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INTELLECTUAL CONTROL ALGORITHM FOR REDUCING THE AERODYNAMIC INTERACTION AT AUTONOMOUS WIND FARM

The article deals with the problem of wind farm intellectual control. It describes an intellectual control algorithm developed by the authors, and considers the aerodynamic interaction of wind turbines which can decrease total energy output. An autonomous wind farm has been modelled in Matlab/Simulink. Wind farm work with the application of an intellectual control algorithm is compared with the conventional one.

INTELLECTUAL CONTROL ALGORITHM; WIND TURBINE; AUTONOMOUS WIND FARM.

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ИНТЕЛЛЕКТУАЛЬНЫЙ АЛГОРИТМ УПРАВЛЕНИЯ СНИЖЕНИЕМ АЭРОДИНАМИЧЕСКОГО ВЛИЯНИЯ В АВТОНОМНОЙ ВЕТРОЭЛЕКТРОСТАНЦИИ

Описана проблема интеллектуального управления ветропарками. Разработан интеллектуальный алгоритм управления, учитывающий аэродинамические взаимодействия ветровых турбин между собой, которые снижают выработку электроэнергии. Автономная ВЭС смоделирована в среде Matlab/Simulink. Проведено сравнение двух режимов работы автономной ВЭС: с применением интеллектуального алгоритма управления и без применения.

ИНТЕЛЛЕКТУАЛЬНЫЙ АЛГОРИТМ УПРАВЛЕНИЯ; ВЕТРОУСТАНОВКА; АВТОНОМНАЯ ВЕТРОЭЛЕКТРОСТАНЦИЯ.

The ways of transforming wind energy into mechanical energy have been known since the ancient times. However, only at the beginning of the XX century V.P. Vetchinkin developed the theory of an ideal wind wheel based on the theory of an ideal propeller and introduced the term «power efficiency coefficient» (*Cp*). Later the German physicist Betz and the Russian scientist N.E. Zhukovsky proved that an ideal wind turbine cannot produce power greater than 16/27 (*Cp* = 0.593) of wind power [1].

From the practical point of view, Professor G.H. Sabinin suggested the most complete description of the «theory of ideal wind turbine». According to him, the ideal wind turbine's power efficiency coefficient is equal to 0.687.

In 2001 the complex analytical model (GGS) based on Navier–Stokes equations was developed. This model states that *Cp* = 61 %. Besides estimation, it was proved on the supercomputer based on the finite element method that the value of *Cp* is inside the interval [0.593; 0.61].

Power, taken from the wind, depends on the power efficiency coefficient and is calculated by the formula [2]:

$$C_p = \frac{P_{WF}}{P_U}, \tag{1}$$

where P_{WF} – wind turbine power; P_U – airflow power.

Thus, power efficiency coefficient C_p is a variable, which depends on two control wind turbine parameters – its blade pitch angle β and rotor's angular velocity ω. Therefore, we may achieve optimal values of airflow power taken for any wind speed: by regulating both control parameters: ω и angle β[3]:

$$C_p = f(\omega, \beta). \tag{2}$$

For low-power wind turbines (up to 50 kW) regulation of the angle is energetically unfavorable, since it requires additional actuators. For them, the immediate challenge is to ensure the optimal rotor speed constant at a fixed angle blade [4].

Current Problems

Wind turbines interrelation is another important problem [4, 5]. Wind farm efficiency

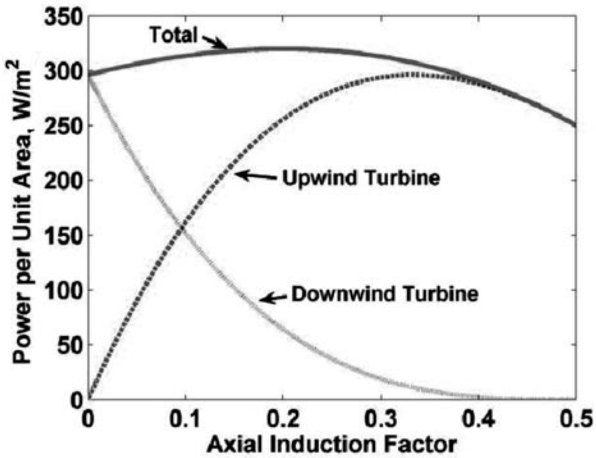

Fig. 1. Wind-produced power versus axial induction factor for a two-turbine array in which one turbine is downwind of the other

is calculated as a ratio of real power produced by the farm to the expected sum of all powers produced by each wind turbine:

$$\eta = \frac{W_{WF}}{W_{WT_i}}, \qquad (3)$$

where W_{WF} — total power produced by wind farm; W_{WTi} — power produced by the turbine with index i.

Thus, power generated by the successive couple of turbines depends directly on an axial induction factor of the first turbine e(Z). As presented in Fig. 1, maximum power of the wind turbine matches the optimal value of an axial induction factor e1 = 0.33, and the power generated by the second wind turbine falls down. And the maximum produced power may be achieved when e1 = 0.2 [6].

This fact proves that wind farm optimization should involve the optimization of each turbine in connection with others. Wind turbines should be considered as a distributed system with strong interactions and each turbine should be optimized as part of the complex system. So the wind farm power regulation requires a special intellectual control algorithm.

Intellectual Control Algorithm

In our work we have designed the system which takes into account the interaction between turbines. However, our approach is not focused on creating the concrete separate algorithms to optimize the work of a turbine in accordance with aerodynamic interaction. In our work we include this important aspect into a global high-level control algorithm for small and medium sized f-grid wind farms, which have the major potential for Russian decentralized regions.

Two major goals are taken into account in this algorithm:

maximizing wind farm's power generation;

providing frequency (50 ± 1Hz) and voltage (380 ± 5 %) stability in off grid power systems [7, 8].

As part of the first objective, we developed a model which includes aerodynamic interactions in the process of calculating the generated power. In our work we suggest applying aerodynamic interaction of wind turbines by evaluating losses. First wind speed behind each turbine is determined as

$$V = u\left(1 - (1 - \sqrt{1-m})\left(\frac{D}{(D+2kX)^2}\right)\right), \qquad (4)$$

where u — wind initial speed before first turbine; V — airflow speed behind the turbine on distance X; D — wind turbine wheel's diameter; m — wind turbine moment of wheel; $k \approx 0.05 - 0.075$ — whirlwind collapse constant.

The parameter m depends on mechanical parameters $m = f(T_c, \beta)$, where T_c — mechanical moment of resistance; β — blade installation angle.

So the effectiveness of a wind turbine as part of the wind farm determent is the following function with m on control parameters:

$$\eta_{WF} = f(\vec{m}, \vec{\varphi}, \vec{\gamma}) \to \eta_{WF} = f(\vec{T}_c, \vec{\beta}, \vec{\gamma}), \qquad (5)$$

where γ — air flow angle relatively rotor's axis.

Power generation effectiveness will be included into a formula of generated power:

$$\begin{aligned} W_{WF} &= \int P_{WF}(u, T_c, \beta, \vec{n}_{WT}, \vec{m}, \vec{\varphi}_t, \vec{\gamma}, \vec{P}_t, \vec{P}_W, \\ & q, L, I, U) = \int [\sum_{i=1}^{n} (N_{WTi}(U_i)\eta_{reg}(T_c, \beta) \times \\ & \times \eta_{or}(\gamma_{ti})\eta_{gen}(P_e)\eta_{gear}(q, P_t)\eta_{el}(P_b))] \times \\ & \times \eta_{tr}(L, I, U)\eta_{diss}(P_w, \vec{\varphi}_t)\eta_{WF}(\gamma_t, \vec{m}). \end{aligned} \qquad (6)$$

The formula contains other coefficients which determine other losses such as η_{reg} — loss-

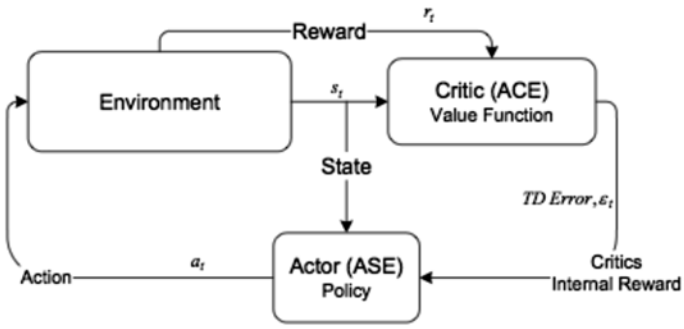

Fig. 2. Adaptive Heuristic Critic (AHC) model

es of rotor's frequency regulation, η_{or} – orientation regulation losses, etc. The final criteria will be as follows:

$$\begin{cases} W_{WF}(\vec{T}_c, \vec{\gamma}_t) \to \max \\ f = (50 \pm 1)Hz \\ U = (380 \pm 18)V \end{cases} . \quad (7)$$

These criteria will be integrated into an algorithm of the agent. This algorithm is based on an adaptive critic design. The structure will be based on two components:

the adaptive critic;

the executor.

The critic's aim is to evaluate the system state and come up with the inner reward, based on this evaluation. In general, it is some sort of the evaluation of function's approximation according to current strategy, which is translated to the executor. Both the executor and the critic may learn at the same time. The executor tries to choose *t*-optimal strategy (strategy which is optimal while time is *t*) based on the value, which is obtained from the critic. At the same time the critic tries to set the evaluation function according to the current strategy, formulated by the executor. The model of an adaptive heuristic critic is shown in Fig. 2.

The multiagent system suggested has a hierarchical structure, which is divided into multiagent groups. Each multiagent group has an agent-parent, which controls the behavior of the whole group by gathering the information about the group using local and group situational vectors and by modifying its behavior using local and group plan vectors [9].

A multiagent system for autonomous wind farm control has a hierarchical structure. The wind farm control panel is situated in the root of the hierarchy and carries out observation and control over the whole system. On the next levels of the hierarchy there are nodes which implement control over wind turbines, then wind turbines. The model of energy consumers is situated on the top level of the hierarchy. The hierarchy of the multiagent system can be

Energy production in two work modes

Wind speed 5 m/s			Wind speed 10 m/s		
	Without control, kWh	Intellectual algorithm, kWh		Without control, kWh	Intellectual algorithm, kWh
Turbine 1	0.238	0.472	Turbine 1	2.311	4.813
Turbine 2	0.052	0.321	Turbine 2	2.235	3.375
Turbine 3	0.052	0.285	Turbine 3	2.128	2.953
Turbine 4	0.016	0.235	Turbine 4	2.056	2.714
Turbine 5	0.013	0.239	Turbine 5	1.999	2.650
$\sum P$	0.371	1.552	$\sum P$	10.729	16.505

viewed as a graph-tree with the only distinction between two direct descendants of one node in the hierarchy, so the additional channels of energy transmission can be introduced. These additional channels can be used for balancing the amount of electrical energy and as an alternative channel for electrical energy delivery in case of main channels failure. [10]

The multiagent system can be viewed as a directed weighted graph. In this graph nodes are intelligent agents and edges of the graph are channels for electrical energy delivery.

Wind speed and direction known at least at one point influence the input data. Output data includes optimal wheel frequency, interpreted by setting electromechanical moment on a turbine generator's shaft regulated by PWM (pulse-width modulation). For blade-rotating turbines frequency is regulated by blade pitch rotation. Data for learning/control grouped into sectors

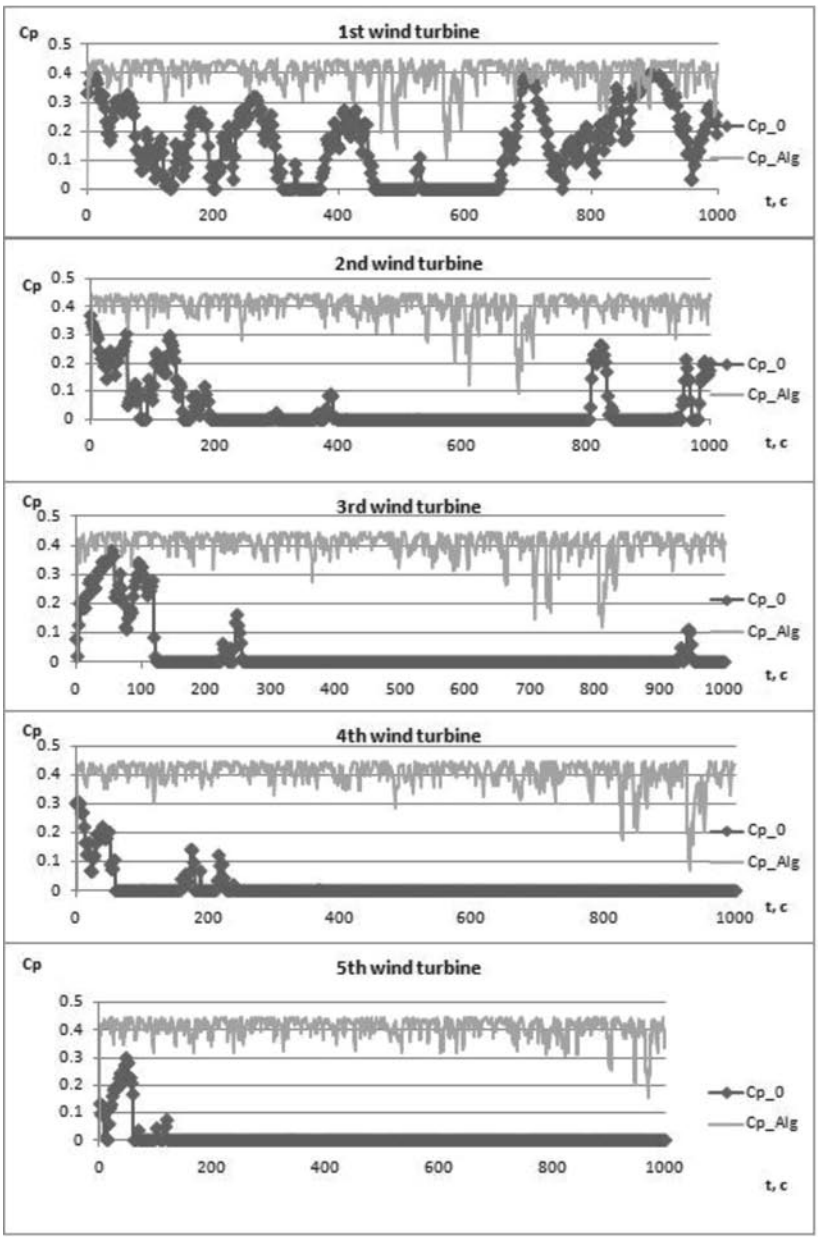

Fig. 3. Comparison of power efficiency coefficient *Cp* using intellectual control algorithm and without control algorithm. Wind speed 5 m/s

(12 units) depends on wind speed. Each control parameter matches its sector. At the same time, during the learning process the delay between the data received from measurement stations and wind farm reaction is considered.

The mathematical model of 100 kW-power wind farm and wind farm control algorithm were implemented in the simulation environment Matlab/Simulink. The wind farm modelled consists of 5 identical wind turbines, 20 kW each. The experiments were conducted to make the comparative analysis.

Wind turbines placements and wind direction were selected in the way the turbines interrelations took place.

Wind farm worked in two modes: with the application of the intellectual control algorithm and without control. Working without control implies turbines rotated at a constant velocity.

Then wind speed was set at two different levels: 5 m/s and 10 m/s.

The goal was to compare the total output power and the power generation of each wind turbine in two control modes.

The intellectual control algorithm allows to increase the output wind farm power in comparison with wind farm work without control. At wind speed of 5 m/s the algorithm efficiency is 318 %, at wind speed of 10 m/s the algorithm efficiency is 53.8%. The results are presented in Table and Fig. 3.

The wind farm power increase was reached by raising power efficiency coefficient and minimizing wind turbines interrelations. The intellectual control algorithm provides stabilized wind farm work even with varying wind speed, wherein every turbine will rotate with optimal rotor's angular velocity. Experiments results show high efficiency of the intellectual control algorithm and the expedience of using it at real wind farms.

REFERENCES

1. **Bogdanov K. Yu.** Science synthesis – weapon of learning in XXI century. *Physics*, 2006, No. 9.

2. **Pandey K., Tiwari A.** Maximum power point tracking of wind energy convertion system with permanent magnet synchronous generator. *Internat. Journal of Engineering Research & Technology,* 2012, Vol. 1, Iss. 5.

3. **Azouz M., Shaltout A., Elshafei M.A.L.** Fuzzy Logic Control of Wind Energy Systems, *Proceedings of the 14th Internat. Middle East Power Systems Conference, Cairo Univ., Egypt,* 2010.

4. **Johnson K., Naveen T.** Wind farm control: addressing the aerodynamic interaction among wind turbines, *American Control Conference*, 2009 .

5. **van Dam F., Gebraad P., van Wingerden J.-W.** A Maximum Power Point Tracking Approach for Wind Farm Control, *Proc. of the 'The Science of Making Torque from Wind' Conference, Oldenburg, Germany,* 2012.

6. **Marden J., Ruben S., Pao L.** A Model-Free Approach to Wind Farm Control Using Game Theoretic Methods, *IEEE Transactions On Control Systems Technology*, Vol. 21, No. 4.

7. **Li T., Feng A.J., Zhao L.** Neural Network Compensation Control for Output Power Optimization of Wind Energy Conversion System Based on Data-Driven Control. *Journal of Control Science and Engineering*, 2012.

8. **Bayat M., Sedighizadeh M., Rezazadeh A.** Wind Energy Conversion Systems Control Using Inverse Neural Model Algorithm. *Internat. Journal of Engineering and Applied Sciences*, 2010.

9. **Shkodyrev V.P.** Innovatsionnyie tehnologii v zadachah upravleniya bolshimi raspredelennyimi sistemami [Innovative technologies in the problems of managing large distribution systems]. *Nauchno-tekhnicheskie vedomosti SPbGPU. Nauka i obrazovanie.* Ustoichivoe razvitie i energetika. St. Peterburg: SPbGPU Publ., 2012, No. 3, Pp. 73–76. (rus)

10. **Arseniev D.G., Shkodyrev V.P., Potekhin V.V., Kovalevsky V.E.** Multiagent approach to creating an energy consumption and distribution system. *Proc. of the VII Internat. Conference International Cooperation in Engineering Education,* St. Petersburg, Russia, 2012.

СПИСОК ЛИТЕРАТУРЫ

1. **Bogdanov K. Yu.** Science synthesis – weapon of learning in XXI century // Physics. 2006. No. 9.

2. **Pandey K., Tiwari A.** Maximum power point tracking of wind energy convertion system with permanent magnet synchronous generator // Internat. Journal of Engineering Research & Technology (IJERT). 2012. Vol. 1. Iss. 5.

3. **Azouz M., Shaltout A., Elshafei M.A.L.** Fuzzy Logic Control of Wind Energy Systems // Proc. of the 14th Internat. Middle East Power Systems Conf. (MEPCON'10), Cairo Univ., Egypt, 2010.

4. **Johnson K., Naveen T.** Wind farm control:

addressing the aerodynamic interaction among wind turbines // American Control Conference. 2009 .

5. **van Dam F., Gebraad P., van Wingerden J.-W.** A Maximum Power Point Tracking Approach for Wind Farm Control // Proc. of the Science of Making Torque from Wind Conf., Oldenburg, Germany. 2012.

6. **Marden J., Ruben S., Pao L.** A Model-Free Approach to Wind Farm Control Using Game Theoretic Methods // IEEE Transactions On Control Systems Technology. Vol. 21, No. 4.

7. **Li T., Feng A.J., Zhao L.** Neural Network Compensation Control for Output Power Optimization of Wind Energy Conversion System Based on Data-Driven Control // Journal of Control Science and Engineering. 2012.

8. **Bayat M., Sedighizadeh M., Rezazadeh A.** Wind Energy Conversion Systems Control Using Inverse Neural Model Algorithm // Internat. Journal of Engineering and Applied Sciences. 2010.

9. **Шкодырев В.П.** Инновационные технологии в задачах управления большими распределенными системами // Научно-технические ведомости СПбГПУ. Наука и образование. Устойчивое развитие и энергетика. СПб.: Изд-во СПбГПУ, 2012. № 3-1(154). С. 73–76.

10. **Arseniev D.G., Shkodyrev V.P., Potekhin V.V., Kovalevsky V.E.** Multiagent approach to creating an energy consumption and distribution system // Proc. of the VII Internat. Conf. International Cooperation in Engineering Education. St. Petersburg, 2012.

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