UDC 621.311.245 (045)

K.M.Sydorenko, A. Ilinca, ScD.

MODELLING OF A WIND POWER PLANT WITH THE DEVICE FOR WIND RECEPTION

A mathematical model of a Low Speed Wind Turbine (LSWT) is observed. A technique of formation of the mathematical description of power processes and a block diagramare presented. Possibilities and prospects of implementation of a technique for researching of energy transformation of weak and migrating streams are defined.

***Keywords**: wind power plant, modeling, convergent tube, experiment.*

К.Н.Сидоренко, А.Илинка, д-р техн. наук

МОДЕЛИРОВАНИЕ ВЕТРОВОЙ УСТАНОВКИ С УСТРОЙСТВОМ ДЛЯ СБОРА ВЕТРА

Рассмотрена математическая модель ветроустановки для среды со слабыми и мигрирующими ветрами, представлены методика формирования математического описания энергетических процессов и их блок-схема, определены возможности и перспективы реализации устройства для исследований энергетических преобразований слабых и мигрирующих потоков.

***Ключевые слова**: ветроустановка, моделирование, конфузор, эксперимент.*

К.М. Сидоренко, А.Ілінка, д-р техн наук

МОДЕЛЮВАННЯ ВІТРОВОЇ УСТАНОВКИ З ПРИСТРОЄМ ДЛЯ ЗБОРУ ВІТРУ

Розглянуто математичну модель вітрової установки для середовища слабких вітрів; представлено методику формування математичного опису енергетичних процесів і їх блок-схему. Визначено можливості і перспективи реалізації пристрою для дослідження енергетичних перетворень слабких і мігруючих потоків.

***Ключові слова**: вітроустановка, моделювання, конфузор, експеримент.*

Introduction

Wind energy has known an accelerate development over the last ten years, the average power installation increasing every year by 20-30 % [1,10,11]. The windiest sites have been already used for implementation of wind turbines and the industry concentrates on increasing wind turbines efficiencies in lower wind speed sites.

More specifically in Ukraine, the wind farms have been developed based on “classical” three blades, horizontal-axis wind turbines mainly in coastal regions of the Black and Azov seas. Such wind turbines are designed to operate at their best efficiency on sites with average annual wind speed of 5,5m/s and more. In Ukraine the speed of the majority of regional-winds is lower than 5 m/s (2-3 m/s near Kiev) [3]. Therefore, it is necessary to use specifically adapted wind conversion systems that operates at maximum efficiency in low wind speeds.

The question of design features of wind turbines suitable for low wind speeds as those in Ukraine is investigated widely by researchers and engineers and confirmed by numerous pat ents [4-6]. The majority of developments are oriented toward the use of air stream devices-collectors (convergent). A functional block diagram of such Low Speed Wind Turbine (LSWT) is represented in Fig. 1 [7].

Theoretical development

The main task of all wind is reception of electric power of definite quality and power at changing turns and changing loading. LSWT may be an object of controlling an automatic system, where voltage preset value is supported. An effective regulation of initial voltage provides comprehension of power processes in WPP, which is attained by a method of structure formation according to a functional purpose of its elements.

LSWT power processes. In LSWT during the passage through the confuser the wind speed gradually increases. For description of the air stream moving in a confuser and definition of its energy such assumptions are accepted:

the stream enters the confuser parallel to its axial line;

the air stream is accepted as perfect fluid;

in one time unit equal air volumes go through any cross-section of the confuser.

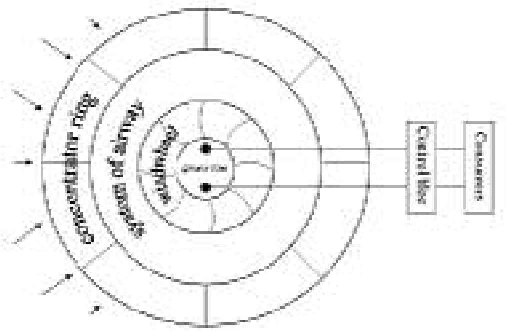

Fig.1. LSWT general block diagram

In an ideal case the stream speed v_2 at the exit from the confuser depends on the speed v_1 at the entry according to the known formula [2]:

$$v_2 = v_1 \frac{A_1}{A_2} = v_1 k, \quad (1)$$

where v_1, v_2 – the speed of the air at the entry and exit of a confuser; A_1, A_2 – accordingly the input and output squares of the confuser.

Character of air moving in the confuser is described by Bernoulli's theorem:

$$p_1 + \frac{\rho}{2} v_1^2 = p_2 + \frac{\rho}{2} v_2^2, \quad (2)$$

where p_1, p_2 – static pressure accordingly at the entry and exit of apertures A_1 and A_2;

$\frac{\rho}{2} v_{1,2}^2$ – the dynamic stream component, which characterises a kinetic energy of a mobile air stream and can be defined by means of a well-known Pitot's principle, by Pitot tube (fig.2).

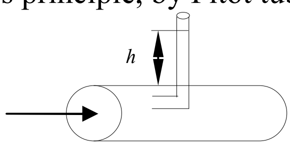

Fig. 2. The functional diagram of Pitot principle

The altitude h of dynamic pressure counterbalanced with the atmospheric pressure is defined by such a formula:

$$h = \frac{v_2^2}{2g}, \quad (3)$$

and speed v_2:

$$v_2 = \sqrt{2gh}. \quad (4)$$

The value of the quantity h according to the formula (3) is an ideal value, which does not consider stream losses on cotraction h_c and stream losses on a friction h_{fr}, thus:

$$h_k = h_c + h_{fr}, \quad (5)$$

where h_k – total amount of losses on cotraction and on friction (dynamic pressure loss).

Losses on cotraction h_c are defined by the formula [2]:

$$h_c = \xi_c \frac{v_2^2}{2g}, \quad (6)$$

where ξ_c –proportionality coefficient, which is defined by the following formula [2]:

$$\xi_c = K_c \left(\frac{1}{E} - 1 \right)^2. \quad (7)$$

Proportionality coefficient K_c depends on the confuser's slope α and is defined according to the table 1:

1. Values of the coefficient K_c

α,	K_c	**α**	K_c
4	0,08	30	0,8
8	0,16	60	0,9
15	0,35		

The compression coefficient E is defined also according to the table (table 2).

2. Values of the coefficient E

A_2/A_1	**E**	A_2/A_1	**E**	A_2/A_1	**E**
0,01	0,611	0,3	0,622	0,6	0,662
0,1	0,612	0,4	0,633	0,7	0,687
0,2	0,616	0,5	0,644	0,8	0,722
				0,9	0,781
				1	1

Thus, the friction loss h_{fr} is presented by the expression [2]:

$$h_{fr} = \frac{\lambda}{8 \sin \frac{\alpha}{2}} \left[1 - \left(\frac{A_2}{A_1} \right) \right]^2 \frac{v_2^2}{2g}, \quad (8)$$

where λ – friction coefficient, which is presented by the following expression:

$$\lambda = \frac{0{,}3164}{\sqrt[4]{\mathrm{Re}}}, \quad (9)$$

where Re – Reynold's number.

And dynamic pressure losses h_k in the confuser reduce the value of h to the amount $h_к$, that is:

$$h_{re} = h - h_k, \quad (10)$$

where h_{re} – quantity value of Pitot's tube column with losses h_k.

By using formulas (3) - (10) we find h_{re}:

$$h_{re} = \frac{v_2^2}{2g} \left[1 - \left[K3 \left(\frac{1}{E} - 1 \right)^2 + \frac{0{,}3164}{8 \sin\left(\frac{\alpha}{2}\right) \sqrt[4]{\mathrm{Re}}} \left(1 - \left(\frac{A_2}{A_1} \right)^2 \right) \right] \right]. \quad (11)$$

Taking into consideration confuser losses, a real speed v_{2re} of an air stream at the exit from the confuser will be smaller than at the entry and is defined by a formula:

$$v_{2re} = \sqrt{2gh_{re}}\,. \qquad (12)$$

With the help of the formula (12) we will find stream speed of taking into account losses on cotraction and on friction. For this purpose, we find h_{re} by formulas (1), (3), (5) – (11) and substitution (11) into (12) and get stream speed of the exit from the confuser taking into account losses on cotraction and stream friction:

$$v_{2re} = \sqrt{v_1^2 k^2 \left[1 - \left[K_c\left(\frac{1}{E}-1\right)^2 + \frac{0{,}3164}{8\sin\left(\frac{\alpha}{2}\right)\sqrt[4]{\mathrm{Re}}}\left(1-\left(\frac{A_2}{A_1}\right)^2\right)\right]\right]}\,. \qquad (13)$$

We input confuser losses coefficient k_{lc}:

$$k_{lc} = \sqrt{1 - \left[K_c\left(\frac{1}{E}-1\right)^2 + \frac{0{,}3164}{8\sin\left(\frac{\alpha}{2}\right)\sqrt[4]{\mathrm{Re}}}\left(1-\left(\frac{A_2}{A_1}\right)^2\right)\right]}\,.$$

Now the expression (13) may be presented like this:

$$v_{2re} = v_1 k k_{lc}\,. \qquad (14)$$

Not taking into consideration losses, energy of the air stream at the exit from the confuser is presented by the following formula:

$$E_{as} = \int F v_2 dt\,. \qquad (15)$$

where F - an air stream force.

By substitution of (14) into (15) we will get an expression for a definition of the air stream energy in the confuser with losses consideration:

$$E_{as} = k k_{lc} \int F v_1 dt\,. \qquad (16)$$

Power of the free air stream at the exit from the confuser is defined by the following formula [7]:

$$W = C_p \frac{1}{2} \rho A_1 k^2 v_1^3\,, \qquad (17)$$

where v_1 – speed of the air stream at the entry in the confuser; A_1 – the confuser's entrance square; C_p – coefficient of the air stream energy usage (for vertical axe WPP $C_{p\ max}$=0,22); k=A_1/A_2 – the relation of the confuser's input square to the output one; A_2 – confuser's output square.

Main stream losses during its moving through the confuser are the losses on narrowing and friction. Considering these losses the formula (17) gets the following look [7]:

$$W = C_p \frac{1}{2} \rho A_1 k^2 v_1^3 k_{lc}^3\,, \qquad (18)$$

where v_1 – the air stream speed at the entry to the confuser; C_p – coefficient of the air stream energy usage; ρ – air density; A_1 – confuser's entrance square, m/s;

k=A_1/A_2 – the relation of the confuser's input square to the output one; $k_{пк}$ – coefficient of losses on cotraction and friction.

The amount of losses depending on the air stream speed influences the stream power. The schedule of dependence of the stream power at the confuser's exit from the speed at the entrance and the coefficient k_{lc}, considering also the stream perception by a wind turbine with a vertical axis of rotation Cp are represented on fig. 3, where the top plane is generated according to the formula (17), and bottom – according to the formula (18). The given schedule is constructed for one sector of a concentration ring of experimental WPP (fig. 4) [8], with following initial data: C_p = 0,22; ρ = 1,225 kg/m^3; A_1 = 0,67 m^2; A_2 = 0,1 m^2; k=A_1/A_2 = 6,7; v_1 = 1 – 5 m/s.

For calculation of the loss factor on cotraction and friction in the confuser k_{lc} the following initial data were used: K_c = 0,85; E = 0,614; Re = 20000; α = π/24 – π/2 (7,5° – 90°).

The fig. 3 shows how the stream power level is decreasing at the exit from the confuser as a result of friction and cotraction losses in it. If in an ideal case at wind speed of 3 m/s initial power is equal to 109W, losses reduce initial power magnitude at 3m/s to 23 – 55W depending on coefficient k_{lc}; i.e.3 m/s power decreasing makes 50 – 78 %. With increasing of stream speed an energy loss remain almost the same. Thus at 5 m/s, in an ideal case, the power at the exit is 506 W, and will be within 109 – 255W, if taking into account losses. In this case real value of W differs from the ideal W on 49,6 – 78 %.

If we use confusers, decrease of losses may be attained only by constructive peculiarities of a concentration ring: confuser's slope; change of relation of the confuser's input square to the output one. The fig. 5 describes the comparative schedule of the free air stream energy, which passes through the square that is equal to the confuser's input square (the bottom plane) and air stream energy at the exit from the confuser taking into account losses (the overhead plane).

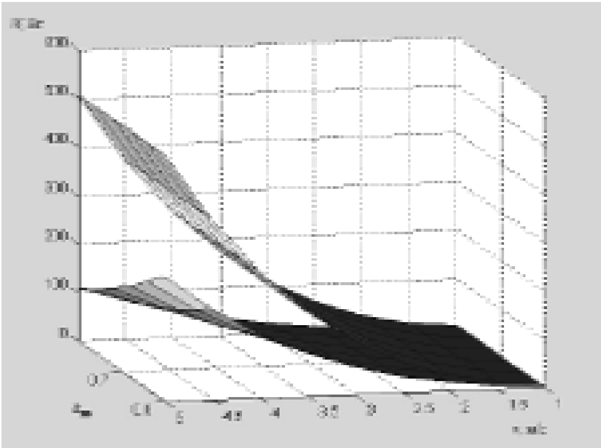

Fig.3. Power of the air stream at the exit of the confuser

Fig.4. Experimental LSWT (Ukraine, Kyiv, National aviation university)

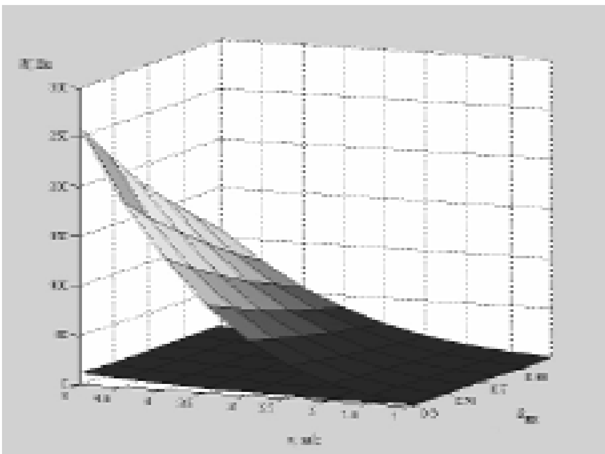

Fig.5. Power efficiency of the confuser

According to the assumption above, the air weight that passes through any cross-section, at time unit, is equal. It is known that *dm* weight, which makes *dl* way during *dt* time, through a cross-section square *A* is equal to density ρ multiplied volume *V*:

$$dm = \rho V = \rho Adl = \rho Avdt\,, \qquad (19)$$

where *vdt* – a way passed by a stream during time *dt* with a speed *dv*.

Using (19) we find a variable on weight at a time, which is presented by the following expression:

$$\frac{dm}{dt} = \rho Av\,. \qquad (20)$$

Pass on in (20) to the operational form we take a transfer function of the block which presents weight change:

$$W_{ch}(S) = \frac{m}{v} = \frac{\rho A}{S}\,, \qquad (21)$$

where *S* – Laplacian.

Newton's second law defines force which is apply to a body with mass *m* as change of a pulse of a body:

$$F = \frac{dp}{dt} = \frac{dmv}{dt} = m\frac{dv}{dt}\,.$$

The air stream speed at the entry in the confuser is speed of the wind which passes through a cross-section of the entrance square of the confuser. The entrance force of the relative wind is defined by the following equation:

$$F_{c\,in}(t) = C_F m\frac{dv_1}{dt}\,, \qquad (22)$$

where v_1 – the air stream speed at the entry to the confuser; C_F – drag coefficient; *m* – weight of air.

Speed of the air stream at the exit from the confuser is a variable quantity which defines force with which the air stream runs on the windmill blades and which depends from the design data of the narrowed channel of the confuser. The incident flow force of the wind on blade $F_{c\ out}$ at the exit from the confuser is presented by the following dependence:

$$F_{c\,out}(t) = C_F m\frac{dv_2}{dt}\,, \qquad (23)$$

where v_2 – the air stream at the exit; C_F – drag coefficient; *m* – mass of air.

If in (23) go to switch from v_2 to v_1 under the known equation from hydroaerodynamics (1) the force of the stream at the exit will be presented by following expression:

$$F_{c\,out}(t) = C_F mk\frac{dv_1}{dt}\,. \qquad (24)$$

The transfer function of the transformation block of wind speed v in force at the entry to the confuser $F_{k\ in}$ is defined, according to (22) following relationship:

$$W_v(S) = \frac{F_{c\ in}}{v_1} = C_F mS\ . \qquad (25)$$

It is known [9], that the stream speed at the exit from the confuser depends linearly from the velocity at the entry. The confuser transfer function is defined as the relation of the delivery air stream speed at the entrance, and to presented the usual amplifier with coefficient of amplification $k=A_1/A_2$:

$$W_c = \frac{v_2}{v_1} = k\ . \qquad (26)$$

Let's note, that in equations (23, 26) v_2 is an outlet velocity from the confuser without losses. And real speed of the stream after the confuser is less than ideal in k_{lc} times.

The moment which is created by the wind turbine at perception of the wind stream depends from the incident flow force of the wind $F_{c\ out}$, and from an angle β between the vector of the stream speed and the tangent to the blade plane in the point at the application of the total speed vector $\sum v_i$ (fig. 6).

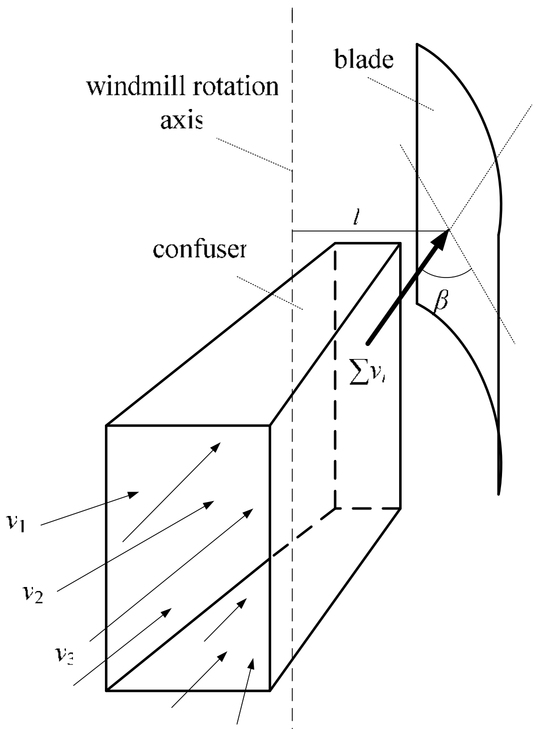

Fig. 6. Run an air stream on the blade

Windmill moment M_{wm} is presented by the following mathematical dependence:

$$M_{wm}(t) = F_{c\ out}(t) \cdot l \cdot \cos(\beta), \qquad (27)$$

where l – the distance from the point of attack of the total speed vector $\sum v_i$ to the windmill spinning axis (see fig. 6).

The turbine with the vertical axis of rotation is described by the known mathematical equation:

$$J\frac{d\omega}{dt} = M_{wm} - M_{el} - M_{fr} = M_t\ , \qquad (28)$$

where J – the turbine moment of inertia, kg·m^2; ω – the turbine angular velocity of rotation, rad/sec; M_{wm} –the force moment of the run wind incident flow of the windmill, N·m; M_{el} – the force moment created on the generator shaft, N·m; M_{fr} – the force moment owing to friction in mount of the bearing and in the generator; M_t – the force moment of the turbine taking into the friction loss and taking into the loading on the generator shaft: $M_t = M_{wm} - M_{el} - M_{fr}$.

The transfer function which describe the block of transition from out force of the air stream to the rotation moment of the wind turbine, according to (27) and (28) is described by the following equation:

$$W_m = \frac{M_{wm}}{\mathrm{F}_{c\ out}} = l \cdot \cos(\beta)\ . \qquad (29)$$

Moment M_t (t) which is created by the windmill, rotating turbine LSWT with angular velocity ω. The turbine transfer function is defined as the relation of out angular velocity ω to moment M_t (t):

$$W_\omega(\mathrm{S}) = \frac{\omega}{M_t(S)} = \frac{1}{mr^2 S}\ , \qquad (30)$$

where ω – the angular velocity of the turbine, rad/sec; M_T(S)– the force moment of the turbine in the operational shape; m – mass of the wind turbine, kg; r – turbine radius, m; S – Laplacian.

The block diagramme of the transformation channel of the wind stream from the entry in the confuser with a speed v_1 to creation of the torque of the wind turbine with angular velocity ω at the generator shaft to constitute the chain consecutive transformation and is show on fig. 7.

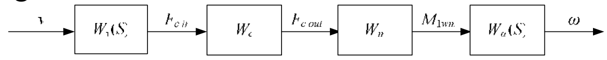

Fig. 7. The block diagramme of the basic (first) transformation channel of the wind stream

The air stream which does not cross the plane of confusers and passes more low them, it appears under wind power plant and participate in formation of draught stream LSWT which appear owing to discharge flue natural ventilation. Air stream induced by the pipe draft is defined by equation [9]:

$$Q = CA\sqrt{2gh\frac{T_l - T_h}{T_l}}, \qquad (31)$$

where Q – blast, m^3/sec; C – the constant of friction equals to 0.65–0.7; A – the tube square, m^2; g – the gravitational acceleration 9.81, м/с^2; h – the tube height, m; $T_в$ – the absolute height temperature, K; $T_н$ – the absolute low temperature, K.

Velocity of the air stream at the exit from the tube is defined by the following equation:

$$v_{ver} = \frac{4Q}{A} = C\sqrt{2gh\left(1 - \frac{T_h}{T_l}\right)}. \qquad (32)$$

The moment which is created by the vertical stream on windmill M_{ver} is described by the following mathematical dependence:

$$M_{ver}(t) = F_{ver}(t) \cdot l_{ver} \cdot \cos(\beta_{ver}), \qquad (33)$$

where $F_{ver}(t)$ – the force of the vertical stream by it runs to the windmill, and is described by the equation to analogously of the equation (22):

$$F_{ver\,in}(t) = C_F m \frac{dv_{ver1}}{dt}. \qquad (34)$$

The transfer function by the entry force which affects by a vertical stream to the windmill, next:

$$W_v(S) = \frac{F_{c\,in}}{v_{ver1}} = C_F mS. \qquad (35)$$

The transfer function of the vertical channel of the narrowed tube-confuser is defined:

$$W_{ver}(S) = \frac{M_{ver}}{F_{ver}} = l_{ver} \cdot \cos(\beta_{ver}). \qquad (36)$$

The block diagramme of the vertical air stream is show on fig. 8.

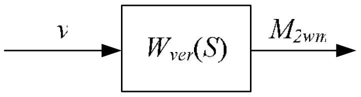

Fig. 8. The block diagramme of the vertical transformation channel of the wind stream

The total moment at windmill $M_{wm} = M_{1wm} + M_{2wm}$ forms the driving force for rotation of generator. The general block diagramme of transformation of the air stream, with the total moment from both channels of power influencing is show on fig. 9.

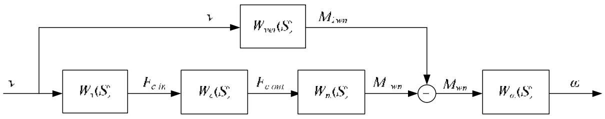

Fig. 9. The general block diagramme of the transformation channel of the basic wind stream

The stream generated by the vertical channel partially transfers the kinetic energy to windmill blades, and other part of energy gets out through the overhead aperture of the tube-confuser where it hitting upon to the overhead blades (fig. 4). The overhead blades is vertical axis windmill with the blades which are concaved so that simultaneously to perceive a free wind stream and to perceive a pulse from the vertical stream created at the exit from the tube-confuser.

The moment which will be created by overhead turbine M_{t2r} develops of two moments: moment $M_{tc\ ver}$ from the vertical stream force from the tube-confuser and moment $M_{wm\ ver}$ from the force of the wind which runs to the blades:

$$M_{t2} = M_{tc\,ver} + M_{wm\,ver}, \qquad (37)$$

where:

$$M_{tc\,ver}(t) = F_{tc\,ver}(t) \cdot l_{tc\,ver} \cdot \cos(\beta_{tc\,ver}), \qquad (38)$$

$$M_{wm\,ver}(t) = F_{wm\,ver}(t) \cdot l_{wm\,ver} \cdot \cos(\beta_{wm\,ver}). \qquad (39)$$

This moments sum, as the overhead turbine is rigidly connected to the internal turbine and they are rotated in same side.

The force which have the air wind stream and the stream from the tube-confuser at hit on the overhead blades are described by following expression:

$$F_{tc\,ver}(t) = C_F m \frac{dv_{tc\,ver}}{dt}, \qquad (40)$$

$$F_{wm\,ver}(t) = C_F m \frac{dv_1}{dt}. \qquad (41)$$

The transfer functions by two streams which form the rotational moment of overhead windmill $W_{tc\ ver}(S)$ and $W_{wm\ ver}(S)$ are presented by such equations:

$$W_{tc\,ver}(S) = \frac{M_{tc\,ver}}{F_{tc\,ver}} = l_{tc\,ver} \cdot \cos(\beta_{tc\,ver}), \qquad (42)$$

$$W_{wm\,ver}(S) = \frac{M_{wm\,ver}}{F_{wm\,ver}} = l_{wm\,ver} \cdot \cos(\beta_{wm\,ver}). \qquad (43)$$

The transfer functions by force from velocity $v_{tc\ ver}$ and v_1 air streams on the overhead blades are defined according to equations (40,41):

$$W_{F\ tc\ ver}(S) = \frac{F_{tc\ ver}}{v_{tc\ ver}} = C_F mS\ , \qquad (44)$$

$$W_{F\ wm\ ver}(S) = \frac{F_{wm\ ver}}{v_1} = C_F mS\ . \qquad (45)$$

The block diagramme of overhead blades LSWT considering equations (37) – (45) it is shown on fig. 10.

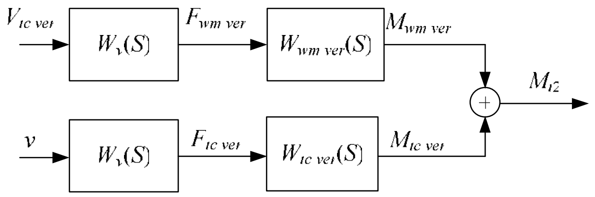

Fig. 10. The block diagramme of overhead blades LSWT

Conjugated the block diagramme of the transformation channel of the main stream (fig. 9) and the block diagramme of overhead blades LSWT (fig. 10) is taked the general block diagramme of transformation energy of the wind stream which is shown on fig. 11.

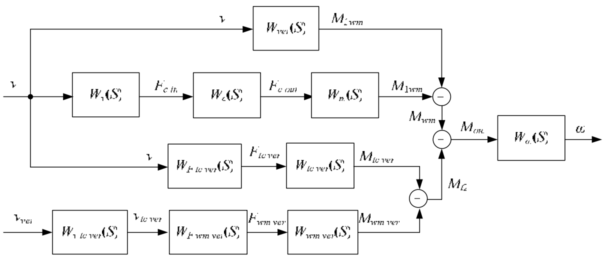

Fig. 11. General block diagramme of transformation energy of the wind stream LSWT

Thus the total moment, which appears at the output shaft LSWT include two moments:

$$M_{out} = M_{wm} + M_{t2}\ . \qquad (46)$$

At conjugation of block diagrammes there was a new block with transfer function $W_{v\ tc\ ver}$ which describes communication between the wind speed and the speed at the exit from the tube-confuser taking into the losses of narrowing and of the friction in the tube. Velocity of the stream in an ideal case is described by the equation (32). Go to through the tube-confuser a velocity of the stream will be increased in k_{tc} times, and losses of narrowing and a friction reduce amounts v_{ver} in k_{lc} times. So, velocity of the real vertical stream at the exit is defined by following expression:

$$v_{re\ ver} = v_{tc\ ver} = v_{ver} k_{tc} k_{lc}\ ,$$

and transfer function $W_{v\ tc\ ver}$ will be following:

$$W_{vtc\ ver} = \frac{v_{re\ ver}}{v_{ver}} = \frac{v_{tc\ ver}}{v_{ver}} = k_{tc} k_{lc}\ .$$

The out moment is proportional to turns of the out shaft. Transition from the moment creation on its shaft to turns is designated by transfer function W_ω (*S*).

Conclusion. The formular description of power processes LSWT gives the chance to investigate character of moving of the air streams at any impulses of winds. Representation of processes LSWT in the differential form at time *t* shows dynamics of work of WPP in a real mode of time. The described mathematical model gives the chance to apply it to integration such LSWT in intellectual power systems, for example, Smart Grid. Presence of a database of meteorological services about winds creates prospects of application of the model for forecasting of quantity of the extracted energy of WPP in real time.

Also, the resulted technique of formation of the mathematical model of LSWT opens possibilities for research of transformations of gentle and migrating streams, and computerisations of diagnostics-operating functions of LSWT for the additional equipment.

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Sydorenko Kostyantyn Mykolayovytch,
graduate, assistant teacher, NAU IACS.
Komarova ave. 1, Kiev, Ukraine, 03058
+38 044 2239229

Adrian Ilinca,
Prof., Director LREE,
LREE, bureau K-213,
300 allée des Ursulines, Rimouski, Canada,
G5L 3A1
+1 418 723-1986 p.1460