POWER MACHINERY

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SYNERGY EFFECT USING VERTICAL-AXIAL WIND POWER PLANTS

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Abstract—*The necessity of using a synergistic effect in energy systems that include vertical axial wind power plants is shown. The ways of achieving a synergistic effect at different levels of the system hierarchy are considered: at the lower level, this is the construction of wind farms, consisting of a group of vertical-axial rotors, located in a certain way in space, at the middle level, the inclusion of wind farms in a hybrid energy system, which may additionally include: solar power plant, wave energy plant, hydroelectric power plant, gas combustion plant, etc. at the upper level – synergies between energy efficiency and renewable energy sources. For the problem solution of synergy effect achievement it is proposed to use the Navier–Stokes differential equations solution for cluster of three wind-energy stations with further optimization based on Genetic algorithm.*

Index Term—Synergy; renewable energy; vertical axial wind turbines; hybrid power plants; energy efficiency.

I. INTRODUCTION

Currently, much attention is paid to the development of green energy, which is associated with the widespread use of renewable energy sources. The world community is faced with the task of reducing greenhouse gas emissions by 50% in the near future.

Wind power is expected to become one of the main sources of clean renewable energy, which will quickly eliminate energy from fossil fuels. In the United States, for example, wind power is projected to provide about 20% of electricity by 2030. As a result, more and more wind farms are being deployed, and further expansion and expansion of these farms is a challenge as the land area required will increase. The main goal of the current research is in such a way as to increase the specific capacity of a wind farm, that is, how much energy can be produced per unit of usable land area.

Modern wind energy is based mainly on the use of wind power plants (WPP) of two main types - horizontal-axial (GO) propellers with a horizontal axis of rotation and vertical-axial (VO) (or orthogonal) with a vertical axis of rotation.

Comparisons of vertical-axis and horizontal-axis propeller wind turbines found in the literature are usually limited to mentioning the advantage of vertical-axis wind turbines due to their main feature – insensitivity to wind direction and, consequently, the possibility of greatly simplifying the design. Moreover, the greatest use of vertical-axial wind turbines is projected in developing countries that do not have modern technologies [1]. As a substantiation of such forecast the constructive simplicity of the vertical-axial wind turbines which do not demand rotary devices and systems is put forward [2] – [4].

Synergetics, a synergetic approach arose in the development of the theory of complex systems. The object of the study of synergetics are complex self-organizing systems. Thus under self-organization the irreversible process leading as a result of cooperative action of subsystems to formation of more difficult structures of all system is understood. The main difference between self-organization and other processes, such as growth processes, is a qualitative change in the state in which the system is, and the fact that this change occurs by leaps and bounds.

In the works [5] – [13] analyzed the characteristics and features of synergetic systems:

- for synergetic systems is characterized by the predominance of cooperative forms of interaction of components both within the system and outside it; self-organization is always associated with cooperative processes, collective coordinated behavior of parts of the system (it is due to such behavior that new structures emerge);
- for the results of the functioning of the synergetic system, and the ability to be endowed with certain properties "responsible" are not individual components of the system, and their collective interactions – consistency, synchronization, coherence;

- coincidence, the real situation is a constructive beginning, the basis for the development process; the process of self-organization appears due to the interaction of chance and need and is always associated with the transition from instability to stability;
- synergetics is based on the principle that the world evolves according to nonlinear laws; nonlinearity in the broadest sense means the variety of ways to choose from alternatives; the synergetic system is characterized by nonlinearity of internal dynamics, the ability to change its structure, while maintaining integrity;
- synergetic system clearly defines energy factors – the emergence of a powerful flow of energy, and its exit from the system;
- the synergetic system is characterized by the constructive nature of the contradictions that arise in the process of interaction;
- in the synergetic system simultaneously presented two trends – the desire to increase entropy and to reduce it (negentropic tendency);
- the predominance of one of these trends determines either the transition of the system to a higher level of development, or the development of the entropy of decline; self-organization is manifested in the ability to resist entropy tendencies.

As you can see from the above, the implementation of the synergistic effect can significantly increase the efficiency of the energy system.

II. PROBLEM STATEMENT

Based on the available sources of renewable energy, including wind, it is necessary to develop an integrated approach to finding ways and their implementation, ensuring the achievement of a synergistic effect for a significant increase in the energy efficiency of the hybrid power plant being developed. To solve the problem, a methodology is proposed

III. METHODOLOGY OF ACHIEVING A SYNERGISTIC EFFECT USING VERTICAL-AXIAL WIND TURBINES

The methodology of achieving a synergistic effect using vertical-axial WPP has a hierarchical structure, which is shown in Fig. 1. This structure has three levels of hierarchy: at the lower level, this is the construction of wind farms, consisting of a group of vertical-axial rotors, located in a certain way in space, at the second level, the inclusion of wind farms in a hybrid energy system, which may additionally include: solar a power plant, an installation using wave energy, a hydroelectric power plant, an installation using the energy of gas combustion, etc., at the third level, the synergy between energy efficiency (EE) and renewable energy sources (RES) Consider the lower level of the hierarchy.

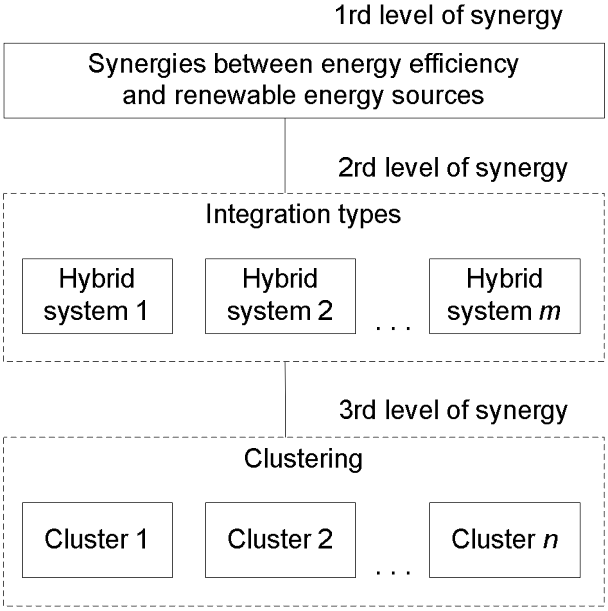


Fig. 1. The structure of the synergy methodology

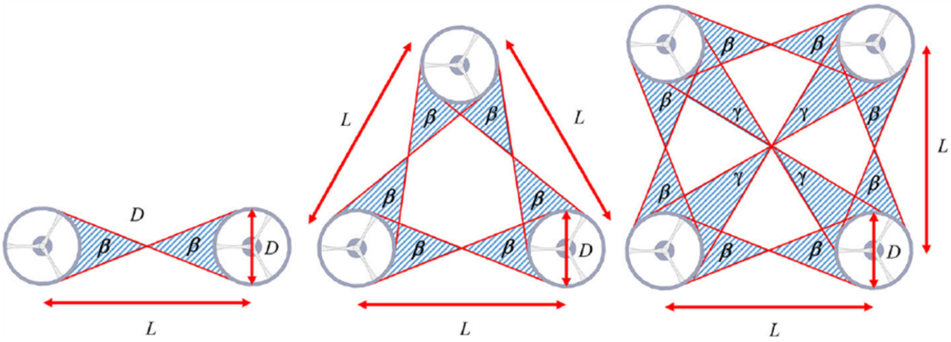
IV. SYNERGISTIC EFFECT BASED ON THE MUTUAL ARRANGEMENT OF VERTICAL-AXIAL ROTORS OF ROTATION

Experiments [14] show that wind turbines with a vertical rotor axis can interact synergistically to increase overall energy production when placed in close proximity. In order to simplify, we use a linear model of executive bodies when simulating a large vortex to test new configurations of wind turbines with a vertical rotor axis of rotation, which use these synergistic interactions. This model is described by the Navier–Stokes differential equations. At the first stage, clusters with three turbines each are designed, remaining insensitive to the wind direction, and the distance between the grouped turbines is optimized. Then the wind turbines are tuned based on clusters, rather than individual turbines. The simulation results show that vertical-axis wind turbines have a positive effect on each other if they are assembled into well-designed clusters: such configurations increase the power generation of one turbine by about 10 percent [14]. In addition, cluster designs can reduce the distance between turbines, which results in an increase in the number of turbines in a given area by about three times compared to traditional configurations.

It has been shown that combining vertical axis wind turbines into small groups has several advantages for electricity generation. [15]. The global performance of the turbines is enhanced since the downstream turbines benefit from the flow-deflection effect and the resulting higher flow speed caused by turbines located upstream. However, depending on the direction of the wind relative to the location of the turbines on the farm, compact clustering can also have negative consequences when one turbine is mainly in the track / shadow of the upstream rotor.

If two turbines are grouped together, the range of wind directions at which one of the turbines is in the shade (partially or fully) of the other is 2β, where$\beta = \tan^{-1}(2D/2L)$ (Fig. 2a), L being the turbine spacing (centre to centre) in a cluster. We note that this is a purely geometric consideration that does not account for the expansion of the wake. On the other hand, when the flow is approximately perpendicular to the centre-to-centre axis, the higher induced speed in-between the two turbines is not being exploited.

By introducing one additional turbine, the range of wind directions where two turbines can directly shadow each other is increased to 6β (Fig. 2b). However, the third turbine can benefit from the higher wind speed induced in-between the two upstream turbines or the two downstream rotors can benefit from the transverse flow deflection of the upstream turbine (depending on wind direction). This can lead to the generation of energy by the three turbines in excess of the power of the three distant, non-interacting ones (this improvement depends on L/D, as shown below). As the number of turbines in a cluster increases to more than three, the flux benefits decrease and the range of wind directions in which the turbines obscure each other increases to n $(n - 1)$ β,where n is the number of turbines in the cluster (e.g., Fig. 2c)



a) b) c)

Fig. 2. Wind directions in which vertical-axis wind turbines are in the wake of an upstream rotor for two, three and four turbines ($\gamma \approx \beta$)

Having chosen an effective cluster design, we now consider the design of trusses based on these clusters. An important parameter in the design and optimization of wind farms is the distance required for wind speed and energy recovery after turbines [14].

The triangular design provides the best use of accelerated flow with minimal track shading.

Effect of distance between turbines depending on their diameter, L/D, was then tested to optimize a single cluster in terms of overall power generated, omni-directional performance, and wake-up recovery distance required. By varying the turbine stroke, the housing z L/D values of 3, 4 and 5 were shown to generate the highest average cluster power. Subsequently, further tests were carried out only at these three time intervals, and the case with $L/D = 5$ emerged as one with the highest average cluster power in all wind directions: the power generated in this case is about 10% higher than that generated by the three insulated turbines. Furthermore, $L/D = 5$ causes the smallest change in the generated power depending on the wind direction, and the trace return distance with the flow is the shortest (since the cluster is more “porous”). So this cluster design has confirmed the use of the synergistic effect of a vertical axis wind turbine to increase energy generation and will generate a higher power density (power generated per unit of land used) due to the proximity of the rotors.

The performed analysis to determine the topology of a cluster of vertical-axial wind turbines and their geometric parameters is rather laborious and costly, since it was implemented on experimental installations. Therefore, in this paper, it is proposed to use mathematical models of clusters consisting of vertical-axis wind turbine (VAWT), the dynamics of which is described by systems of Novier–Stokes equations with additional elements that take into account the effect of the vortex field of one turbine on others. It is advisable to solve these equations using the ANSYS software package. Choosing the electric power generated by the cluster as a fitness function and using a two-level algorithm as an optimization one, it is possible to find the optimal number of VAWTs included in the cluster, their geometric parameters and the distances between them. This is especially important because the mathematical model can take into account the direction and speed of the wind, natural relief and other environmental parameters.

The two-level optimization algorithm consists of the following algorithms: hybrid genetic and gradient ADAM algorithm [16]. At the first stage of the optimization process, a hybrid genetic algorithm is used, which makes it possible to “roughly” determine the structure and parameters of the VAWT. At the second stage, the ADAM algorithm is used, which makes it possible to refine the parameters found as a result of the first stage.

That is why VAWT was adopted for the construction of large wind farms. The trusses, which use this advanced cluster design and sufficient track recovery distance between the 10D and 20D clusters, were then compared to the aligned and offset configurations for the prototypes for infinitely large wind farms with different horizontal turbine slopes: 5D, 10D and 20D. For selected very large wind farms, the results show that the average power factor of wind farms using two different normalizations is much higher for shifted triangular clusters than for wind farms with a regular configuration. By using these average power factor results and the simple cost of capital function for the entire wind farm, as well as changing the ratio of land costs to turbine costs, we have also shown that the unfolded wind farm cluster design is optimal (among those discussed here) in terms of cost per unit of energy produced. Significant power increases and lower capital costs can be achieved by harnessing the ability of vertical axis wind turbines to positively increase power generation from adjacent turbines if properly tuned. Another important aspect of the results is that in addition to the interaction of turbines within the cluster, the clusters themselves act synergistically, further increasing energy production. One of the criteria for the optimization of clusters and farms was multidirectional. It is necessary to choose a configuration with characteristics that are not strongly dependent on the wind direction as this is also the main advantage of individual vertical axis wind turbines. However, if this criterion is weakened, for example in locations with a predominant wind direction, the optimal cluster designs can be very different and can also exploit this synergy between clusters with potentially higher power densities.

According to the above methodology, the next step is to incorporate wind farms into the hybrid energy system.

There are several solutions of renewable energy sources (RES) integration [17]:

- connecting spatially distributed generators;
- the use of additional and / or controlled generators in hybrid configurations;
- application of requirements and flexible loads;
- implementation of energy storage;
- large size and power for hydrogen;
- use of the concept of "vehicle-power" - the use of electric vehicles as a warehouse;
- forecasting of RES generation.

It should be noted that renewable energy sources, which are components of a hybrid power plant, complement each other during operation.

The first is the hybridization of energy sources (e.g. solar wind, wind-water, etc.), and the second is the use of the spatial distribution of power plants for the smooth generation of electricity by given RES. Both approaches are based on the complementary (to a different extent) nature of renewable energy sources.

Complementarity should be understood as the ability to complement each other. Complementarity can be seen in time, space and together in both areas.

Spatial complementarity - can be observed between one or more types of energy sources. This is a situation where energy resources complement each other in a given region. A complement to the shortage of one RES in region x is its availability in region y. An example of spatial complementarity is the effect of smoothing spatially dispersed wind generators, the energy generation trends of which show a decrease in the correlation coefficient with increasing distance between facilities.

Temporary Complementarity - Can be observed between two or more energy sources in the same region. This is understood as a phenomenon in which RES show periods of availability that complement each other in the time domain. An example is the annual patterns of wind and solar energy availability in Europe, where the former is plentiful in the fall / winter period and the latter in the spring / summer period.

An example of building a hybrid power plant, including a wind farm with a vertical rotor and a solar power plant, implemented at the National Aviation University under the leadership of the author, is shown in Fig. 3.

Fig. 3. Hybrid power plant

Space-time complementarity – (complementarity in time and space) is considered for one or more energy sources, the complementarity of which is studied simultaneously in the temporal and spatial realms.

In order to ensure the efficiency of the functioning of the hybrid power plant, it is necessary to assess the complementarity using statistical indicators.

Correlation coefficients and indices are used as such indicators. Correlation coefficients are the most widely used measure of the relationship between two random variables.

According to the above methodology, the next step in the proposed methodology is the synergy between energy efficiency and renewable energy sources.

The synergy between EE and RE can be framed in the following ways:

1) In developing the upper tier of synergies, the focus should be on the ultimate goals, including reducing greenhouse gas emissions, increasing energy availability and enhancing energy security in the most realistic ways.

Also, it should enable the realization of EE and RE measures through proof of achievement, such as carbon reduction certificates. This can be done in a variety of ways, including via open markets for EE, demand management, energy storage, carbon storage, RE generation, use of energy-efficient equipment and other solutions.

2) New policy thinking is required as policy implementation progresses. This could include processes to reduce complexity, and tools or analysis to evaluate the effect of policies on the energy system and achievement of end goals. The “Clean energy for all Europeans” package [18] is an example that combines governance, EE, RE and electricity market design.

3) Technology innovation needs adaption to policy formulation so that it can influence energyrelated behaviour and consumption. An example is energy service models that integrate energyefficient equipment with smart meters or renewable electricity and storage systems to create an efficient building [19].

4) Sufficiency strategies begin with the evaluation of everyday routines and lifestyles in order to reconcile them with demands for sustainability. The results influence fundamental approaches to reduction, substitution and adaptation. The framework conditions are structurally and politically designed in such a way that EE becomes more acceptable in everyday life.

There are potential losses at each stage of the energy supply chain, from extraction to end use. So, each stage has the potential to increase the EE of the overall system. Renewables are capable of providing more primary energy when overall energy demand is lowered using EE measures. Renewables like wind, solar and hydropower do not need thermal energy conversion, so they are inherently more efficient.

Using distributed renewables could also reduce losses in the transmission and distribution grid because the production is on-site and is closer to the consumption.

The synergy provided by EE and RE measures vary from country to country. Based on the place of implementation, the factors shown in the image affect the potential synergy that the same measures could achieve.

Energy efficiency and RE can create synergies in different ways.

- *Timing synergies*. The energy-saving potential of EE is significant in the short to medium term, but EE solutions are not infinite. Therefore, renewables are needed to supply energy in the short term and also to expand opportunities in the long term.
- *Economic synergy.* According to most studies, energy efficiency has the lowest levelized energy cost compared to power generation technologies. In addition, renewable energy technologies can compete in cost with traditional power generation technologies. Using both solutions at the same time can reduce the overall cost of the power system. Moreover, by creating investment and jobs in various sectors, the pursuit of energy efficiency and renewable energy can increase economic growth.

- *Geographic synergies.* The potential for implementing RE is dependent on the location, while most EE solutions are not location-specific. In locations with a lack of suitable RE resources, the system could utilise more EE to compensate for this shortage.
- *Power system synergies.* The effect of EE and RE on grid load varies over time. For example, on a hot summer day, EE could reduce the load and RE technologies (e.g. PV power) could fulfil the remaining load. Also, they could increase grid reliability by diversifying the supply sources [20].

V. CONCLUSIONS

The problem of achieving a synergetic effect in the construction of energy systems based on the use of renewable energy sources is considered. The use of installations with a vertical axis of rotation of the rotor is envisaged as a wind turbine. A methodology for achieving a synergetic effect by solving the problem at three levels is proposed. The proposed approach can significantly increase the efficiency of hybrid energy systems.

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В. М. Синєглазов. Синергетичний ефект з використанням вертикально-осьових вітроенергетичних установок

Показано необхідність використання синергетичного ефекту в енергетичних системах до складу яких входять вертикально-осьові вітроенергетичні установки. Розглянуто шляхи досягнення синергетичного ефекту на різних рівнях системної ієрархії: на нижньому рівні це побудова вітростанцій, що складаються з групи вертикально-осьових роторів, певним чином розташованих у просторі, на верхньому рівні – включення вітростанцій до складу гібридної енергетичної системи, до складу якої додатково можуть входити: сонячна енергетична установка, установка використовує енергію хвиль, гідроелектростанція, установка, що використовує енергію горіння газу, тощо; на верхньому рівні – синергія між енергоефективністю та відновлювальними джерелами енергії. Для вирішення завдання досягнення синергетичного ефекту пропонується використовувати розв'язання рівнянь Нав'є–Стокса для кластера з трьох вітроенергетичних станцій з подальшою оптимізацією на основі генетичного алгоритму.

Ключові слова: синергетика; відновлювальні джерела енергії; вертикально-осьові вітроустановки; гібридні енергетичні установки; енергетична ефективність.

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В. М. Синеглазов. Синергетический эффект с использованием вертикально-осевых ветроэнергетических установок

Показана необходимость использования синергетического эффекта в энергетических системах в состав которых входят вертикальные осевые ветроэнергетические установки. Рассмотрены пути достижения синергетического эффекта на разных уровнях системной иерархии: на нижнем уровне это построение ветростанций, состоящих из группы вертикально-осевых роторов, определенным образом расположенных в пространстве, на верхнем уровне – включение ветростанций в состав гибридной энергетической системы, в состав которой дополнительно могут входить: солнечная энергетическая установка, установка использующая энергию волн, гидроэлектростанция, установка, использующая энергию горения газа и др.; на верхнем уровне – синергия между энергоэффективностью и возобновляемыми источниками энергии. Для решения задачи достижения синергетического эффекта предлагается использовать решение уравнений Навье–Стокса для кластера из трех ветроэнергетических станций с дальнейшей оптимизацией на основе генетического алгоритма.

Ключевые слова: синергетика; возобновляющие источники энергии; вертикально-осевые ветроустановки; гибридные энергетические установки; энергетическая эффективность.

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