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COMPUTER SIMULATION OF AN AUTONOMOUS CONTRA-ROTATING WIND TURBINE TAKING INTO ACCOUNT PARAMETER DIFFERENCES AND WIND ROTOR WORK CONDITIONS

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Abstract. The work of an autonomous contra-rotating vertical axis wind turbine (VAWT), which uses a special device, i.e. a rotary transformer, has been examined in the article. The latter performs two functions: contactless transmission of generated electric energy from the moving armature of synchronous generator with permanent magnets and automatic control of VAWT electrical load. To construct the quasi-optimal control system, the estimator of average wind speed, which covers two wind rotors, was developed. Computer simulation was carrying out on a test wind profile taking into account parameter differences and work conditions of two wind rotors. The results showed satisfactory efficiency of VAWT work at such conditions.

Key words: vertical axis wind turbine (VAWT), contra-rotating wind turbine, transformer with rotating half, computer simulation.

1. Introduction

For the most regions of Ukraine, wind energy potential is characterized by low average annual wind flow rates equal to 4–5 mps. For such winds low-powered vertical axis wind turbines (VAWT) can be used with a maximum efficiency owing the next advantages: self-support work from changeable wind direction, simplicity and reliability of a construction because of absence of a step-up gear, the possibility of their installation directly on buildings, low noise level.

Considering the low-power autonomous wind turbines, the most important problem is an optimal correlation between energy efficiency and low cost. For electrical energy generating with maximum energy efficiency, a multi-pole permanent magnet synchronous generator (PMSG) and a direct drive between a wind rotor (WR) and the low-speed PMSG is used in the VAWT. In this case the size and cost of the last one are increasing.

There are two main options for the takeoff of electrical energy from the PMSG: unregulated, i.e. PMSG loading through a passive rectifier (a diode bridge) directly on a storage battery (SB), and adjustable – with the electronic control of PMSG electrical load [1].

The first option is simple and economically sound for a particular PMSG with the optimal chosen number of SBs. However, in this case it is impossible to provide its work at the point of the maximum wind power takeoff. At low wind speed the PMSG has too small voltage to charge the SB, and at high wind speed it usually overloads the SBs with charging current, which significantly reduces their lifetime [2].

The second option requires the use of power semiconductor converters, for example, a DC-DC converter in a DC link or an active voltage rectifier. In such cases it is possible to work constantly at the point of a maximum wind power takeoff, and at the same time to solve other problems of automatic control, including correct work of the SB [2]. However, such systems are expensive, which significantly increases the wind turbines payback period.

2. Analysis of recent publications

A specific value of a generator for the VAWT (USD/kW) is inversely proportional to its nominal angular velocity [3]. We propose using the contra-rotating VAWT (Fig. 1) consisting of two WRs and the PMSG, which inductor (rotor) is connected to one WR and the armature (contra-rotor) – to the other. In addition to these conditions the rotor and a contra-rotor are rotating in opposite directions. Due to such VAWT design the angular speed of a generator increases and is equal to $\omega_G = \omega_1 + \omega_2$, where ω_1 and ω_2 are rotor and contra-rotor angular velocities respectively. If $\omega_1 = \omega_2$, the using contra-rotating system allows us to double the generator angular speed. This significantly reduces its size and cost [4].

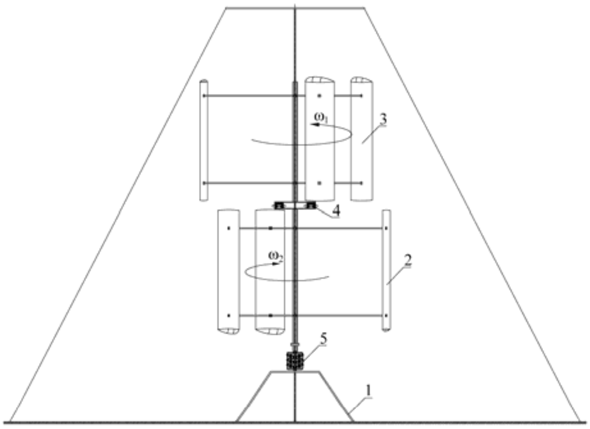

Fig. 1. Autonomous contra-rotating VAWT: 1 – frame, 2 – WR 1, 3 – WR 2, 4 – generator, 5 – rotary transformer.

However in the contra-rotating VAWT there is a problem with the transmission of produced electrical energy from the PMSG armature which is joined with contra-rotor. The standard solution to this problem is to use slip rings, but they reduce the reliability of the VAWT.

We propose using a rotary transformer (RT) for contactless transmission of produced electric energy from the moving parts of the VAWT and its simultaneous control. Terminals on its secondary winding allow us to control output voltage and load of the PMSG under the law for maximal wind power takeoff.

Analyzing the functional and structural features we have adopted a RT option. Its primary and secondary windings of each phase are inserted in separate half-cores, which can rotate in relation to each other [5]. The RT is considered to be rather atypical object of electromechanics. As a basis of its design the method of the calculation of traditional low-power transformers has been taken. But in this method the next special features of the RT were taken into account: the presence of the air gap and increase of losses associated with it, variable frequency and voltage which come from the generator and also the force of attraction between the two half-cores [4].

The model of one phase for a three-phase RT with power equal to 400 W has been made as a result of the calculation (Fig. 2). In general, experimental studies confirmed and clarified the used design methodology [6].

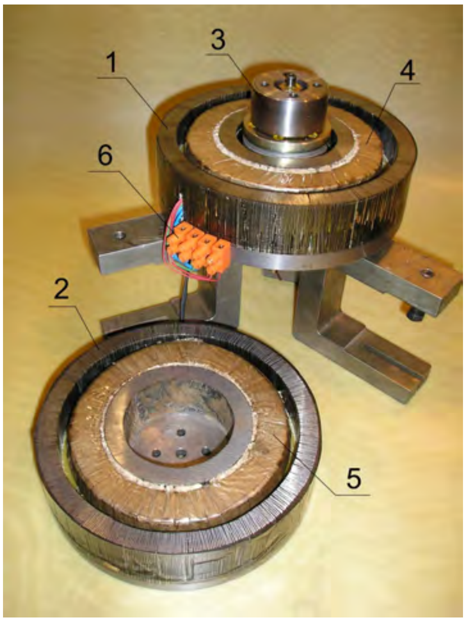

Fig. 2. Model of TRH: 1 – immobile half-core, 2 – movable half-core, 3 – slewing gear, 4 – secondary (immobile) winding, 5 – primary (movable) winding, 6 – terminals of secondary winding.

3. Objectives

The objectives of this work are the development of an average wind speed estimator and the computer simulation of the autonomous contra-rotating sensorless VAWT for estimating the efficiency of its work under the terms of disparity in parameters of WRs and its interaction with different speed turbulent winds.

4. Structure and mathematical model of VAWT

The main components of the autonomous contra-rotating VAWT are: frame with two H-type WRs, RT, electronic switch triac block controlled with a microcontroller, rectifier (on diodes) and SB.

To create a computer simulation model of the RT, we used a T-equivalent circuit, in which the secondary winding of the RT is aggregated to the primary one. We made a number of experiments to determine the parameters of the equivalent circuit of one phase of the RT on the produced model [7].

For a mathematical modeling of the work of the contra-rotating VAWT we need to know functional dependences of its main parameters, i.e. output power P_{WT} and output torque T_{WT} from a wind speed V_{W}:

$$P_{\mathrm{WT}} = \rho\, A\, C_{\mathrm{P}}(\lambda) V_{\mathrm{W}}{}^{3}; \qquad (1)$$

$$T_{\mathrm{WT}} = 0{,}5\, \rho\, \grave{A}\; r\, (\tilde{N}_{\mathrm{Ð}}(\lambda) / \lambda) V_{\mathrm{W}}{}^{2}, \qquad (2)$$

were ρ is air density, $A = \pi\, r^2$ is the washing area of one WR, $C_{\mathrm{P}}(\lambda)$ is the wind power conversion efficiency factor of the WR, $\lambda = \omega r / V_{\mathrm{W}}$ is the tip speed ratio (TSR) of the WR, ω is the angular speed of the WR, and r is the WR radius.

The wind power conversion efficiency factor of the WR nonlinearly depends on its TSR. Moreover, for each VAWT there is a curve, which can be obtained by experiments in a wind tunnel. Typical dependences $C_{\mathrm{P}}(\lambda)$ for the VAWT with the H-type WR are shown in Fig. 3, in optimal point λ_{opt} of which a maximum wind-power take-off is provided, i.e. for each wind speed value there is the optimal value of WR angular speed directly proportional to it [8]. For a fast operating optimal control of the last one, we need a wind speed sensor, but the using of it increases the cost of the VAWT. Besides, it measures wind speed only in a fixing point. That cannot clearly show the work of two WRs, installed on different altitudes, especially in conditions of turbulent and gusty wind. We propose using the estimator for determining average speed whose addition decreases the cost of the VAWT and also increases reliability and accuracy of its work. The last one will allow the online calculation of average speed of wind flow which covers the whole washing area of two WRs.

Fig. 4 shows the functional scheme of the contra-rotating VAWT. Electric energy generated by the PMSG transfers to RT with two terminals and further through a diode bridge DB is accumulated in a storage battery SB and transported to a load L. A control system CS contains of the estimator E for determining wind speed, a three-position controller TPC for quasi-optimal control of angular speed, and the converters of estimated values in proportional coordinates. We need the last to construct an automatic control system based on deviation, i.e. the estimated value of wind speed is converted into the optimal input angular speed value of WR ω_{opt} and armature voltage frequency f of PMSG in its angular speed ω.

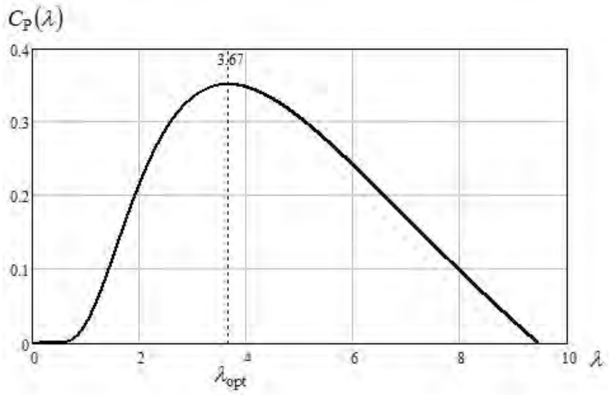

Fig. 3. Wind power conversion efficiency factor of the WR versus TSR.

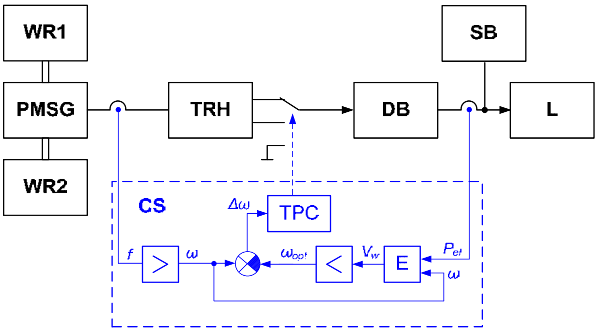

Fig. 4. Functional scheme of the control system of contra-rotating VAWT with RT.

5. Wind speed estimator

The expression for determining of the wind speed we write using (1) as a base:

$$\hat{v}_W = \sqrt[3]{\frac{P_{\text{WT}}}{\rho\, A\, C_{\text{P max}}}}\,. \tag{3}$$

After grouping of all known values we get:

$$\hat{v}_W = k_W \sqrt[3]{P_{\text{WT}}}\,, \tag{4}$$

where $k_W = \left(\rho\, A\, C_{\text{P max}}\right)^{-1/3}$ is a constant coefficient for the VAWT with specific parameters.

For determining mechanical power P_{WT} we use readily available value of electric power P_{el}, which charges the SB, the efficiency of the whole system η and the dynamic mechanical power ΔP of the VAWT, which accumulates in the flyweights of its rotating parts at angular speed changing [9]:

$$P_{\text{WT}} = \frac{P_{\text{el}}}{\eta(P_{\text{el}})} + \Delta P\,. \tag{5}$$

The dynamic power of the VAWT depends on changing velosity of angular speed and on the moment of inertia J of the system:

$$\Delta P = J\frac{d\omega}{dt}\omega\,. \tag{6}$$

So, having substituted (5) and (6) in (4), we get an expression for defining the wind speed, which is used as the base for developing the wind speed estimator:

$$\hat{v}_W = k_W \sqrt[3]{\frac{P_{\text{el}}}{\eta(P_{\text{el}})} + J\frac{d\omega}{dt}\omega}\,. \tag{7}$$

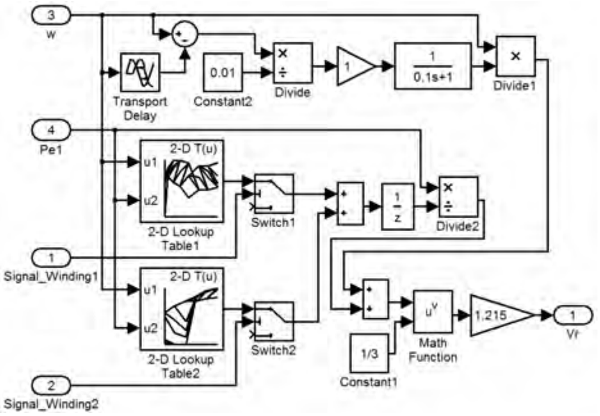

Fig. 5. Computer model of wind speed estimator.

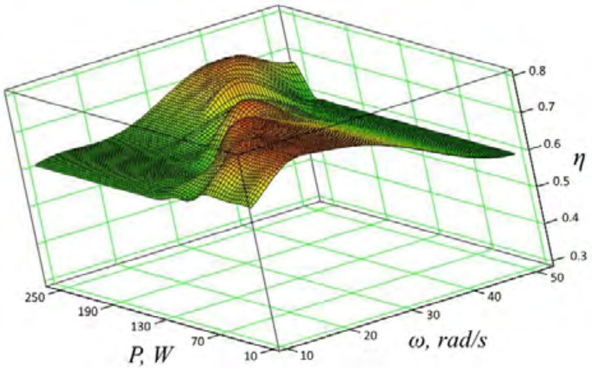

Fig. 6. Efficiency dependence of whole VAWT system for the first RT terminal.

The subsystem of wind speed estimator, made in software environment MATLAB/Simulink, is shown in Fig. 5. Input signals of the subsystem are the angular speed ω of the PMSG and electrical power P_{el}. The increment of the angular speed $\Delta\omega$ is formed by Transport Delay block with 0.01 s delay time. After dividing $\Delta\omega$ by the time increment Δt = 0.01 s, we get $d\omega/dt$. Efficiency dependences for the whole system take into account both electromechanical and aerodynamic processes in the VAWT. They are the functions of two parameters, i.e. electric power and angular speed of the PMSG. These dependences are formed as tables for each RT terminal: 2-D Lookup Table 1 for the first one (Fig. 6) and 2-D Lookup Table 2 for the second one (Fig. 7). To fill the tables, we experimentally obtained the efficiency values of the whole system for different values of ω and P_{e1}. The results are shown as the surfaces of efficiency values depended on the parameters showed above.

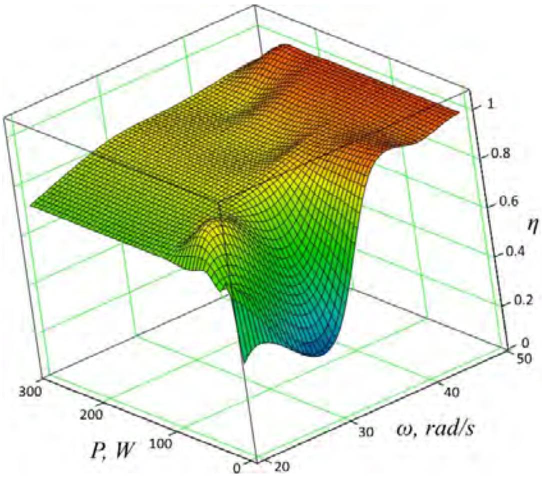

Fig. 7. Efficiency dependence of whole VAWT system for the second RT terminal.

6. Computer simulation

Previous computer simulations of VAWT work on a test wind profile was carried out for the contra-rotating VAWT, both WRs of which had the same aerodynamic parameters, i.e. the same dependences of wind power conversion efficiency factor on the TSR $C_{\text{P}}(\lambda)$ [7]. As in practice differences usually occur, then to verify system work efficiency, we took WRs with different aerodynamic parameters (Fig. 8).

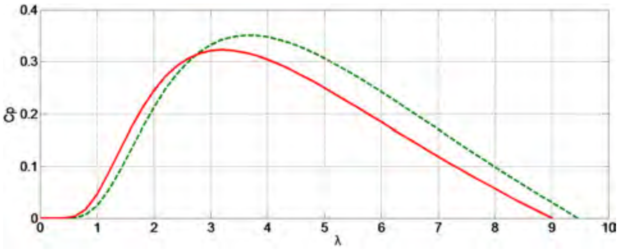

Fig. 8. Dependences of power conversion efficiency factor from TSR for two WRs: (- - - -) – WR 1; (——) – WR 2.

Subsystem Signal Winding performs switching between two terminals according to the formed deviation algorithm (Fig. 9). It provides a quasi-optimal control of the generator angular speed (Fig. 10). The electric power takeoff in time is shown in Fig. 11.

From obtained waveforms we can see that when angular speed of generator is increasing the wind energy is accumulating in VAWT flyweights and the output electric power is getting lower. The opposite situation arises when an angular speed is decreasing i.e. released energy of rotating mass through a generator transforms into electric energy and the electric power exceeds the power value which is taken off from wind by two WRs. Electric load switches off at a low rotating frequency. The efficiency of energy takeoff (Fig. 12) is confirmed by nearly maximum values of power conversion efficiency factors (Fig. 13) for both the first WR ($C_{\text{Pmax WR1}} = 0.351$), and the second one ($C_{\text{Pmax WR2}} = 0.323$). The wind speed estimator also works correctly (Fig. 14).

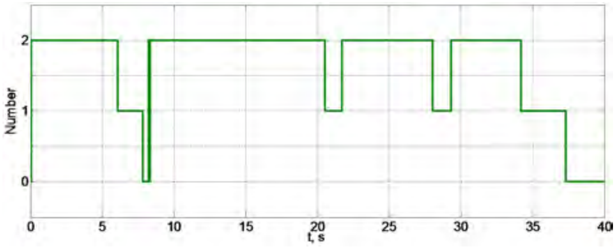

Fig. 9. Simulated waveform of the switching of RT second winding terminal.

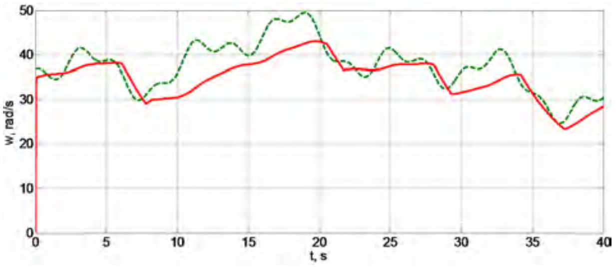

Fig. 10. Simulated waveforms of the PMSG angular speed: (- - - -) – optimum, (——) – real.

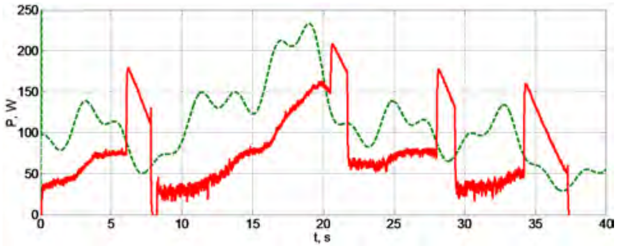

Fig. 11. Simulated waveforms of the powers: (- - - -) – mechanical input, (——) – electrical output.

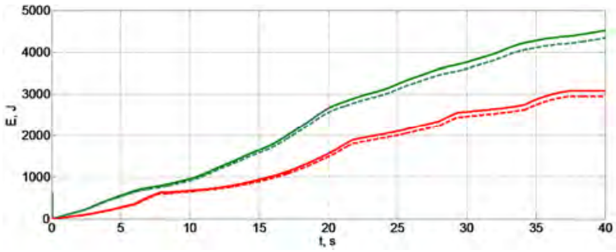

Fig. 12. Simulated waveforms of the energies: mechanical input for WRs with the same parameters (——) and with the different parameters (- - - -), electrical output for WRs with the same parameters (——)and with the different parameters (- - - -).

The analysis of integral results (Fig. 12) shows that 68 % of input mechanic energy is utilized. This result is not bad for mechanic-electric transformations in such devices. We can see slightly less energy take-off in compare with the VAWT with the same parameters of WRs because of lower value of power conversion efficiency factor of the second WR, which is 0.323.

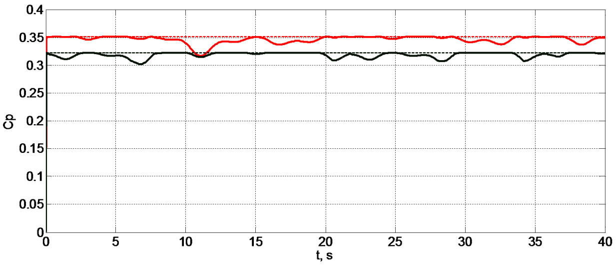

Fig. 13. Simulated waveforms of the power conversion efficiency factor: (——) – WR 1, (——) – WR 2.

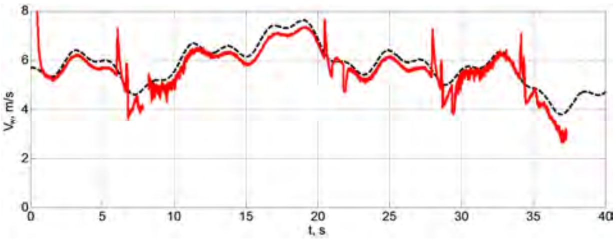

Fig. 14. Simulated waveforms of the wind speeds: (- - - -) – real, (——) – determined by estimator.

The wind speed is different on different altitudes [9]. In case of our contra-rotating VAWT we also observe the interplay of turbulent wind flows of both WRs. That is why the next verification of work efficiency of the made quasi-optimal control system for autonomous contra-rotating VAWT is done when two WRs interact with wind flows which have slightly different speeds (Fig. 15).

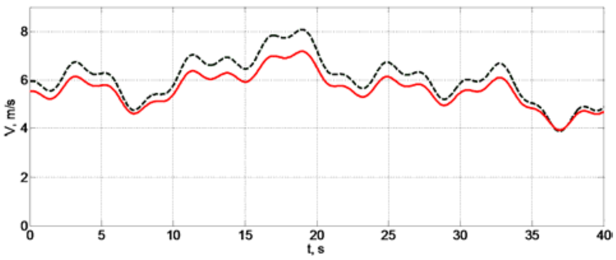

Fig. 15. Simulated waveforms of the wind speeds: (- - - -) – near the WR 1, (——) – near the WR 2.

A switching algorithm according to deviation works similarly as for previous case ensuring the correct work of the VAWT (Fig. 16).

The efficiency of using the proposed design of the autonomous contra-rotating VAWT can be confirmed by total energy indices. Its analysis shows that using of input mechanic energy reaches 70%. The takeoff energy from wind in the case of different wind speeds interacting with WRs is higher than for a contra-rotating VAWT on which the wind flow effects on both WRs with the same speed. It can be explained due to the fact that wind speeds differ from one another in their average values as well as in turbulent intensity.

The wind speed estimator copes with the task of the indirect determination of the average wind speed at the unequal interaction of the last one with two WRs (Fig. 17).

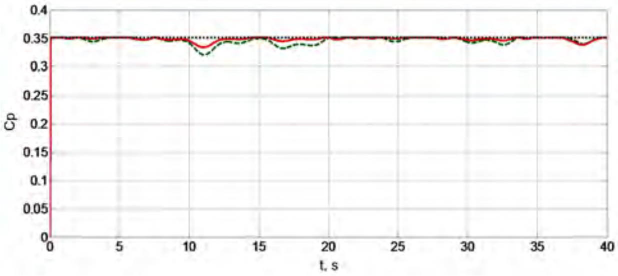

Fig. 16. Simulated waveforms of the power conversion efficiency factor: (- - - -) – WR 1, (——) – WR 2.

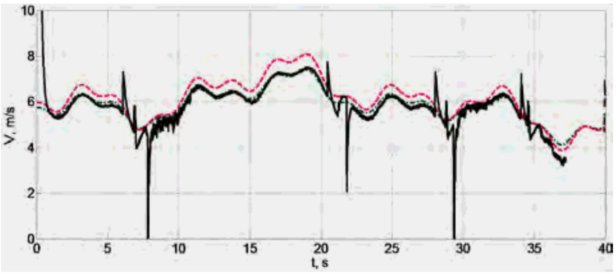

Fig. 17. Simulated waveforms of the wind speeds: real, which acts with WR 1 (- - - -) and WR 2 (— · —), (——) – average determined by estimator.

7. Conclusion

The estimator of average wind speed with such input data as output electric power of the VAWT and generator angular speed was developed. It allowed us to decline the use of the wind speed sensor that made the VAWT cheaper and increased the reliability of its work.

The verification of the work of the made quasi-optimal control system of the autonomous contra-rotating VAWT at different parameters of two WRs and at different wind speeds which interact with WRs showed indexes of system energy efficiency high enough in both cases. Those indexes are close to analogous values obtained before for the case with identical parameters of both WRs at their interaction with the same wind speed.

Total energy indices measured during 40 s of VAWT work, confirm the efficiency of using the proposed design of the autonomous contra-rotating VAWT. After electromechanical transformations the SB accumulates 68-70% from received mechanic power from WRs which is not bad for such devices.

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ІМІТАЦІЙНЕ МОДЕЛЮВАННЯ РОБОТИ АВТОНОМНОЇ КОНТРРОТОРНОЇ БЕЗДАВАЧЕВОЇ ВІТРОЕЛЕКТРОУСТАНОВКИ З УРАХУВАННЯМ РОЗБІЖНОСТІ ПАРАМЕТРІВ ТА УМОВ РОБОТИ ВІТРОРОТОРІВ

Ігор Щур, Андрій Ковальчук

Досліджено роботу малопотужної автономної контрроторної вітроелектроустановки (ВЕУ) з вертикальною віссю обертання, у якій застосовується спеціальний пристрій – трансформатор із обертовою половиною. Останній виконує дві функції: безконтактну передачу згенерованої електричної енергії від рухомого якоря синхронного генератора з постійними магнітами та автоматичне регулювання електричного навантаження ВЕУ. Для побудови системи квазіоптимального керування розроблено естиматор середньої швидкості вітру, який охоплює два віткроротори. Імітаційне моделювання проводилося на тестовому профілі вітру з урахуванням розбіжності параметрів та умов роботи віткророторів. Результати показали задовільну ефективність роботи ВЕУ в таких умовах.

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