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The Modelling of Operation of Wind-Driven Power Plant of Small Capacity

Roman Zinko, *Lviv Polytechnic National University, Institute of Engineering Mechanics and Transport*

Abstract. **The use of graphs is proposed for the research of operation of autonomous low-going wind-driven power plant, which is assigned for work under conditions of weak and mild air flows. Calculation scheme is formed on the basis of graph of structure of the vehicle constructive scheme. Further, the graph of level structure of couplings of generalized coordinates of mathematical model is written. It allows writing a mathematical model of the corresponding difficulty depending on the set tasks of the research. Equations make it possible to research and forecast mode of its work under various conditions of the wind loading as well as selection of power.**

Keywords: **structural schemes, structural synthesis of the mechanism, graphs of structure of couplings of generalized coordinates, autonomous wind-driven power plant, electrodynamic brake, optimal control.**

I. INTRODUCTION

The problem of energy supply becomes topical in the modern world. It is interwoven with issues of ecology and economical consumption of the existent resources. Special place among alternative resources of energy is given to the energy of air masses, which is widely used in the world practice.

The characteristic feature of air masses (AM) of Ukraine is their relatively small power density that does not allow extensive usage of world practice experience of wind-driven energy plant building (WEP). That is why the elaboration of cheap WEP of small single power supply which works by weak average annual winds is urgent now. They can be important for small enterprises with technological processes of low energy consumption. They can also be proposed as the alternative to the electricity transmission lines for the development of green tourism, hotel business in the mountain area and outside cities.

II. THE ANALYSIS OF RECENT STUDIES

The principle of operation of profile (specific) rotating blades of wind wheel (WW) in the air flow is examined in works [1-6]. The classification of wind turbines is proposed in works [7-11], taking into consideration tendencies of their development. The comparison of characteristics of wind turbines with blades of screw and sail types has been carried out. There is also defined power, which is chosen by the section of blade of elementary area of low-going wind wheel of sail type. Experimental researches of wind speed change in the plane of WW rotating under the full-scale conditions have been conducted depending on the frequency of the WW rotation. It is done for the detection of dependency of wind speed distribution on the winded area of WW [12-14]. The algorithm of control that provides a maximal power of WEP in the scheme “generator-rectifier-inverter” with the variable frequency of the generator rotation, has been elaborated and examined on the imitative model. All the above-mentioned can be seen in the work [15,16].

III. GENERAL PART

It is necessary to solve the task of power balance – during arbitrary energy consumption – for the provision of work of WEP in the typical modes. Similarly, it is necessary to provide conditions of work of electric generator in the wide range of wind speed change. The use of low-going wind wheel with spring regulator of blade rotation and electrodynamic brake can be considered a possible variant for the solving of the task. The use of low-going wind wheels within the construction of WEP makes it possible to use them in districts with low and medium speeds of wind flows, as well as setting directly near the dwelling houses. Spring regulator, besides regulating functions, provides protection of wind wheel blades from damages during squally rushes of wind.

Two tasks appear by the projecting of autonomous WEP. Firstly, it is necessary to ensure work conditions of electric generator during high speeds or wind rushes simultaneously with little selection of generated capacity or its absence. Secondly, it is important to support energy supply under the conditions of low speed of wind or calm wind. All these problems can be solved, by using a circuit of feedback with an element of regulation of reverse redirection of power and accumulator of electric energy in the chain of transmission of power from the wind wheel to the customer. The amount of energy, detached from wind stream for the saving of general balance, is carried out with the help of spring regulator that changes the angle of wind wheel rotation with regard to direction of wind. Structural scheme of WEP with electrodynamic brake and spring regulator of wind wheel is presented in the Fig.1

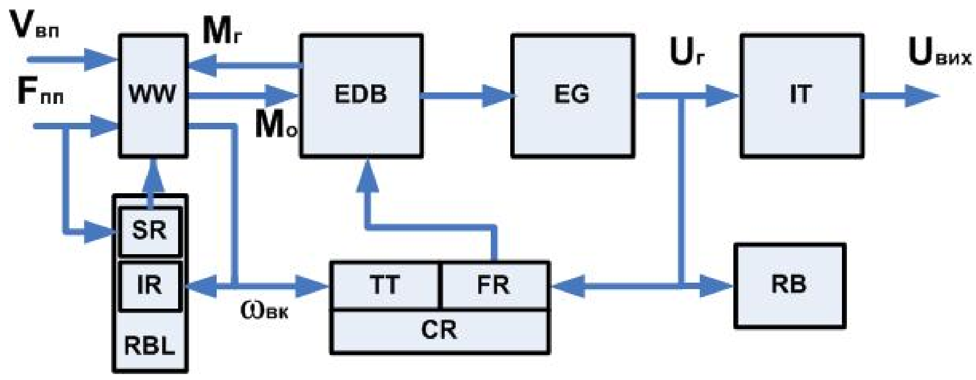


Fig.1. Structural scheme of WEP:
WW – wind wheel; EDB – elecrodynamic brake; EG – electric generator; IT – intermediate transformer; RBL – regulator of the blade location; SR – spring regulator; IR – inertial regulator; FR – force regulator; RB – rechargeable battery; TT – tachotransformer; CR – central regulator.

Wind stream at the speed $V_{ВП}$ acts upon wind wheel (WW) on the structural scheme. Rotational moment Mo is transmitted on the electric generator (EG) through the shaft of eletrodynamic brake (EDB). Produced by an intermediate transformer (IT), electric energy is formed into the qualitative sinusoid voltage Uвих that is transmitted to the customers. Little excessive voltage is used for the charging of rechargeable battery (RB), which creates reserve energy supply at the absence of generated capacity. During the breach of power balance that excels the norms of initial voltage Uг of electric generator (EG) or excels the calculating speed of rotation $\omega_{вк}$ of wind wheel, signals come into the central regulator (CR) from the tachotransformer (ТП) and initial outlets of electric generator (EG). The central regulator (CR) produces a control signal for the force element (FE), which transmits part of the initial power of electric generator (EG) to the electrodynamic brake (EDB). Electrodynamic brake (EDB) creates additional braking torque Mr on the shaft of wind wheel (WW), stabilizing speed of its rotation on the account of blades turning against resistance of elements of spring regulator (SR). Autonomous WEP that is built on the basis of structural scheme and designed for the average statistical speed $V_{ВПS}$ for the place of its erection can provide reliable and qualitative electrical energy generation.

Let us write kinematic scheme of WEP with the use of graphs of its structure [17]. The graph of constructive scheme structure of vehicle is such a graph that shows couplings of vehicle elements taking into consideration its constitution and external influence. The element of scheme – chain – is depicted as a circle, and the rigid kinematic coupling between two elements – as the straight line, spring coupling – as the wavy line (Fig. 2).

It is necessary to use a graph of structure of the level couplings of coordinates of mathematical model for the determination of complexity of the model and its structure [18, 19]. The graph of structure of generalized coordinate couplings of the mathematical models is the one that displays enumeration of generalized coordinates in mathematical models and couplings between them. These coordinates are placed according to the levels of dependencies. These levels are marked one after another from the bottom to the top, starting at zero. It is done for the representation of the level of dependencies of the one generalized coordinates on the other.

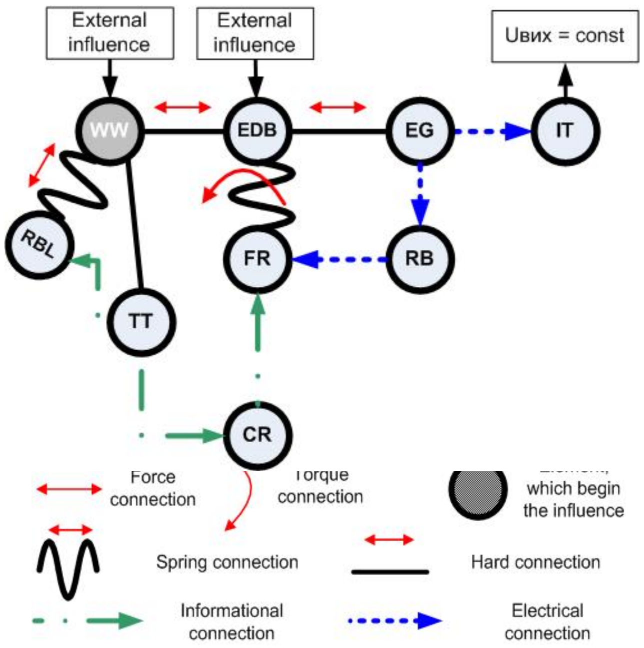
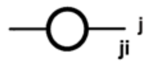


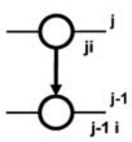
Fig. 2. Graph of structure of WEP

Such marking is used in the graphs of structure of generalized coordinate couplings:

i-та generalized coordinate of 0 level that corresponds to the absolute coordinate;



i-та generalized coordinate of j-level that corresponds to the relative coordinate;



subordinate connection (indicator shows direction of the subordination of the generalized coordinates: i-та coordinate of j- го level of dependency is subordinated to the i-й (j-1)-го of the dependency level)

The structure of levels of couplings between generalized coordinates is displayed in Fig.3.

Three absolute coordinates $\varphi_{вк}$, $\varphi_{ед}$ and $\varphi_{ег}$ are placed on the Zero level

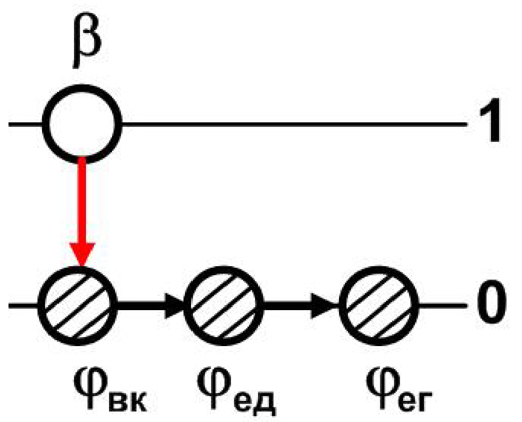


Fig.3. The graph of structure of level couplings between generalized coordinates of the projected mathematical model.

The process of calculation and construction of autonomous WEP, which is carried out according to the beforehand set technical characteristics corresponding to the conditions of territory of their erection, is impossible without the analysis of the typical modes of work. Nominal WEP parameters are calculated under the conditions of generating the nominal power by the average annual wind speeds $V_{ВПном}$. Calculations on the reliability are carried out under the critical conditions or in specific modes. The parameters of modes are set into the generalized system of equations for the calculation of the basic characteristics and for the constructive calculations. Analyzing conditions of WEP work, four typical modes can be distinguished: minimal, nominal, excessive and critical.

Upon the minimal mode, speed of the wind stream $V_{ВП}$ is insufficient for the minimal possible operational voltage on the outlets of the electric generator (EG).

Energy supply of customers is maintained owing to the charge of the rechargeable batteries (RB), and the duration of work on such mode Tp is determined $Q_{АБ}$ by the capacity of rechargeable battery $I_{сп}$ and average current of consumption:

$$TP = \frac{Q_{АБ}}{I_{сп}} \tag{1}$$

The capacity of the rechargeable battery (RB) is calculated according to the set values Tp and $I_{сп}$.

Nominal mode corresponds to the calculating average statistical speed of the wind. The selected by the wind wheel voltage is equal to the nominal, and voltage $U_{Г}$ on the outlets of the electric generator (EG) equals nominal voltage $U_{Гном}$, current $I_{АБ}$ equals charge or discharge of the rechargeable battery (RB), and current $I_{ЕД}$ of electrodynamic brake (EB) feeding is equal to zero. Thus, in the generalized system of equations values are substituted:

$$\begin{cases} V_{вп} = V_{вп.мом} \\ \omega_{вк} = \dfrac{d\varphi_{вк}}{dt}\omega_{вк.мом} \\ U_{г} = U_{г.мом} \\ I_{г} = I_{сп} \\ I_{АБ} = I_{ЕД} = 0 \end{cases} \tag{2}$$

Excess mode is characterized by the higher than nominal wind speed $V_{ВП}$, but such speed that doesn not come outside the possible calculating values. In such a mode speed of the wind wheel $\omega_{вк}$ rotation is higher than the nominal value, voltage $U_{Г}$ of the generator gives the possibility to create current that goes to the charge of rechargeable battery, and the excessive current of the generator is transmitted to the elecrtodynamic brake (EDB); braking torque and the action of the stream squeezes spring elements, turns blade under the lower angle of the turning to the wind stream, approaching speed of the wind-wheel rotation to the nominal value:

$$\begin{cases} V_{вп} > V_{вп.мом} \\ \omega_{вк} \ge \omega_{вк.мом} \\ U_{г} \ge U_{г.мом} \\ I_{г} = I_{сп} + I_{АБ} + I_{ЕД} \end{cases} \tag{3}$$

Critical mode corresponds to the squally wind rushes with the speed of wind stream $V_{ВП}$. Upon the sudden increase in the angle speed $\omega_{вк}$ of the wind wheel rotation, the central regulator (CR) opens the force element (FE) in full and the whole generated power of the electric generator (EG) is transmitted to the electrodynamic brake (EDB) that produced maximum explicit braking torque Mг on the shaft of the wind wheel. Wind stream, while acting on the blades of the wind wheel, overcomes the resistance of spring elements, rotating their planes along the direction of the wind stream. The speed of the wind wheel rotation and voltage on the outlets of the electric generator are lower than the nominal values. Energy consumption is carried out on the account of rechargeable battery (RB). Values of the calculating quantities are substituted into the generalized system of equations:

$$\begin{cases} V_{вп} = V_{кр} \\ \omega_{вк} < \omega_{вк.мом} \\ U_{г} \ge U_{г.мом}\omega_{вк} \\ I_{г} = I_{ЕД} \\ I_{сп} = I_{АБ} \end{cases} \tag{4}$$

Regulation of the flows of power in the WEP is carried out by the spring regulator and electrodynamic brake, whose moment of resistance is the function of the angle speed $\omega_{вк}$ of the rotation of the rotor and current $I_{ЕД}$ that flows along the stator winding. Voltage on the outlets of the generator depends on the angle speed of the rotor rotation, current of the excitation and the output current. That is why general moment of the resistance on the shaft of the wind wheel is described by the power function of the secondary order from the angle speed $\omega_{вк}$ and other parameters. By using Lagrange equation of second genus, it is possible to write equation of the blade motion: wind wheel, speed of the wind wheel rotation, rotors of the electrodynamic brake and generator (5) as:

$$\begin{cases} I_л \frac{d^2\beta}{dt^2} = -C_л\left(\beta-\beta_л\right) + 2\pi\rho V_{вп} h_л \cdot \\ \cdot \int_R^R \left(V_{вп}\cos\left(\gamma_г+\beta\right) - \dot{\varphi}_к r\cdot\sin\left(\gamma_г+\beta\right)\right)dr \\ I_к \frac{d^2\varphi_к}{dt^2} = -C_{кг}\left(\varphi_к-\varphi_{ед}\right) + M_{вк}\cdot \\ I_{ед}\frac{d^2\varphi_{ед}}{dt^2} = -C_{кг}\left(\varphi_к-\varphi_{ед}\right) - \\ -C_{г.ег}\left(\varphi_{ед}-\varphi_{ег}\right) - A_{ед}\frac{d\varphi_{ед}}{dt}i_{ед} \\ I_{ег}\frac{d^2\varphi_{ег}}{dt^2} = -C_{ед.ег}\left(\varphi_{ег}-\varphi_{ед}\right) - A_{ег}\frac{d\varphi_{ег}}{dt}i_{ег} \\ \frac{M_{вк}-M_{ед}}{U_г}\frac{d\varphi_{ег}}{dt} = i_{ег} = i_{сп}+i_{ед}+i_{АБ} \\ M_{вк} = 2\pi\rho V_{вп}\int_R^R r^2 (V_{вп}\cos\left(\gamma_г+\beta\right) - \\ -\dot{\varphi}_к r\cdot\sin\left(\gamma_г+\beta\right))\sin\left(\gamma_г+\beta\right)dr \\ M_{ед} = C_M \omega_{ВК} i_{ед} \\ U_г = C_E\omega_{ВК} i_{зб} - i_{ег}R_о \end{cases} \quad (5)$$

In the system of equations $I_Л$, $I_К$, $I_{ЕД}$, $I_{ЕГ}$ – moments of inertia correspondingly to the blades, wind wheel, rotors of the electrodynamic brake and electric generator as to its own axes of rotation; β, $\varphi_К$, $\varphi_{ЕД}$, $\varphi_{ЕГ}$ – correspondingly angles of blade rotation as to amplitude of wind wheel, rotors of electrodynamic brake and electric generator as to its own axes of rotation; $C_Л$ – rigidiness of the spring elements of the reverse motion of the blades; $C_{КГ}$, $C_{ЕД.ЕГ}$ – correspondingly to the rigid spring elements, with the help of which wind wheel and electrodynamic brake as well as electrodynamic brake with electric generator are interconnected; $\beta_П$ – initial angle of the blade setting; ρ – specific air mass; $V_{ВП}$ – speed of the air flow; $h_Л$ – arm of the resultant force of the air flow relatively the axis of amplitude; $R_{ВН}$, $R_{ЗВ}$ – correspondingly internal and external lengths of blades; r – variable radius; $\gamma_Г$ – angle of the blade profile on the distance r; $A_{ЕД}$, $A_{ЕГ}$ – external mechanical parameters correspondingly and electrodynamic brake and electric generator; $M_{ВК}$, $M_{ЕД}$ – correspondingly rotational and braking torques and electrodynamic brake; $i_{ЕГ}$, $i_{ЕД}$, $i_{АБ}$, $i_{СП}$ – momentary values of currents corresponding to the electric generator, electrodynamic brake, rechargeable batteries and loading of the WEP; $U_Г$ – voltage on the outlets of the electric generator; $C_М$, $C_Е$ – constructive constants of the electrodynamic brake and electric generator correspondingly; $R_о$ – resistance of the force winding of the electric generator.

The given system of equations (5) is the mathematical model of the WEP work, and that is a collection of interconnected of the non-linear differential equations, analytical solution of which is problematic. That is why the block of applied programs "WindMod" was elaborated for its numerical solution.

The results of the numerical modelling are represented in the schemes (Fig. 4). Values of theoretical power P, voltage on the terminals of rectifier $U_Г$ are presented by different intervals of variation of the regulated parameters and by different modes of WEP work.

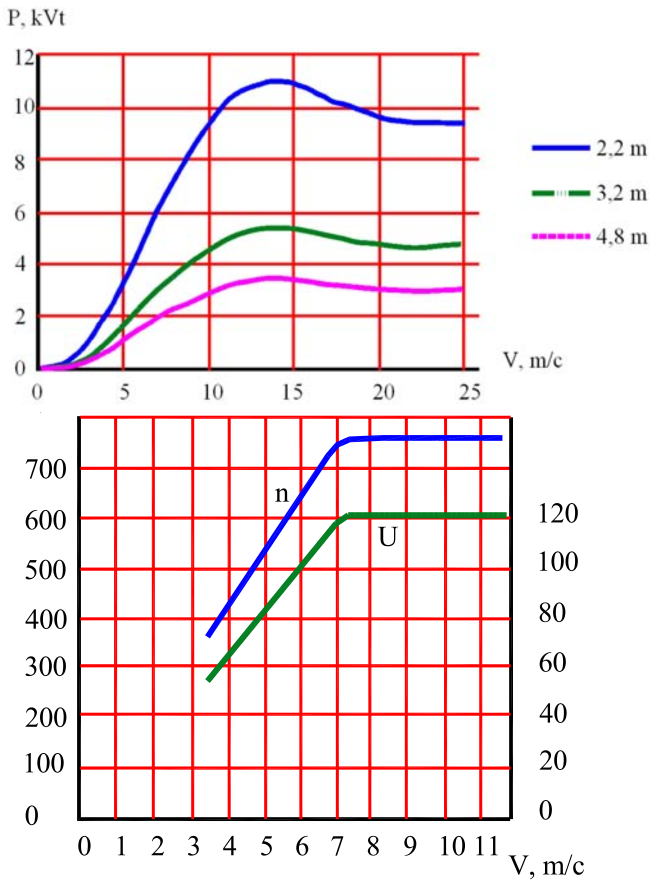


Fig.4. The results of the numerical modelling

IV. Conclusions

The proposed methodology of creation of mathematical models with the use of graphs of the necessary difficulty will allow describing of physical processes of WEP work quickly and qualitatively. By the use of mathematical model, it is possible to calculate (sufficient for production accuracy) characteristics of elecrodynamic brake, spring elements and central regulator correspondingly to the WW of the autonomous WEP and conditions of its operation. It allows increasing the efficiency of its usage up to the 5 – 18% depending on the area of usage on the territory of Ukraine. The created programs of the numerical analysis allow automation of these calculations, analyzing operation of WEP in all modes of its exploitation.

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Roman Zinko, Candidate of Technical Science Degree, Associate Professor, Lviv Polytechnic National University (Ukraine), Institute of Engineering Mechanics and Transport, Department of Mechanics and Automatization of Engineering.
Address: apt.32 LPNU Bandera Street, Lviv, Ukraine
E-mail: rzinko@gmail.com

Romāns Zinko. Zemas jaudas vēja enerģijas iekārtas darba modelēšana
Ir piedāvāta grafu izmantošana autonomās lēngaitas vēja enerģētikas iekārtas darba pētīšanai, kas domāta darbam vājas un mērenas gaisa plūsmas apstākļos. Aprēķinu shēma tiek veidota, izmantojot mašīnas konstruktīvās shēmas struktūras grafu. Iekārtas konstruktīvās shēmas elementus apzīmē ar apļiem, kas skaitās grafa virsotne. Saikne starp elementiem tiek apzīmēta ar dažāda veida līnijām, atkarībā no saiknes fiziskās dabas. Struktūras grafs ļauj analizēt iekārtas konstrukciju un noteikt parametrus, kas ir nepieciešami izmanošanai matemātiskajā modelī. Turklāt ir ņemta vērā ārējo izraisītāju ietekme, kas tiks iekļauti autonomās lēngaitas vēja enerģētikas iekārtas darba matemātiskajā modelī. Matemātiskā modeļa veidošanas nākamajā posmā tiek ierakstīts matemātiskā modeļa vispārināto koordinātu saikņu līmeņu struktūras grafs. Grafa izmanošana ļauj ierakstīt atbilstošas sarežģītības matemātisko modeli atkarībā no pētījumam izvirzītajiem uzdevumiem. Tajā pašā laikā tiek ietaupīts laiks matemātiskā modeļa ierakstīšanai un noregulēšanai. Matemātiskā modeļa vienādojumi dod iespēju pētīt un prognozēt autonomās lēngaitas vēja enerģētikas iekārtas darba režīmu pie dažādiem vēja slodzes apstākļiem, vēja rata apgriezieniem, tādiem vēja rata ģeometriskajiem parametriem kā spārnu slīpuma pret gaisa plūsmu leņķis, iekšējais un ārējais rādiuss, spārna platums, elektroenerģijas patēriņa jauda, kā arī ņemt vērā dažādus jaudas atlases režīmus.

Роман Зинко. Моделирование работы ветроэнергетической установки малой мощности
Предложено использование графов при создании математической модели функционирования автономной тихоходной ветроэнергетической установки, которая предназначена для работы в условиях слабых и умеренных потоков воздуха. Расчетная схема математической модели формируется на основе графа структуры конструктивной схемы машины. Элементы конструктивной схемы установки обозначаются кружками и считаются вершинами графа. Связи между элементами обозначаюся линиями разного рода зависимо от физической природы связи. Граф структуры позволяет проанализировать конструкцию установки и определить параметры, необходимые для использования в математической модели. При этом учитывается влияние внешних возбудителей, которые будут внесены в математическую модель работы автономной тихоходной ветроенергетической установки. На следующем этапе создания математической модели записывается граф структуры уровней связей обобщенных координат модели. Использование графа позволяет записать математическую модель соответствующей сложности зависимо к поставленным заданиям исследований. При этом економится время на запись и отладку математической модели. Уравнения математической модели дают возможность исследовать и прогнозировать работу автономной тихоходной ветроенергетической установки при разных потоках воздуха, оборотах ветроколеса, таких геометрических параметрах ветроколеса, как угол наклона лопастей к потоку воздуха, внутренний и внешний радиусы, ширина лопасти, мощности потребления электроэнергии, а также учитывать разные режимы отбора мощности.