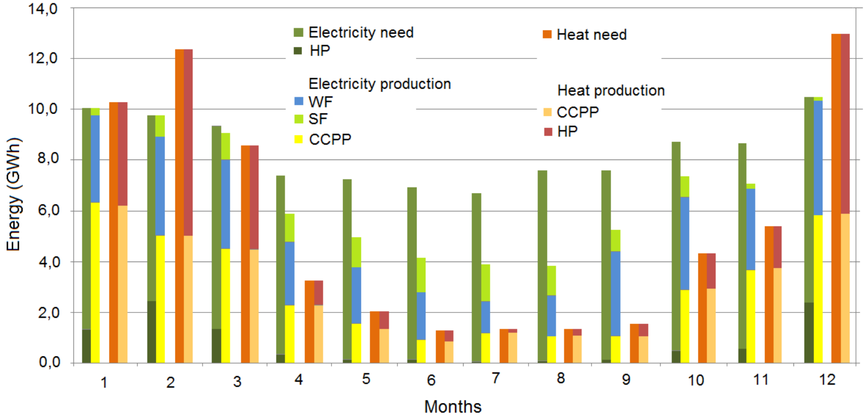


Fig. 3.6 Results of electric and thermal energy balancing (model with CCPP and heat pump)

Table 3.5 WF energy balance CCPP and heat pump set technical parameters

Parameter	Need	CCPP	HP	HA	SF	**WF**
Power, MW	–	$20_{e}+20_{\check{s}}$	$-6_{e}+18_{\check{s}}$	–	13	**16**
Electricity, MWh	100 775,1	36 449,2	9 473,6	–	10 907,2	**35 008,8**
Heat, MWh	64 870,0	36 449,2	28 420,8	50,1	–	–

Research results show that the use of heat pumps for generation of heat energy according to consumers demand enables to balance 16 MW of the wind farm installed capacity instead of 6 MW without heat pumps. Use of heat pumps increases 2,7 times the effectiveness of wind power plant energy balancing.

On the basis of results by using the second model of wind power plant energy balancing (Table 3.5) it is stated that wind farm power balancing according to heat consumers demand efficiency index is 0,247 MW_e/GWh_h, heat and electric power expansion index for distributed generation combined cycle power plants is 0,308 MW/GWh_h, heat pumps power expansion index is 0,278 MW_h/GWh_h, heat accumulator capacity expansion index is 0,772 MW_h/GWh_h and solar farm power expansion index is 0,200 MW_e/GWh_h.

Annual demand of centrally supplied heat energy in Lithuania is 10TWh (Association of Lithuanian Heat Supplirs [ALHS], 2012). For the heat demand of cities rejected annual heat demand of district towns us 3,8 TWh. Using power expansion indexes of small electrical power system equipment, it is possible to employ the given heat demand for installation into electrical power system additional 350 MW (first model) or 939 MW (second model) of wind power plant capacity. To achieve such wind power plant capacity integration it is necessary to install into electrical power system 1170 MW of electric and heat capacity distributed generation combined cycle power plants, 1056 MW of boiler house or heat pump capacity and 2934 MWh of heat accumulators. Besides, it is possibility to install in the electrical power system 585 MW (first model) or 760 MW (second model) of solar power farm capacity.

3.3. Wind power plant power balance research

Investigations of power balancing in small electrical power systems are carried out through the use of power balancing mathematical model created in the section 2.3 and the second energy balancing model (fig. 2.1b) for estimated power values of wind power plant, combined cycle power plant and heat pump, and by use of the forecast predicted by regression model of wind electric power forecasting. Combined cycle power plant modelled consists of 13,5 MW gas turbine and 6,5 MW steam turbine installed capacity. Capacities of primary and secondary reserves are chosen on the basis of Benaičiai wind power plant generation change 30 s standard deviation $3\sigma = 1{,}17$ MW and 15 min $-3\sigma=2{,}43$ MW values determined by statistical studies (Table 3.1). The average hourly power value generated by wind power plant and equal to 12,2 MW is predicted 24 h before by use of statistical regression model developed to forecast power of wind farm in the established time interval. Active power loss of small electrical power system is included into consumers' power demand. Forecasted 12,9 MW power of consumer demand is established on the basis of known relative main error equal to 2 % of load power (Baranauskas, Ažubalis, 2014). Main hourly 4,8 MW electric power of heat pump is determined according to heat demand established by wind farm energy balancing model. Main hourly 5,5 MW power of combined cycle power plant is computed according to (2.10) balance equation. Unbalanced power appears due to deflection of WF gross output and load power from predicted power values. That power deflection is established according to the equation

$$P_{\text{balance}} = P_{\text{WFavail}} - P_{\text{WFpredict}} - P_{\text{Loadreal}} + P_{\text{Loadpredict}}; \qquad (3.3)$$

where P_{balance} is the balanced power, P_{WFavail} is the wind farm available power, $P_{\text{WFpredict}}$ is the wind farm predicted power, P_{Loadreal} is the real load power and $P_{\text{Loadpredict}}$ is the predicted load power. All power components are measured in MW. Balanced power of small electrical power system distribution in EA, HP and CCPP is determined by the following equation

$$P_{\text{balance}} - P_{\text{HPcons}} - P_{\text{HPset}} \pm \Delta P_{\text{EA}} - P_{\text{CCPPgo}} + P_{\text{CCPPset}} = P_{\text{SEPSunb}}; \qquad (3.4)$$

where P_{HPcons} and P_{HPset} are consumed and preset heat pump powers, ΔP_{EA} are the electricity accumulator power changes, P_{CCPPgo} and P_{CCPPset} are gross output and preset power of combined cycle power plant, and P_{SEPSunb} is unbalanced power of small electrical power plant.

Power equipment dynamic parameters necessary for SEPS power balancing are presented in Table 3.6. Program PowerFactory14 was used for investigation of WF power balancing.

Table 3.6 Modelled small electrical power system dynamical parameters

Parameter	L	T2	T3	EA	HP	CCPP
U_n (kV)	110	110/20	110/10	2	10	10
P_n (MW)	-	-	-	3,5	6	20
S_n (MV*A)	-	25	25	-	-	-
C_n (F)	-	-	-	2,8	-	-
J (kg/m^2)	-	-	-	-	301,1	2085,3
ω (rad/s)	314	314	314	-	157	314
τ (s)	0,006	0,07	0,07	0,005	0,15	0,275

In the case when power unbalance of the SEPS appear according to equation 3.4 heat pump is influenced at first increasing or reducing power consumption during microseconds. If heat pump power consumption is of limiting preset value or the value close to it power balancing is performed by electricity accumulator of large capacity. CCPP reaction to power unbalance is the slowest.

Common unbalance of all EPS may be detected due to control system of SEPS response time and inertia of balancing equipment. Results of balancing investigation in SEPS are given in fig. 3.7 and fig. 3.8.

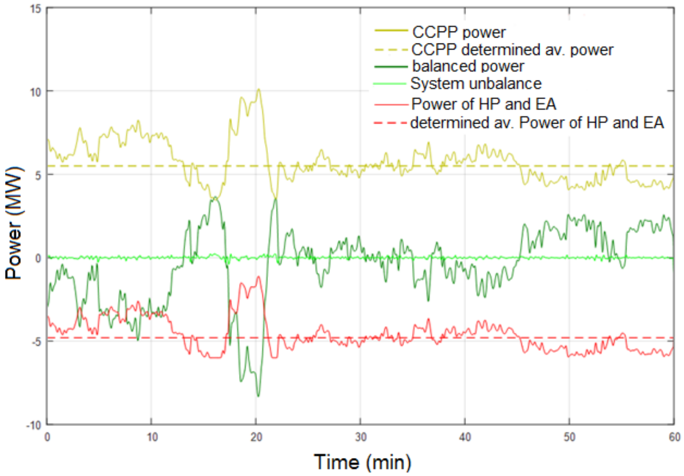


Fig. 3.7 Change of WF power and unbalance

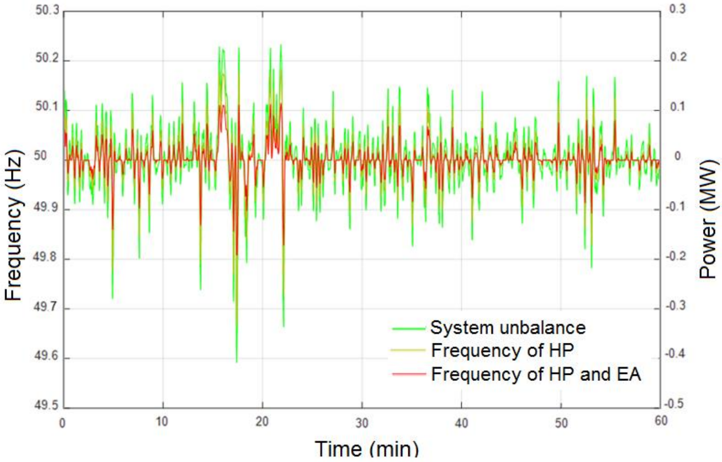


Fig. 3.8 Frequency changes in SEPS

Wind power plant farm power balancing research results show that for equipment selected technical parameters and received characteristics in case of the largest determined WF power change, SEPS can be balanced minimally exceeding permitted frequency deviation limit of 0,4 Hz. By use electricity accumulator maximum deviation of frequency is 0,19 Hz, i. e. doesn’t exceeds the limit ± 0,2 Hz. Therefore in the case of EPS failure researched SPS stays stable and is able to supply consumers by quality heat and electricity.

3.4. Wind farm power statistical regression prediction model's precision research

Statistical regression model for the prediction of wind farm power, consisting of the prediction and statistical parts, has been proposed on the basis of linear regression analysis methodology formed in Chapter 2, exponential regression equation obtained (20) and regression equation coefficients for wind directions set (fig. 3.9).

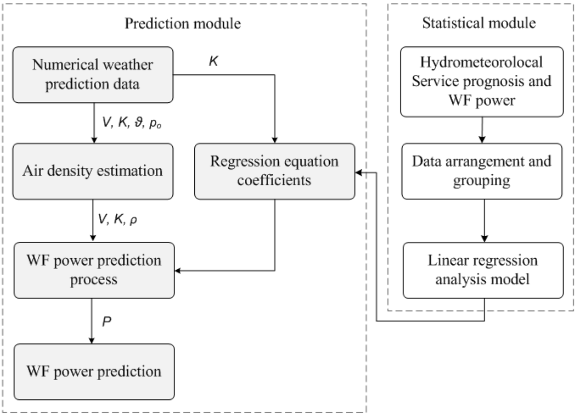


Fig. 3.9 Wind farm power prediction statistical regression model

The statistical module accumulates data from Hydrometeorological Service and wind speed, wind direction, atmosphere pressure and air temperature predictions data for the same period from the closest station, while WFs SCADA system directly delivers the information about the gross output and the number of plants operating. These data are grouped according to wind directions; the data when not all plants were operating are rejected. Gross output of wind farm data are analysed and compared to wind parameters by using linear regression analysis model; exclusions are identified and rejected. Based on finally selected data, regression analysis model calculates regression equation coefficients for each wind direction. Coefficients set are periodically renewed and sent to the prediction module.

For the prediction of WF power, numerical weather prediction block of the prediction module is uploaded with the prediction period data on wind speed and direction as well as other atmosphere metrological data, grouped according to wind directions. After that, air density estimates are calculated for all wind directions and all necessary regression equation coefficients are chosen from the block of regression equation coefficients according to wind directions. WF power prediction block identifies the farm's power for the prediction period according to regression equation (20) and wind directions. WF power prediction can be used for the organisation of the wind farm's work, evaluation the possibilities of participation in the electricity market, etc.

One of the most comprehensive periods, namely 15-22 July 2009, has been chosen for the prediction preciseness research. Numerical weather prediction data on wind and atmosphere in this period were regenerated by *Harmonie* model. Benaičiai WF’s wind speed and direction were regenerated using data base of *HIRLAM* model and recalculated to the height of 100 m vertically, while horizontally it was recalculated so that wind prognosis and WF’s coordinates would match as accurately as possible. For the period set, numerical weather prediction on hourly wind and atmosphere data were delivered 24 hours forward and renewed four times per day (12 AM, 6 AM, 12 PM, and 6 PM). The proposed prediction model (fig. 3.10) was used for the prediction of Benaičiai WF gross output.

Data on Benaičiai WF actual gross output and wind speed and direction values measured in the farm for the same period were used for statistical regression model preciseness research. Estimates of relative average errors (SVP) were calculated hourly for the comparison and preciseness evaluation of prediction models:

$$SVP = \frac{1}{nP_{\text{inst}}} \sum_{i=1}^{n} \left| P_{i\,\text{fact}} - P_{i\,\text{pr}} \right|, \tag{3.5}$$

where n is number of data estimates; $P_{i\ \text{fact}}$ is actual power; $P_{i\ \text{pr}}$ is predicted power, and P_{inst} is installed power of wind farms.

WF power prediction, using statistical regression model created, precision analysis and the results obtained show that hourly estimate of one-week equated daily relative average error, taking into account wind direction, changes from 7,51% to 9,72%, and increases up to 8.16–10.91 % of WF’s installed power without taking into account wind direction (fig. 3.10). After calculation of equated day relative average error, it has been identified that power prediction errors, taking into account wind direction, do not exceed 8,66%, while without taking into account wind direction the value of error increases up to 9,24%. For the assessment of model developed, the same power predictions were made by comparative time series model; and it was identified that hourly relative average error fluctuates in a rage of 8,73–

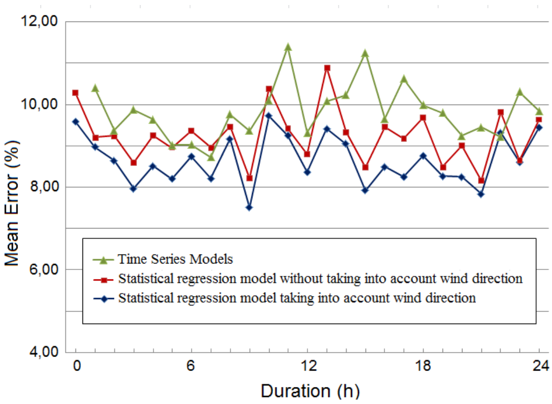


Fig. 3.10 Wind farm power prediction’s relative average errors

11,39%, while daily relative average error reaches 9.82% of WF's installed power.

More precise WF power fluctuation prognosis during the next 24 hours is necessary for operators of power-supply system and wind farm owners aiming to develop balance equipment work schedules and participate in the electricity market.

The prediction is made for 21 July 2009; the initial data are given in Figure 3.11. The diagrams show also the predicted average wind speed per day, WF actual wind speed of 10 minutes, and actual average gross output of the farm per minute.

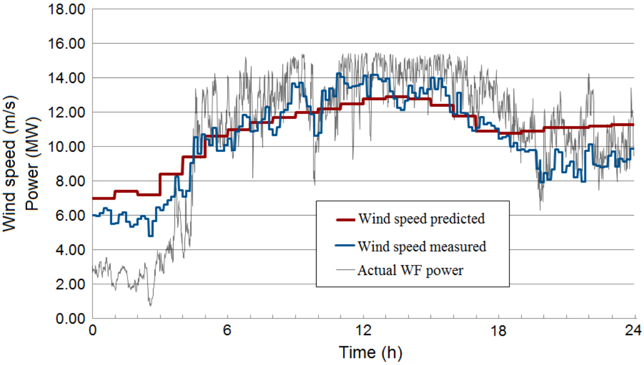


Fig. 3.11 Wind farm's day time predicted, measured wind speed and the gross output (21/07/2009)

The predicted wind speeds and actual wind speeds per day are quite similar, however the prediction of prognosis is not the same ant it is not sensitive to short-time changes of wind speed. This may have quite a significant influence on the preciseness of statistical regression power prediction model.

Hourly WF power of one day (fig. 3.12) was predicted on a basis of initial prediction data and WF's power prediction statistical regression model; the data were renewed each 6 hours (6 AM, 12 PM, and 6 PM). The figure also shows WF average gross output per minute and per hour.

The analysis of predicted and measured data shows (fig. 3.12), that discrepancies in predicted and actual power during the first three hours of the operation may be explained by the operation of not all plants due to too low wind speed at the some wind plants. Results of the calculation of WF's average 5,43 m/s wind speed in 10 minutes interval show that the wind speed next to some wind plants was from 3,3 to 5,9 m/s on the same time. Wind plants of V100–2,75 type in Benaičiai farm start operating when the average wind speed of 10 minutes reaches 4,0 m/s and stop when the wind speed is 3,0 m/s. Such WF work settings are used aiming to reduce the number unnecessary connections to the electrical network. It shows that wind plants cannot start operating on the same time, if the wind speed is close to the initial WF operation speed depending on plants' layout in the farm and different wind speeds. Also, in initial wind speed prognosis it was not possible to more precisely evaluate the reduction of wind speed at 10–11 o’clock AM and after 6 o’clock PM. The diagram (fig. 3.12) shows that the initial prognosis of 0,00 PM and 6 PM were not precise enough for the last four hours of the day. It also affected total preciseness of WF power prediction.

The estimated one-day relative average error for non-regenerated prediction is 7,52 %, while the estimate of relative average error for regenerated prediction each 6 hours decreases down to 7,42%. Based on the analysis of research results, it can be concluded that the statistical regression power prediction model created is suitable and well-regarded to prediction wind farm power.

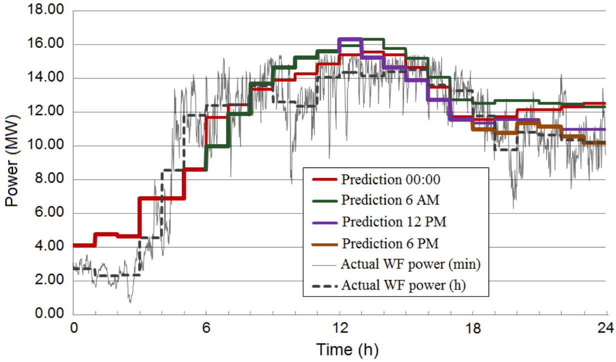


Fig. 3.12. Wind farm’s predicted and actual power per day (21/07/2009)

After the comparison of model results with the studies of other authors given in literature, it was identified that prediction errors obtained are similar or in some cases even lower than typical relevant average errors in the most of models that fluctuate in a range of 10% in regards WF’s installed power (Costa, A., et al. 2008; Junga, Broadwater, 2014).

The results obtained allow it to be stated that the statistical regression prediction model developed is suitable for WF power prediction and can be a versatile prediction model taking into accounts not only wind parameter errors, but also the effect of changing WF environmental factors.

4. CONCLUSIONS

Wind farm energy and power balancing according to electricity and heat demand of local consumers as well as statistical regression prediction technique and models are presented in the disertation. They are devoted to study possibilities of wind power plants integration into electrical power system. The technique proposed enables to develop in electrical power system idependently controlled small electrical power systems and to determine their technical parameters by use of proposed models. Assurance of quality operation conditions for systems created possesses a positive influence to electrical power system. Results of scientific study allow to conclude the following statements.

1. Standard deviations of wind farm main power changes of 30 s duration doesn‘t exceed 1,31 % of capacity installed, and power change correlation between farms is positive but weak and equal to 0,01. These parameters of 15 min duration main power changes increase to 3,39 % and 0,53 correspondingly. An influence of wind direction and geographical location of plants on the Benaičiai farm gross output constitutes 4,2 % of total capacity installed.
2. Balancing of 350 MW of wind power plants is possible on the purpose to meet total district heat demands in Lithuania if additional heat is produced in boiler houses and up to 940 MW is generated by heat pumps without reducing the transfer capability of electricity transmission network and by installing of 1170 MW of distributed generation combined cycle power plants.
3. Frequency deflection in small electrical power systems slightly exceeds ±0,4 Hz due to balancing of wind farm changeable power by combined cycle power plant and heat pump. On conditions of the electricity accumulator used deflection of frequency doesn‘t exceeds ± 0,2 Hz. It can be stated that in the case of total failure in the electrical power system the small power system stays stable, successfully operates and supplies quality heat and electricity to consumers.
4. Improved wind farm power prediction model assesses the wind speed and direction, atmosphere pressure and air temperature, systematic errors of wind and atmosphere prediction, location of power plants in farm territory, natural and artificial obstacles, roughness of the earth surface and permanent changes of these parameters. Relative mean one day error of the model used doesn‘t exceeds 7,52% of installed farm capacity.

5. REFFERENCES

ANDRIUŠKEVIČIUS, R., ir kt., Vėjo elektrinių generuojamos galios svyravimų ir jų galimos įtakos Lietuvos elektros energetikos sistemos darbui įvertinimas. // Lietuvos mokslų akademijos leidykla, *Energetika*. 2004, nr. 3, p.45–50.

AŽUBALIS M., et al. Estimation of the Feasible Wind Power in a Small Power System. // *Electronics and Electrical Engineering*. – Kaunas: Technologija, 2011. No. 1(107). p. 79–82.

BARANAUSKAS, A., and M. AŽUBALIS. The evaluation of the load and wind power forecasting errors // Electrical and control technologies: proceedings of the 9thinternational conference on electrical and control technologies ECT 2014 / Kaunas University of Technology, IFAC Committee of National Lithuanian Organisation, Lithuanian Electricity Association. Kaunas: Technologija. ISSN 1822–5934. 2014, p. 162–167.

BIRGIOLAS, E., ir V. KATINAS. Vėjo srauto parametrų kitimo dėsningumų tyrimas Lietuvos pajūryje. // Lietuvos energetikos institutas, Lietuvos mokslų akademijos leidykla, *Energetika* 2006. Nr. 2. P. 29 – 33.

CONNOLLY, D., et al. 2010. A review of computer tools for analysing the integration of renewable energy into various energy systems, Applied Energy 87(4) [interaktyvus]: 1059–1082. [žiūrėta 2012 03 16] Priega per: http://www.sciencedirect.com/

COSTA, A., et al. A review on the young history of the wind power short-term prediction *Renewable and Sustainable Energy Reviews*, [interaktyvus] 2008 Volume 12, Issue 6, August 2008, Pages 1725–1744. [žiūrėta 2013 04 19] Priega per: http://www.sciencedirect.com/

CHATTERJEE S., and J. S. SIMONOFF. Wiley Handbooks in Applied Statistics: Handbook of Regression Analysis : *NJ*, USA: Wiley, 2013.- 252 pp

CHEN, X ., et al. Increasing the Flexibility of Combined Heat and Power for Wind Power Integration in China: Modeling and Implications. [interaktyvus] Power Systems, IEEE Transactions on 2015 Volume:30, Issue: 4 ISSN: 0885–8950 p. 1848 – 1857 [žiūrėta 2015 02 24] Priega per: http://ieeexplore.ieee.org/

ČEKANAVIČIUS V., ir G. MURAUSKAS. Statistika ir jos taikymai. D.2- Vilnius: TEV, 2004.- 272p. ISBN 9955-491-16-7

DEKSNYS R. P., and R. STANIULIS. Penetration and integration of wind power plants into Lithuanian power system // Oil Shale, Estonian Academy Publishers, 2009 ISSN 0208–189X, Oil Shale, Vol. 26, No. 3 Special, pp. 319–330

DEKSNYS R. P., and D. ALIŠAUSKAS. Transient processes and dynamic of variable speed pump storage unit // Oil Shale, Estonian Academy Publishers, 2013 ISSN 0208–189X, Oil Shale, Vol. 30, No. 2S, pp. 244–256

ERNST, B. Short – Term Power Fluctuations of Wind Turbines from the Ancillary Services Viewpoint. Institut für Solare Energieversorgungstechnik Königstor 59 D-34119 Kassel Germany 2005, [interaktyvus]. [žiūrėta 2014 03 20] Priega per: http://www.iset.uni-kassel.de

FOLEY, M., et al. Current methods and advances in forecasting of wind power generation *Renewable Energy* [interaktyvus] 37 2012 1e8 [žiūrėta 2013 04 19] Priega per: http://www.sciencedirect.com/

GASSET, N., et al. Comparison of Wind Flow Models for Wind Resource Assessment in Wind Energy Applications *Energies* 2012, 5, 4288-4322; doi:10.3390/en5114288 [žiūrėta 2014 03 22] Prieiga per: http://www.mdpi.com/1996-1073/5/11/4288

GAUR, AJAI S., (2007) Statistical methods for practice and research: a guide to data analysis using SPSS. New Delhi: Response Books.

GELAŽANSKAS, L., et al. Hybrid wind power balance control strategy using thermal power, hydropower and flow batteries. Electrical Power and Energy Systems 74 (2016) 310–321. 2015 [interaktyvus]. [žiūrėta 2015 08 16] Priega per: http://www.sciencedirect.com/

GOMES, P., and R. Castro. Wind Speed and Wind Power Forecasting using Statistical Models: AutoRegressive Moving Average (ARMA) and Artificial Neural Networks (ANN) *International Journal of Sustainable Energy Development* (IJSED), Volume 1, Issues 1/2, March/June 2012. V.

HAMMONS, T. J. Dispersed generation and its impact in europe on power system structure and secure power system operation. *Cybernetics & Systems* July 2007. [interaktyvus]. [žiūrėta 2013 04 20]. Priega per internetą http://ieeexplore.ieee.org

HEDEGAARD, K., et al. Wind power integration using individual heat pumps - Analysis of different heat storage options. [interaktyvus] *Energy* 11/2012; 47(1):284–293. DOI: 10.1016/j.energy.2012.09.030 [žiūrėta 2015 03 21] Prieiga per: http://www.researchgate.net/

YANG, Y., et al. The large-scale wind power integration using the integrated heating load and heating storage control. [interaktyvus] PowerTech, Conference, Eindhoven. IEEE 2015, p. 1–6 [žiūrėta 2015 08 14] Priega per: http://ieeexplore.ieee.org/

JUNGA, J., and R. BROADWATER, Current Status and Future Advances for Wind Speed and Power Forecasting Renewable and Sustainable *Energy Reviews* [interaktyvus] Volume 31, March 2014, Pages 762–777 [žiūrėta 2015 04 25] Priega per: http://www.sciencedirect.com/

KUHI–THALFELDT R., and J. VALTIN Combined Heat and Power Plants Balancing Wind Power// Estonian Academy Publishers, Oil Shale, 2009, Vol. 26, No. 3 Special, pp. 294–308 ISSN 0208–189X

KULKARNI, S. S. AND A. G. THOSAR. Mathematical Modeling and Simulation of Permanent Magnet Synchronous Machine, *International Journal of Electronics and Electrical Engineering*, vol. 1, 2013

Lietuvos šilumos tiekėjų asociacija [interaktyvus] [žiūrėta 2014-03-30]. Prieiga per: http://www.lsta.lt/files/statistika/19493_LSTA_Ukines%20veiklos%20apzvalga_2012_WEB.pdf

LIWEI WANG J. J. et al. Re-examination of Synchronous Machine Modeling Techniques for Electromagnetic Transient Simulations, IEEE *TRANSACTIONS ON POWER SYSTEMS*, [interaktyvus] vol. 22, 2007. 1221 - 1230 [žiūrėta 2013 04 14] Priega per: http://ieeexplore.ieee.org/

LU, Y., et al. Intelligent Islanding Technique Considering Load Balance for Distribution System with DGs. *Cybernetics & Systems* October 2006. [interaktyvus]. [žiūrėta 2013 04 20]. Priega per: http://ieeexplore.ieee.org

LUND, H., et al. From electricity smart grids to smart energy systems e A market operation based approach and understanding. [interaktyvus] *Energy*.

06/2012; 42(1):96–102. DOI: 10.1016/j.energy.2012.04. [žiūrėta 2015 03 21] Prieiga per: http://www.researchgate.net/

MARČIUKAITIS, M. Vėjo elektrinių galios prognozavimo galimybės Lietuvoje // Lietuvos energetikos institutas, Lietuvos mokslų akademijos leidykla, *Energetika*. 2007. T. 53. Nr. 3. P. 72–76

MCCLAVE, JAMES T. Statistics for business and economics. (2006) Upper Saddle River : Pearson Prentice Hall

SHENBO YU. and R. TANG. Electromagnetic and Mechanical Characterizations of Noise and Vibration in Permanent Magnet Synchronous Machines, IEEE *TRANSACTIONS ON MAGNETICS*, [interaktyvus] vol. 42, 2006. 1335 – 1338 [žiūrėta 2013 04 14] Priega per: http://ieeexplore.ieee.org/

SIDERATOS, G. and N. D. HATZIARGYRIOU. An Advanced Statistical Method for Wind Power Forecasting Power Systems, [interaktyvus] IEEE *Transactions on*, 2007, Volume 22 , Issue 1 ISSN : 0885-8950 p. 258 – 265 [žiūrėta 2014 03 24] Priega per: http://ieeexplore.ieee.org/

SUWANNARAT, A., et al. Power System Operation with Large Scale Wind Power Integration. *Power Tech*, 2007 IEEE Lausanne [interaktyvus]. [žiūrėta 2015 08 16] Priega per: http://ieeexplore.ieee.org/.

SORKNÆS, P., et al. Overview of current status and future development scenarios of the electricity system in Denmark – allowing integration of large quantities of wind power [interaktyvus] Facilitating energy storage to allow high penetration of intermittent renewable energy 2013 [žiūrėta 2015 02 27] Priega per: www.store-project.eu

WAN, Y. Summary Report of Wind Form Data September 2008. Technical Report, NREL/TP-500-44348 May 2009. [interaktyvus]. [žiūrėta 2014 03 20] Priega per: http://www.nrel.gov/docs/fy09osti/44348.pdf

PUBLICATIONS ON THE SUBJECT OF THE DISSERTATION

Articles published in scientific publications situated in the International databases

In the Institute for Scientific Information database “ISI Web of Science’’ Publications with a citation index

1. Deksnys, Rimantas Pranas; **Stankevičius, Aldas**; Investigation of wind power generation in Lithuania // Oil Shale. Tallin, Estonian Academy Publishers. ISSN 0208-189X. 2011, Vol. 28, sp. iss. SI. 2011.

2. Deksnys, Rimantas Pranas; **Stankevičius, Aldas**; Statistical analysis of power generation of wind parks // Elektronika ir elektrotechnika = Electronics and Electrical Engineering. Kaunas, KTU. ISSN 1392-1215. 2012, nr. 2(118). 2012.

In other international database publications

3. Deksnys, Rimantas Pranas; **Stankevičius, Aldas**; Investigation of changes in power generation in wind power parks // Electrical and Control Technologies: proceedings of the 6th international conference on Electrical and Control Technologies ECT 2011 / Kaunas University of Technology, IFAC Committee of National Lithuanian Organisation, Lithuanian Electricity Association. Kaunas : Technologija 2011. p. 299-302. ISSN 1822-5934.
4. Deksnys, Rimantas Pranas; **Stankevičius, Aldas;** Modelling and analysis the compensation of power fluctuation of wind power farm // Electrical and control technologies : proceedings of the 8th international conference on electrical and control technologies ECT 2013, May 2-3, 2013, Kaunas, Lithuania / Kaunas University of Technology, IFAC Committee of National Lithuanian Organisation, Lithuanian Electricity Association. Kaunas, Technologija. ISSN 1822-5934. 2013.
5. Deksnys, Rimantas Pranas; **Stankevičius, Aldas**; Modelling and analysis of wind and solar generation // Electric power quality and supply reliability: 9th international conference PQ2014, June 11-13, 2014, Rakvere, Estonia : conference proceedings / Tallinn University of Technology. Piscataway, NJ: IEEE, 2014. p. 139-142.

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REZIUMĖ

Darbo tikslas yra sukurti kintančia galia dirbančių elektrinių energijos ir galios balansavimo modelius, įvertinančius vietinių vartotojų elektros ir šilumos energijų poreikį ir nustatančius mažosios energetikos sistemos įrenginių parametrus.

Mokslinis naujumas:

1. Sukurta saugios ir savarankiškai dirbančios mažosios energetikos sistemos sudarymo metodika vėjo elektrinių parkų energijai ir galiai balansuoti pagal vietinių vartotojų elektros ir šilumos poreikius, nesumažinant elektros perdavimo tinklo pralaidumo.
2. Statistinė regresinė vėjo elektrinių parko generuojamos galios prognozavimo metodika papildyta matematiniais modeliais, leidžiančiais išsamiau įvertinti vėjo elektrinių parko generuojamą galią įtakojančius veiksnius ir padidinti prognozavimo tikslumą.

Disertacijoje atliktus mokslinius tyrimus apibendrina išvados:

1. Nustatyta, kad tirtų vėjo elektrinių parkų 30 s trukmės vidutinės galios pokyčių standartiniai nuokrypiai yra nedideli ir neviršija 1,31 % įrengtosios galios, o galios pokyčių koreliacija tarp parkų yra teigiama, bet silpna 0,01. Vėjo elektrinių parkų 15 min. trukmės vidutinės galios pokyčių standartiniai nuokrypiai padidėja iki 3,39 % įrengtosios galios, o teigiama galios pokyčių koreliacija tarp vėjo elektrinių parkų padidėja iki 0,53. Taip pat nustatyta, kad vėjo krypties ir elektrinių geografinio išsidėstymo įtaka Benaičių parko generuojamai galiai sudaro iki 4,20 % įrengtosios suminės galios.
2. Nustatyta, kad užtikrinant visos Lietuvos rajoninius šilumos poreikius būtų galima subalansuoti iki 350 MW vėjo elektrinių galios, kai papildoma šiluma gaminama katilinėse ir iki 940 MW – šilumos siurbliais, nesumažinant elektros perdavimo tinklo pralaidumo ir įrengiant iki 1 170 MW galios paskirstytosios generacijos kogeneracinių elektrinių.
3. Nustatyta, kad balansuojant vėjų elektrinių parko kintančią galią kogeneracine elektrine ir šilumos siurbliu mažosios elektros energetikos sistemos dažnio nuokrypis nežymiai viršija ±0,4 Hz, o panaudojus ir elektros energijos kaupiklį dažnio nuokrypis neviršija ±0,2 Hz. Šie rezultatai rodo, kad įvykus totalinei elektros energetikos sistemoje avarijai, sukurta mažoji energetikos sistema galėtų likti stabili ir sėkmingai dirbti bei aprūpinti vartotojus kokybiška šiluma ir elektra.

4. Patobulinto vėjo elektrinių parko galios prognozės modelio, įvertinančio vėjo greitį ir kryptį, atmosferos slėgį ir temperatūrą, vėjo ir atmosferos prognozių sistemingąsias paklaidas, elektrinių išdėstymą parko teritorijoje, natūralias ir dirbtinas kliūtis, žemės paviršiaus šiurkštumą ir nuolatinį jų kitimą, vienos paros santykinė vidutinė paklaida neviršija 7,52 % įrengtosios galios.

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