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Energy-shaping optimal load control of PMSG in a stand-alone wind turbine as a port-controlled Hamiltonian system

***Abstract**. This paper presents energy-based control system of the stand-alone wind turbine. The procedure of the control system synthesis is performed at first separately for a mechanical part considered as two-mass and an electromagnetic part – PMSG with active rectifier. Then the obtained regulators are composed together. In order to create a sensorless control system the energy-shaping control is combined with the well-known Morimoto's maximum power point tracking (MPPT) control. This system operates in optimal response mode that provides the improvement of energy extraction compared to Morimoto on 0.7-16% at different winds.*

Streszczenie.** Artykuł przedstawia syntezę systemu sterowania autonomicznej turbiny wiatrowej w oparciu o podejście energii. Procedurę syntezy przeprowadzono oddzielnie dla części mechanicznej, która jest traktowana jako układ dwumasowy, i elektromagnetycznej – PMSG z prostownikiem aktywnym. Następnie otrzymane sterowniki składają się razem. W celu stworzenia bezczujnikowego systemu sterowania, sterowanie kształtowane energetycznie połączono z klasyczną kontrolą MPPT według Morimoto. Powstały system pracuje z optymalną wydajnością, co zwiększa odbieraną energiję w porównaniu do Morimoto na 0,7-16% przy różnych wiatrach. **(Energetycznie kształtowana optymalizacja obciążenia PMSG w autonomicznej elektrowni wiatrowej jako sterowanym układzie Hamiltona)

Keywords: wind energy conversion system, energy-shaping control, port-controlled Hamiltonian system, sensorless control.
Słowa kluczowe: elektrownia wiatrowa, sterowanie kształtowane energetycznie, sterowany układ Hamiltona, sterowanie bezczujnikowe.

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Introduction

The gradual depletion of organic energy resources has caused rapid development of "green energy." Wind energy converted systems (WECS) are becoming more and more widespread in particular, many of which are stand-alone low-power systems meant for use by individual consumers. Such WECS are usually made with a permanent magnet synchronous generator (PMSG), and with a vertical axis (VAWT), which eliminates the problem of wind orientation and allows for better work in gusty and turbulent winds (TW) [1]. These systems can have two versions: gearless, when VAWT is directly connected to a low-speed generator by a long (flexible) shaft; and traditional – with a gear. In both cases it makes sense to consider WECS as a two-mass mechanical system [2].

Because of low wind potential, the problem of maximum efficiency becomes acute in small WECS, which in addition to an efficient electromechanical part, requires special approaches to the development of an optimal control system, which will ensure maximum energy extraction from the wind. Yet another requirement for the control system is reducing the mechanical stress caused by the elastic properties of the WECS mechanical part and by the turbulent wind flow.

Aerodynamic part

As we know, the mechanical power and torque of wind turbine (WT) depend on wind velocity V_w and are determined by the following equations [1]:

$$P_{WT} = 0.5\,\rho\,A\,C_P(\lambda)\,{V_w}^3\,, \tag{1}$$

$$T_{WT} = \frac{P_{WT}}{\omega} = 0.5\,\rho\,A\,C_P(\lambda)\left(\frac{R}{\lambda}\right)^3\omega^2\,, \tag{2}$$

where ρ is the air density, A is the washing area of WT, $C_P(\lambda)$ is the wind power conversion efficiency factor of WT, $\lambda = \omega R/V_w$ is the tip speed ratio, ω is the turbine angular speed, and R is the radius of WT.

To provide maximum power extraction from the wind, according to equation (1), it is necessary to maintain the maximum value of the power factor $C_{P\max}(\lambda) = C_P(\lambda_{opt})$, and therefore an optimal WT speed $\omega_{opt} = \lambda_{opt}V_w\,/R$. This is achieved by the automatic regulation of the generator electric load.

Morimoto's control principle

Since the dependence $C_P(\lambda)$ is nonlinear, for maximum wind energy extraction an extreme control algorithm is needed. One of the most commonly used is the well-known sensorless (without wind speed sensor) generator load optimal control according to Morimoto's approach [3], which follows from equation (2) and consists in the formation of the load torque proportionally to the square of the measured VAWT angular speed:

$$T_{Mor} = 0.5\,\rho\,A\,C_{P\max}\left(\frac{R}{\lambda_{opt}}\right)^3\omega^2 = K_m\omega^2\,. \tag{3}$$

Control by law (3) provides the going of VAWT speed to the optimal for the specific wind velocity – maximum power point tracking (MPPT) control.

Such regulation response will depend on the value of the VAWT mechanical time constant [4]:

$$T_m = \frac{k_{WT}}{V_w}\,, \tag{4}$$

where $k_{WT} = \left(J_m\lambda_{opt}^2\right)\big/\left(0.5\rho\,C_{P\max}AR^2\right)$ is constant coefficient for specific VAWT and J_m is the total moment of inertia of VAWT with generator.

Since T_m is inversely proportional to the wind velocity, the high system response by Morimoto's control would be achieved only at operation in high winds.

Energy-based approaches

A great number of non-linearities in WECS (the dependences $C_P(\lambda)$ and $T_m(V_w)$, the non-linearities in the PMSG, the presence of gaps in the gear meshing) considerably complicate the synthesis and debugging of the automatic control system (ACS). Among the most promising methods of ACS synthesis of complex nonlinear objects are those based on energy approaches [5]. The energy-shaping control system (ESCS) is one of such methods.

Energy-shaping control consists in the control system assuring the passivity of the whole system. This allows the system to operate in a desired equilibrium point, since passivity itself provides oscillation damping in the system and its stable operation in the selected point [5].

To simplify ESCS synthesis procedure, known energy approaches [5 - 7] can be used, such as representing a control object and all ACS as a Euler–Lagrange system (ELs) [5] or the port-controlled Hamiltonian system (PCHs) [6].

System representation as PCHs makes it possible to consider the physical structure of the control object, which, in turn, greatly simplifies the part-differential equations to which the synthesis procedure is reduced; it also allows to simplify and make more transparent the stability analysis. PCHs model is as follows [6]:

$$\begin{cases} \dot{\mathbf{x}}(t) = [\mathbf{J}(\mathbf{x}) - \mathbf{R}(\mathbf{x})]\dfrac{\partial H}{\partial \mathbf{x}} + \mathbf{G}(\mathbf{x}) \cdot \mathbf{u}(t) \\ \mathbf{y}(t) = \mathbf{G}^{\mathrm{T}}(\mathbf{x})\dfrac{\partial H}{\partial \mathbf{x}} \end{cases}, \tag{5}$$

where $\mathbf{x}(t)$ is the state vector of the controlled system (the object), $\mathbf{J}(\mathbf{x}) = -\mathbf{J}^{\mathrm{T}}(\mathbf{x})$ is a skew-symmetric matrix which reflects the interconnection structure of the system, $\mathbf{R}(\mathbf{x}) = \mathbf{R}^{\mathrm{T}}(\mathbf{x}) \geq 0$ is a symmetric positive semi-definite matrix which reflects the dissipation in the system, $H(\mathbf{x})$ is the energy function of the controlled system, $\mathbf{G}(\mathbf{x})$ is the port matrix, and $\mathbf{u}(t)$ and $\mathbf{y}(t)$ are vectors of input and output system energy variables.

Energy function determines not only steady state behavior, but also behavior in transient conditions thanks to the control of the energy flows between subsystems.

In general synthesis ESCS consists in decomposing the system into simpler subsystems interlinked in some way, and finding such additional interconnections and subsystems, and such intensity of their interactions (IDA) [7] that total energy of a closed loop system $H_{\mathrm{d}}(\mathbf{x})$ would attain a minimum in the desired (defined by the asking signal) equilibrium point $\mathbf{x}_0$ [6]:

$$H_{\mathrm{d}}(\mathbf{x}) = H(\mathbf{x}) + H_{\mathrm{a}}(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x}_0)^{\mathrm{T}}\mathbf{D}^{-1}(\mathbf{x} - \mathbf{x}_0), \tag{6}$$

where $H_{\mathrm{a}}(\mathbf{x})$ is the energy function of the control system.

The desired model of the asymptotically stable close loop passive Hamiltonian system is described by the following equation [5]:

$$\dot{\mathbf{x}}(t) = [\mathbf{J}_{\mathrm{d}}(\mathbf{x}) - \mathbf{R}_{\mathrm{d}}(\mathbf{x})]\frac{\partial H_{\mathrm{d}}}{\partial \mathbf{x}}, \tag{7}$$

where $\mathbf{J}_{\mathrm{d}}(\mathbf{x})$ is the desired matrix of interconnection and $\mathbf{R}_{\mathrm{d}}(\mathbf{x})$ is the desired damping matrix.

Since the interconnections reflect the energy flows between the subsystems, the injection of additional interconnections (known as control by interconnection) is done to change these flows, which, in turn, leads to the appearance of new forces that will move the system to the desired equilibrium point:

$$\mathbf{J}_{\mathrm{d}}(\mathbf{x}) = \mathbf{J}(\mathbf{x}) + \mathbf{J}_{\mathrm{a}}(\mathbf{x}) = -\mathbf{J}_{\mathrm{d}}^{\mathrm{T}}(\mathbf{x}), \tag{8}$$

where $\mathbf{J}_{\mathrm{a}}(\mathbf{x})$ is the matrix of additionally injected factitious interconnections.

Introduction of the additional damping (known as damping injection) is done for natural energy redistribution, which leads to the oscillation damping in the system and ensures its asymptotic stability. The desired damping is achieved through a combination of controlled object's own damping and the control system damping:

$$\mathbf{R}_{\mathrm{d}}(\mathbf{x}) = \mathbf{R}(\mathbf{x}) + \mathbf{R}_{\mathrm{a}}(\mathbf{x}) = \mathbf{R}_{\mathrm{d}}^{\mathrm{T}}(\mathbf{x}) \geq 0, \tag{9}$$

where $\mathbf{R}_{\mathrm{a}}(\mathbf{x})$ is the matrix of factitious damping, provided by the control system.

According to [8], ESCS synthesis procedure is reduced to the writing of the mathematical model of the object in the PCHs (5) form, the selection of a matrix of the control system and, thanks to the energy shaping principles (6), interconnection and damping assignment (8), (9), to the solving of the following matrix equation:

$$\begin{aligned} &[\mathbf{J}(\mathbf{x}) + \mathbf{J}_{\mathrm{a}}(\mathbf{x}) - (\mathbf{R}(\mathbf{x}) + \mathbf{R}_{\mathrm{a}}(\mathbf{x}))]\frac{\partial (H_{\mathrm{d}} - H)}{\partial \mathbf{x}} = \\ &= [\mathbf{J}_{\mathrm{a}}(\mathbf{x}) - \mathbf{R}_{\mathrm{a}}(\mathbf{x})]\frac{\partial H}{\partial \mathbf{x}} + \mathbf{G}(\mathbf{x}) \cdot \mathbf{b}(\mathbf{x}) \end{aligned}, \tag{10}$$

where $\mathbf{b}(\mathbf{x})$ is the vector of input system energy variables, formed through feedback.

Energy-shaping control of the mechanical part of the WECS

One of the benefits of energy approaches to the control systems synthesis is that they allow you to decompose a complex system into subsystems [5], carry out ACS synthesis for each of them, and then combine the synthesized systems into the general ACS of the whole system. Therefore, in order to simplify the entire WECS (Fig.1) ACS synthesis, we will perform separately the control systems synthesis of the mechanical (VAWT-Mechanical part of PMSG) and electromagnetic (PMSG-Power converter-Load) parts.

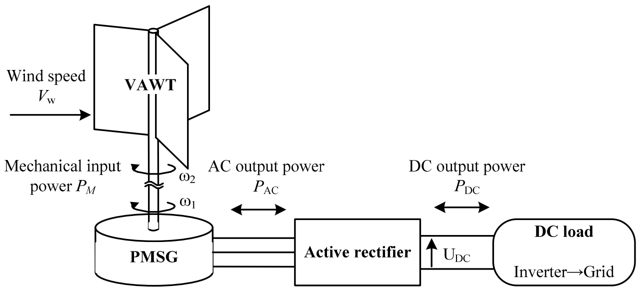

Fig.1. Function scheme of WECS

According to the approach described above, ESCS of the two-mass mechanical system were synthesized, the mathematical model of which in the PCHs form is shown below:

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} b_1 + \beta & -\beta & -c \\ -\beta & b_2 + \beta & c \\ c & -c & 0 \end{bmatrix} \times \begin{bmatrix} \omega_1 \\ \omega_2 \\ \Delta\varphi \end{bmatrix} + \begin{bmatrix} T_{\mathrm{em}} + T_{\mathrm{s1}} \\ -T_{\mathrm{WT}} + T_{\mathrm{s2}} \\ 0 \end{bmatrix} \tag{11}$$

where $x_1 = J_1\omega_1$, $x_2 = J_2\omega_2$ and $x_3 = c\,\Delta\varphi$ are the elements of the state vector, J_1 and J_2 are moments of inertia of the PMSG rotor and the VAWT respectively, ω_1 and ω_2 are generator angular speed and the angular speed of VAWT reduced to generator shaft respectively, T_{em} is the PMSG electromagnetic torque, T_{s1} and T_{s2} are static torques (of dry friction), acting on generator and VAWT respectively, b_1 and b_2 are coefficients of external viscous friction in the generator and VAWT bearings respectively, c is a compliance (stiffness) of the flexible connection between VAWT and PMSG, β is the internal damping of the flexible connection, and $\Delta\varphi$ is the twist angle of the flexible mechanical link.

According to [7] control system matrices should look similar to the matrices of the controlled system (11). Consequently, let's take the following form of the two-mass

VAWT system control matrix:

$$\text{(12)}\quad \mathbf{J}_{\text{am}}=\begin{bmatrix}0 & 0 & -B_{13}\\ 0 & 0 & -B_{23}\\ B_{13} & B_{23} & 0\end{bmatrix},\ \mathbf{R}_{\text{am}}=\begin{bmatrix}A_{11} & A_{12} & 0\\ A_{12} & A_{22} & 0\\ 0 & 0 & A_{33}\end{bmatrix},$$

where B_{13} and B_{23} are control system interconnections that should be found, and A_{11}, A_{12}, A_{22}, and A_{33} are control system damping coefficients.

Substituting (12) and other expressions in equation (10), we obtain a system of three equations, written in the matrix form. From the second and the third equations, through the coefficients A_{12}, A_{22}, and A_{33}, we obtain parameters B_{23} and B_{13} respectively. Substituting them in the first equation, we will obtain the equation of the regulator, which forms the electromagnetic torque value that should be reached by PMSG:

$$\text{(13)}\quad \begin{aligned}T^{*}_{\text{em}}&=T_{\text{s}1}+T_{\text{s}2}+b_1\omega_{1.0}+b_2\omega_{2.0}-\\ &-A_{11}(\omega_1-\omega_{1.0})-2A_{12}(\omega_2-\omega_{2.0})-\\ &-\frac{A_{22}(\omega_2-\omega_{2.0})^2+A_{33}(\Delta\varphi-\Delta\varphi_0)^2}{\omega_1-\omega_{1.0}}\end{aligned}.$$

T^{*}_{em} in (13) is the reference electromagnetic torque of the machine, corrected by the regulator. In the desired equilibrium point of the system, VAWT speed and generator speed are the same and equal to the desired speed signal – $\omega_{1.0}=\omega_{2.0}=\omega_0$, and the twist angle is $\Delta\varphi_0=(T_{\text{s}2}+b_2\omega_0)/c$.

Synthesized ESCS of WECS mechanical part will form the signal of reference electromagnetic torque, needed for desired speed tracking and providing a desired system response.

Energy-shaping control of PMSG

Electromagnetic time constants are much smaller than the mechanical ones, and that is why at two-mass mechanical systems ACS synthesis the inertia of the current circuit is usually not taken into account. However, in the WECS case the current loop effect is quite important, as it should provide a minimization of losses in the generator – in order to produce maximum WECS output power. That is why we will synthesize ESCS of WECS electromagnetic part (PMSG – Power converter – Load), the mathematical model of which in PCH form is given below:

$$\text{(14)}\quad \begin{aligned}\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\end{bmatrix}&=\begin{bmatrix}-R_{\text{s}} & 0 & pL_q i_q\\ 0 & -R_{\text{s}} & -p(L_d i_d+\Phi)\\ -pL_q i_q & p(L_d i_d+\Phi) & 0\end{bmatrix}\times\\ &\times\begin{bmatrix}i_d\\ i_q\\ \omega\end{bmatrix}+\begin{bmatrix}u_{dc}\mu_d\\ u_{dc}\mu_q\\ -T_{\text{s}}\end{bmatrix}\end{aligned}$$

where $x_1=L_d i_d$, $x_2=L_q i_q$ and $x_3=J_1\omega_1$ are the elements of the state vector, L_d and L_q are *d*-axes and *q*-axes stator inductances respectively, i_d and i_q are *d*-axes and *q*-axes projections of the stator current vector respectively, R_{s} is the stator resistance per phase, p is the number of rotor pole pairs, u_{dc} is a constant voltage in DC output circuit of power converter, μ_d and μ_q are the duty ratio functions of power converter in *d-q* reference frame, Φ is the rotor flux linkage, and T_{s} is a total mechanical torque.

Let's select the following form of the control system matrix:

$$\text{(15)}\quad \mathbf{J}_{\text{ae}}=\begin{bmatrix}0 & -J_{12} & -J_{13}\\ J_{12} & 0 & -J_{23}\\ J_{13} & J_{23} & 0\end{bmatrix},\ \mathbf{R}_{\text{ae}}=\begin{bmatrix}r_1 & 0 & 0\\ 0 & r_2 & 0\\ 0 & 0 & r_3\end{bmatrix},$$

where J_{12}, J_{13}, J_{23} are the elements of the control system interconnections matrix that are responsible for its structure and should be found, and r_1, r_2 and r_3 are the damping coefficients which express the electrical and mechanical damping of the control system.

Then the expressions describing the ESCS regulators of WECS PMSG load, are as follows:

$$\text{(16)}\quad \begin{cases}u_{dc}\mu^{*}_d=-r_1(i_d-i_{d0})-k(i_q-i_{q0})+R_{\text{s}}i_{d0}-\\ \quad -pL_d i_{q0}(\omega-\omega_0)-pL_q i_q\omega_0\\ u_{dc}\mu^{*}_q=-r_2(i_q-i_{q0})+k(i_d-i_{d0})+R_{\text{s}}i_{q0}+\\ \quad +pL_q i_{d0}(\omega-\omega_0)+p(\Phi+L_d i_d)\omega_0\\ T^{*}_{\text{em}}=T_{\text{s}}-r_3(\omega-\omega_0)\end{cases},$$

where μ^{*}_d and μ^{*}_q are the reference duty ratio functions in *d-q* frame, k is the decupling coefficient, which compensates the cross-links between *d*-axes and *q*-axes voltage control channels, and i_{d0} and i_{q0} are respectively *d*-axes and *q*-axes projection signals of the objective current vector.

Synthesized ESCS of WECS electromagnetic part will ensure the given WECS load for desired speed tracking providing the minimization of losses in the generator (by the objective current signals).

Energy-shaping control of the entire WECS

To obtain ESCS of the entire WECS, let's combine its components' regulators – that is, replace in the ESCS (16) mechanical part regulator (the third equation) with the WECS mechanical part regulator (12). Then WECS ESCS regulators will be the following:

$$\text{(17)}\quad \begin{cases}u_{dc}\mu^{*}_d=-r_1(i_d-i_{d0})-k(i_q-i_{q0})+R_{\text{s}}i_{d0}-\\ \quad -pL_d i_{q0}(\omega-\omega_0)-pL_q i_q\omega_0\\ u_{dc}\mu^{*}_q=-r_2(i_q-i_{q0})+k(i_d-i_{d0})+R_{\text{s}}i_{q0}+\\ \quad +pL_q i_{d0}(\omega-\omega_0)+p(\Phi+L_d i_d)\omega_0\\ T^{*}_{\text{em}}=T_{\text{WT}}+\omega_0(b_1+b_2)-A_{11}(\omega_1-\omega_0)-\\ \quad -2A_{12}(\omega_2-\omega_0)-\dfrac{A_{22}(\omega_2-\omega_0)^2}{\omega_1-\omega_0}\\ \quad -\dfrac{A_{33}(\Delta\varphi-\Delta\varphi_0)^2}{\omega_1-\omega_0}\end{cases},$$

In the synthesized ACS the objective current signal i_{d0} is formed according to the maximum moment per ampere (MMA) control law for a particular type of PMSG [9], which ensures maximum energy efficiency of the generator, and the signal i_{q0} is known from the electromagnetic torque equation: $i_{q0}=2/(3p)\cdot T^{*}_{\text{em}}\big/\left[(L_d-L_q)i_{d0}+\Phi\right]$.

In order to form the desired equilibrium point $\mathbf{x}_0$, the ESCS (17) inputs should be provided with the desired speed signal, equal to optimum speed – $\omega_0=\omega_{\text{opt}}=\lambda_{\text{opt}}V_{\text{w}}/R$, as well as the signal of VAWT torque (equation (2)), which could be replaced with the objective torque signal, optimal for specific wind velocity $T_{\mathrm{WT}} = T_0 = 0.5\rho\ A\ R\ C_{\mathrm{P\,max}} V_{\mathrm{w}}^{\ 2} / \lambda_{\mathrm{opt}}$.

Giving zero values to certain coefficients of regulators (17), we can change the structure of the controller in the direction of simplification. To improve the accuracy of the performance of both the speed objectives and the current projections objectives, the correction coefficient k should be used. Using electrical damping coefficients r_1 and r_2 is ineffective. As for the parameters of the mechanical part controller, A_{11} is the most effective and fully independent coefficient, which makes it possible to significantly improve system performance; coefficients A_{12} and A_{22} allow us accelerate the transition process, although they also give rise to some fluctuations in the system; A_{33} is the least effective coefficient, which is also the hardest one to realize, as it requires regular torque monitoring. Taking also into account the fact that for VAWT the PMSG with magnets on the rotor surface ($L_d = L_q$) are usually used, and in that case MMA control law will be achieved if $i_{d0} = 0$ [9], the simplified WECS ESCS regulators equations will be the following:

$$(18)\quad \begin{cases} u_{dc}\mu_d^* = -k\left(i_q - i_{q0}\right) - pL_d i_{q0}\left(\omega_1 - \omega_0\right) - pL_q i_q \omega_0 \\ u_{dc}\mu_q^* = \ k i_d + R_{\mathrm{s}} i_{q0} + p\left(\Phi + L_d i_d\right)\omega_0 \\ T_{\mathrm{em}}^* = T_\Sigma - A_{11}\left(\omega_1 - \omega_0\right) - 2A_{12}\left(\omega_2 - \omega_0\right) \end{cases},$$

where $T_\Sigma = T_{\mathrm{WT}} + \omega_0\left(b_1 + b_2\right)$.

Sensorless energy-shaping control of WECS

To find objective optimal signals of speed and torque, we should know the operating wind speed. The latter can be obtained from the wind speed sensor or calculated with some accuracy [10], but this makes the system more complicated, increases its cost and reduces its reliability.

To provide effective sensorless control, energy-based control system synthesis can be combined with traditional methods [5]. That is why for the synthesis of ESCS without a wind speed sensor, it has been proposed to complement ESCS regulators (18) with Morimoto's regulator (3). It will determine the desired equilibrium point by forming the optimal load torque: $T_{\mathrm{WT}} = T_{\mathrm{Mor}}$.

Maximum VAWT energy extraction from the wind is directly dependent on the provision of the optimal VAWT speed $\omega_{\mathrm{opt}}(V_{\mathrm{w}})$; however, in the absence of a wind speed sensor, the procedure of finding this optimal speed becomes very complicated. That is why we propose to send to the objective speed signal input the operating speed signal of generator: $\omega_0 = \omega_1$. This will ensure a stable work of the system in the optimal point $\mathbf{x}_0$, determined by regulator (3). Then the sensorless ESCS regulators (ESCS & MPPT) will have the following form:

$$(19)\quad \begin{cases} u_{dc}\mu_d^* = -k\left(i_q - i_{q0}\right) - pL_q i_q \omega_1 \\ u_{dc}\mu_q^* = \ k i_d + R_{\mathrm{s}} i_{q0} + p\left(\Phi + L_d i_d\right)\omega \\ T_{\mathrm{em}}^* = K_{\mathrm{m}}\omega_1^{\ 2} + \omega_1\left(b_1 + b_2\right) \end{cases}.$$

The resulting system provides faster transients flow and increases the static accuracy in comparison with the use of the regulator (3) alone. It also improves the form of current transients. However, thanks to $\omega_0 = \omega$, it lacks most of the dynamic adjusting components in equation (18) that, naturally, would accelerate the transient. In particular, we lose the ability to use for the purposes of response change the most effective coefficient, which is the mechanical damping coefficient A_{11}. This will leads to the formation of the transient difference between the signals in the assignment channel ($\omega_0 = \omega_1$) and the speed feedbacks ($\omega_1 = \omega_{z1}$ and $\omega_2 = \omega_{z2}$) – namely "$\omega_{z1} - \omega_1$" and "$\omega_{z2} - \omega_1$", that, in turn, expand the regulation capabilities of the system and still provide the stable operation in determined by regulator (3) optimal point $\mathbf{x}_0$. In order to expand the regulation properties of ESCS with Morimoto (19) it has been proposed to inject in PMSG and VAWT speed feedbacks by first-order transfer functions, in the outputs of which the speed signals with delays ω_{z1} and ω_{z2} will be obtained.

The new sensorless ESCS (ESCS & MPPT & Tw) will be the following:

$$(20)\quad \begin{cases} u_{dc}\mu_d^* = -k\left(i_q - i_{q0}\right) - pL_d i_{q0}\left(\omega_{z1} - \omega_1\right) - pL_q i_q \omega_0 \\ u_{dc}\mu_q^* = \ k i_d + R_{\mathrm{s}} i_{q0} + p\left(\Phi + L_d i_d\right)\omega_0 \\ T_{\mathrm{em}}^* = K_{\mathrm{m}}\omega_1^{\ 2} + \omega_1\left(b_1 + b_2\right) - A_{11}\left(\omega_{z1} - \omega_1\right) \\ \quad - 2A_{12}\left(\omega_{z2} - \omega_1\right) \end{cases},$$

where $\omega_{z1} = \omega_1 / \left(T_{\mathrm{w1}}s + 1\right)$ and $\omega_{z2} = \omega_2 / \left(T_{\mathrm{w2}}s + 1\right)$ are the angular speed signals with delays, and T_{w1} and T_{w2} are the time constants of transfer functions in the feedback of PMSM and VAWT speed loops respectively.

Optimal response mode

When operating in TW, one of the important indicators is system response, as we must be able to react to wind flow speed change in time – in order to maximize the power coefficient C_{P}, i.e. to ensure $\omega = \omega_{\mathrm{opt}}$. On the other hand, system response should be limited due to the losses in the generator, which occur during the transient.

Thus, as shown in [11], while working in TW, WECS have to operate in optimal response mode, in terms of maximum output energy of the system. This mode can be achieved with equality of the derivatives of energy extracted from the wind W_{w} and the windings losses $\Delta P = \frac{3}{2}\left(i_d^{\ 2} + i_q^{\ 2}\right)R_{\mathrm{s}}$ over rms of the operating VAWT speed (ω) from the it optimal value (ω_{opt}) – σ_ω, which was used to evaluate system response:

$$(21)\quad \left|\frac{dW_{\mathrm{w}}}{d\sigma_\omega}\right| = \left|\frac{d\Delta P}{d\sigma_\omega}\right| .$$

Equation (21) is a necessary condition for maximum energy extraction by the WECS – $K_{\mathrm{ext}} \Rightarrow \max$. K_{ext} is the energy extraction efficiency coefficient of WECS [4], which was chosen to evaluate the energy efficiency of WECS operation and which is the ratio of energies received at the system output for a test period by the investigated and ideal WECS: $K_{\mathrm{ext}} = W / W_{\mathrm{id}}$. The ideal WECS is the one with almost zero inertia and controlled by Morimoto's ACS [11].

Thus, we can say that the presence of the controlled system response is an important feature of WECS ACS.

Computer simulation

In order to analyze the synthesized ESCS, we conducted a series of comparative studies of ESCS with regulators (18), (19), (20) on different its settings and the control system based on Morimoto's regulator (3) (Figs. 1, 2). These studies were carried out by computer simulation in MATLAB/Simulink for WECS with the following PMSG and VAWT parameters: R_{s} = 2.8 Ohm, L_{d} = 5 mH, L_{q} = 5 mH, F = 0.4 Wb, p = 20, A = 9.3 m^2, R = 2.16 m, J_1 = 1.5 kg·m^2, J_2 = 60 kg·m^2, c = 14680 N·m,

β = 0.03 N·m·s, $b_1 = b_2 = 0$, T_{s1} = 0.6 N·m, T_{s2} = 8 N·m, and P = 1.7 kW at V_w = 10 m/s. The optimal value of the tip speed ratio and the maximum power coefficient for the given VAWT are as follows: C_{Pmax} = 0.351 and λ_{opt} = 3.67. In this case, PMSG controlled by the active voltage rectifier can work in the generator mode or in the motor mode, consuming the accumulated energy in the latter case.

The studies were conducted by the following algorithm. At the initial time VAWT operates in the wind with the constant speed $V_{w.mid}$. By means of additional drive torque, VAWT accelerates to the constant angular speed, optimal for present wind velocity. After that, additional torque is removed and the system operates in steady state. At a specific time, a turbulent component of wind speed is added to the wind flow [12]. From this point, the test period countdown for our study begins – in the conditions of TW with the period of recurrence t_{TW} = 400 s. For the last 20 s the turbulent component is turned off, and the system returns to the initial constant speed of the VAWT. This ensures equality and a sustainable value of the initial and final VAWT speeds, between which the power generated by WECS in TW is integrated. This ensures a correct comparison of different WECS ACSs.

The ESCSs operation was examined with the following regulator settings:

I) $k = -100$, $r_1 = r_2 = A_{12} = 0$, $A_{11} = 8$ (18);

II) $k = 0$, $r_1 = r_2 = A_{12} = 0$, $A_{11} = 0$, +Morimoto (19);

III) $k = -100$, $r_1 = r_2 = A_{12} = 0$, $A_{11} = 5$, +Morimoto, + $+T_{w1} = 0.1$ s (20).

Fig.2 shows the work of the ideal WECS, WECS driven by Morimoto and ESCSs with different settings throughout the research period.

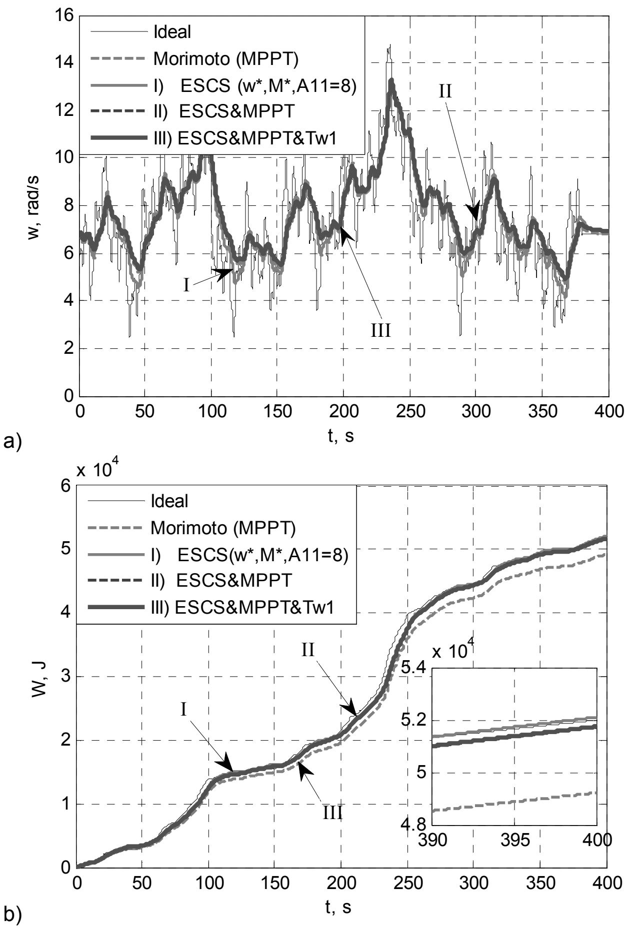

Fig.2. Time dependences of WECS operation with different control systems at $V_{w.mid}$ = 4 m/s: a) the PMSG angular speed, b) energy obtained from the generator during the experimental period

As you can see, ESCSs operated on optimal response mode provide more effective energy extraction from wind in comparison with Morimoto (Fig.2b). Working on optimal response mode provides ongoing support of VAWT speed about the optimal (Fig.3a), which ensures a large power conversion efficiency factor (Fig.3b). However, this response requires temporary crossing of PMSG on the motor mode and as a result the accumulated energy consumption (Fig.3c).

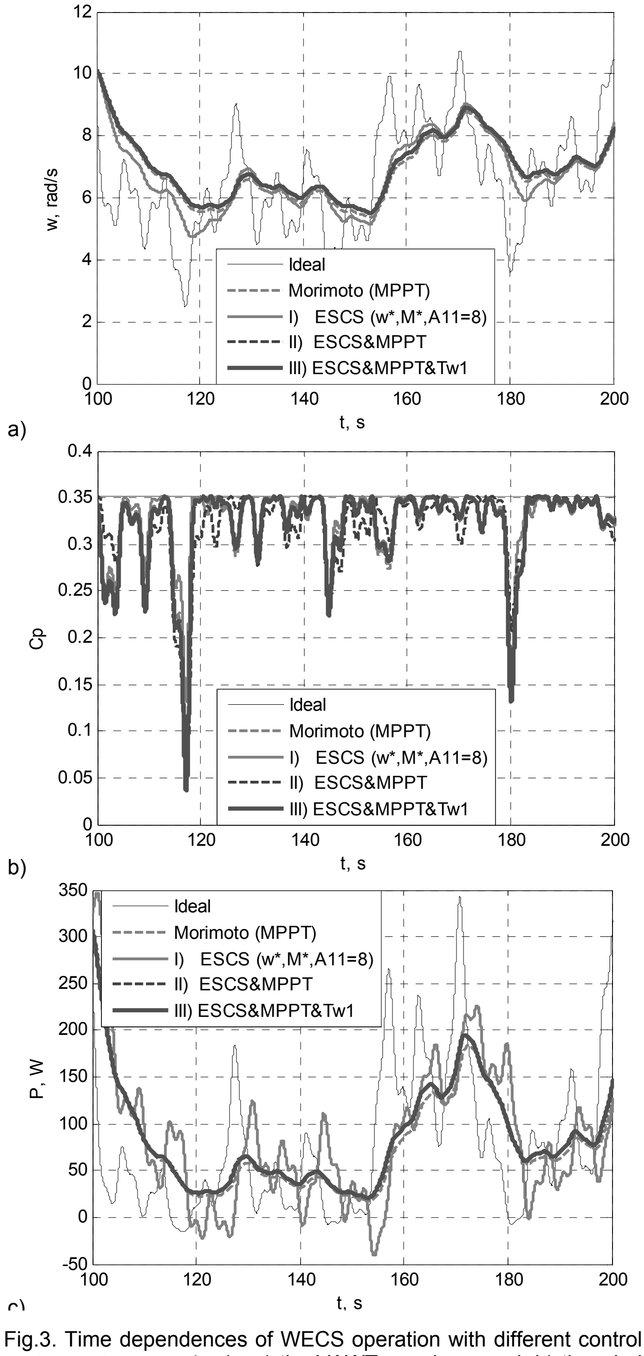

Fig.3. Time dependences of WECS operation with different control systems at $V_{w.mid}$ = 4 m/s: a) the VAWT angular speed; b) the wind power conversion efficiency factor; c) power, obtained from the generator during the fragment of the experimental period

The research results are summarized in the Table 1, where are presented: the relative windings losses ΔP for research period, the average efficiency of the PMSG $\eta_{G.av}$ determined by these losses, deviation of VAWT angular speed σ_ω, the average value of wind power conversion efficiency factor $C_{P.av}$, the stored by WECS energy W, and the extraction efficiency coefficient K_{ext}.

Table 1. Simulation results

	ΔP [%]	$\eta_{G.av}$ [%]	σ_ω [%]	$C_{P.av}$	W [J]	K_{ext} [%]
Ideal	9.7	91.2	0	0.351	51984	100.00
MPPT	8.1	92.2	20	0.329	49216	94.67
I_{ESCS}	9.7	91.2	24	0.333	51927	99.89
II_{ESCS}	8.5	92.1	31	0.327	51727	99.51
III_{ESCS}	8.5	92.1	30	0.328	51742	99.53

Based on the researches it was found that simple sensorless ESCS & MPPT system provides sufficient WECS response to operate in near-optimal response mode.

When WECS with ESCS is working on high winds (8-15 m/s) the reducing energy gain compared with Morimoto down to 0.7% is observed. This is due to a decreasing of T_m and consequently to increasing the response of WECS.

It was also conducted a number of studies in the presence of gearbox in the system with backlash of 5° and it was found that its does not affect the operation of WECS driven by ESCS.

Physical experiment

In order to confirm the results obtained by computer simulation an experimental setup (Fig.4) which simulate the WECS operation in TW was created. It consists of: the designed axial type PMSG 4; the DC motor 3, which imitate the work of VAWT at TW; the belt drive 8, which makes the system more flexible and provides it the properties of two-mass systems; controlled active rectifier 6, which forms the optimal WECS load; and accumulator 7 (plays a role of electric load).The modeling of the wind flow is carried out by programmed industrial controller VIPA313s 1 which forms the signal of reference wind torque and provides it to the DC-DC converter 2 controlled the DC motor 3. The formation of WECS optimal load according to the regulators (3), (18), (19) or (20) is realized by means of the computer 5 which controls the active rectifier 6 through microcontroller Atmega128-16au.

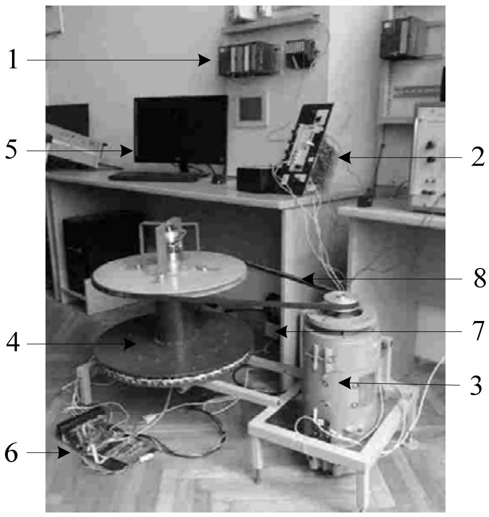

Fig.4. The experimental WECS setup

This setup is at the final stage of setting-up, so the results of its work are not presented in this article.

Conclusions

The energy-based approaches provide simplicity and clarity procedure of the control systems synthesis. They allow us to synthesize easy the control systems of any complex nonlinear objects, such as WECS. This is achieved thanks to the ability of decomposing it into simpler parts, in this case – mechanical and electromagnetic, and their control systems synthesis followed by the combinations of obtained regulators. To improve the operation of synthesized systems the energy approaches can also be combined with the classical ones. Thus, for the synthesis of the sensorless WECSs, ESCS has been combined with Morimoto's MPPT. The injection of the additional forcing by mechanical coordinates allows to improve the sensorless ESCS performance. The main advantage of proposed systems is their ensuring of the WECS operation on optimal response mode what is directed to such combination of mechanical wind energy extraction by VAWT and electric energy losses in PMSG, where the maximum of WECS output energy is obtained. So, ESCS improves the WECS energy extraction compared with controlled by Morimoto on 0.7-16%, for different winds and different ESCS settings.

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