The Effect of Vertical Wind Turbines Position Pattern on Their Aerodynamic Characteristics

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Abstract. The article is devoted to the actual problem of increasing efficiency in the field of wind energy. Today, in order to overcome the energy crisis in Ukraine, more and more attention is paid to renewable energy sources. Traditionally, in our country, horizontal wind generators are used. Total power which is produced by wind turbines in Ukraine is nearly 1170 MW this is approximately 18% of whole green power produce in our country. The number of «wind farm» gives a lot of options for optimization. Horizontal wind generators characteristics are well studied, and the existing engineering methodologies and design methods make it possible to create efficient wind power plants. However, the efficiency of vertical wind turbines remains underestimated. Especially in matters of their mutual influence. In this regard, the article devoted to the study of the wind generator pattern position influence on their aerodynamic characteristics is relevant. Both analytical and numerical approach were used to carry calculation with different rotors position. It is shown that with some variation of rotors position their total efficiency can be increased.

Keywords: Vertical wind turbines · Rotor · Position pattern · Synchronous operation · Numerical approach · Management system

1 Introduction

Today, special attention is paid to the wind turbine rotors position, which is vital in the design of a wind turbine management system. Moreover, in most of the works devoted to both experimental and theoretical studies, the joint operation of wind turbine rotors with a horizontal axis of rotation (Fig. 1, a) is considered [1, 2]. Therefore, the study of the effect of the distance between the rotors of wind turbines with a vertical axis (Fig. 1, b) and their relative position is of current interest. This can help to find an optimal position and number of wind turbines installed together in order to increase total productivity. Special attention should be paid for wind turbines which are installed along the highways. Their position affects directly on total efficiency as the use not only wind energy but also the turbulence from the vehicle with certain velocity.

Several factors should be considered – rotors mutual location, delay time for each rotor, number of blades for each turbine. In current work 2d approach was used for both analytical method and numerical simulation. CFD method was used for verification purpose.

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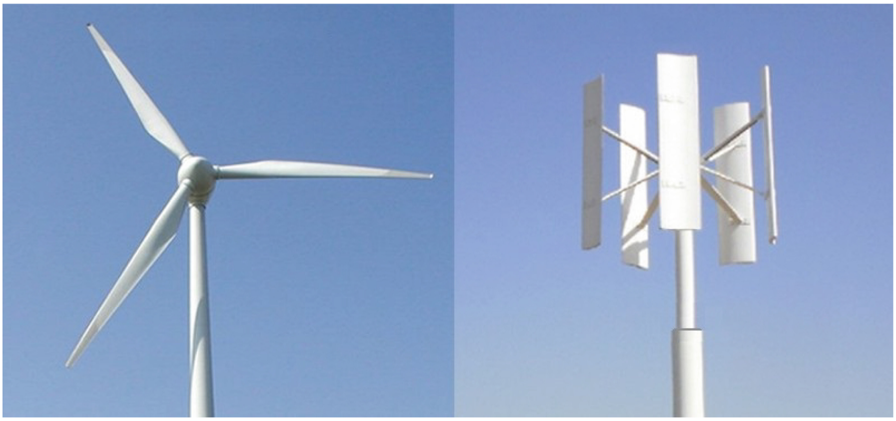

a b

Fig. 1. Horizontal (a) and vertical (b) wind turbine

2 Analytical Model

Current study considers the synchronous operation of two wind turbine rotors with a vertical axis of rotation, located one after the other along the axis ***0**x* (Fig. 2, a) and along the axis ***0y*** (Fig. 2, b).

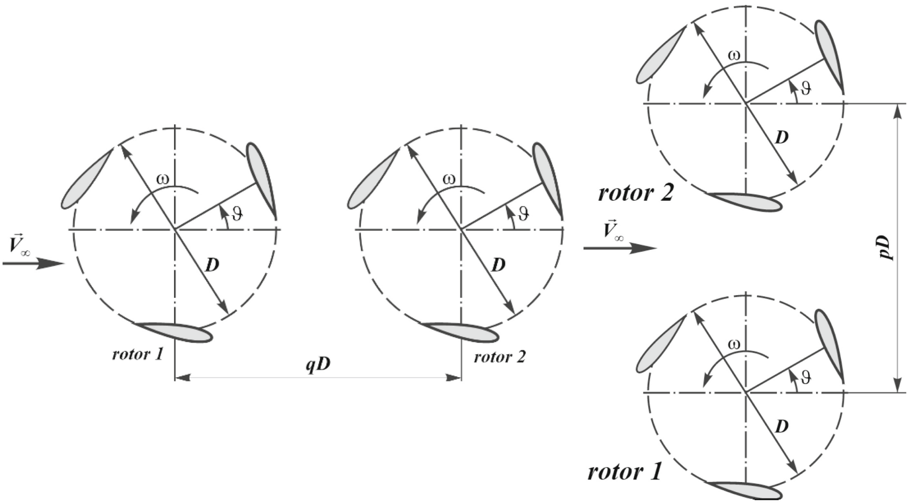

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Fig. 2. Variants of mutual arrangement of wind turbine rotors

The distance between the centers of the rotors was varied and its influence on the dependence of the torque coefficient $\mathbf{c_m}(\mathbf{z})$ on the values of the maximum torque $\mathbf{c_m}_{\max}$ and maximum speed $\mathbf{z}_{max}$ (with a wind energy utilization factor equal to zero) was investigated as well as the dependence of the angles of attack $\boldsymbol{\alpha}(\boldsymbol{\vartheta})$ and the relative resultant speed $\overline{\mathbf{W}}(\boldsymbol{\vartheta})$ on the swept circle with the azimuthal angle ϑ.

The study of the joint operation of wind turbine rotors with a vertical axis of rotation was carried out using a model of potential flow around a rotating permeable cylinder [3].

Expressions for the relative normal and tangential velocity components on the swept circles of the rotors are given with equations:

$$\overline{V}_{r1R_i} = \frac{V_{r1R_i}}{V_\infty} = \left(1 - R^2 \frac{1-K}{1+K} \sum_{j=1}^{k} \frac{1}{\left(x_{R_i} - x_{c_j}\right)^2 + \left(y_{R_i} - y_{c_j}\right)^2}\right) cos\,\vartheta,$$

$$\overline{V}_{\vartheta 1R_i} = \frac{V_{\vartheta 1R_i}}{V_\infty} = -\left(1 + R^2 \frac{1-K}{1+K} \sum_{j=1}^{k} \frac{1}{\left(x_{R_i} - x_{c_j}\right)^2 + \left(y_{R_i} - y_{c_j}\right)^2}\right) sin\,\vartheta$$

$$+ zR\left(1 + \frac{1-K}{1+K}\right) \sum_{j=1}^{k} \frac{1}{\sqrt{\left(x_{R_i} - x_{c_j}\right)^2 + \left(y_{R_i} - y_{c_j}\right)^2}},$$

$$\overline{V}_{r2R_i} = \frac{V_{r2R_i}}{V_\infty} = \overline{V}_{r1R_i},$$

$$\overline{V}_{\vartheta 2R_i} = \frac{V_{\vartheta 2R_i}}{V_\infty} = -\left(1 - R^2 \frac{1-K}{1+K} \sum_{j=1}^{k} \frac{1}{\left(x_{R_i} - x_{c_j}\right)^2 + \left(y_{R_i} - y_{c_j}\right)^2}\right) sin\,\vartheta$$

$$+ zR\left(1 + \frac{1-K}{1+K}\right) \sum_{j=1}^{k} \frac{1}{\sqrt{\left(x_{R_i} - x_{c_j}\right)^2 + \left(y_{R_i} - y_{c_j}\right)^2}},$$

where $x_{R_i} = x_{c_i} + qD$ and $y_{R_i} = y_{c_i} + pD$ – the coordinates of the swept circle of the ***i***-th rotor;

$\mathbf{x}_{c_j}$ and y_{c_j} – coordinates of the center of the **j**-th rotor;
k – number of rotors;
q and **p** – coefficients that determine the distance between the rotors, proportional to their diameter;
D and **R** – diameter and radius of the rotors, m;
$K = \left(1 - \sigma_{o\kappa p}\right) e^{-z\left(0,823 + 0,628\,\lg \sigma_{o\kappa p}\right)}$ – permeability coefficient [3];
$\sigma_{o\kappa p} = \frac{i\, b_\pi}{\pi\, D}$ – "Circumferential" filling factor of the rotor, which is the ratio of the sum of the chords of the blades to the length of the swept circle $l_{o\kappa p} = \pi D$ [3];
z – speed factor;

For each rotor on the windward side, i.e. at $\frac{\pi}{2} \le \vartheta \le \frac{3\pi}{2}$, we work with the velocity components with the index "1" ($\overline{V}_{r1_{R_i}}$ and $\overline{V}_{\vartheta 1R_i}$), and on the leeward side, i.e. for $-\frac{\pi}{2} < \vartheta < \frac{\pi}{2}$ - with the index "2" ($\overline{V}_{r2_{R_i}}$ and $\overline{V}_{\vartheta 2R_i}$) (Fig. 3).

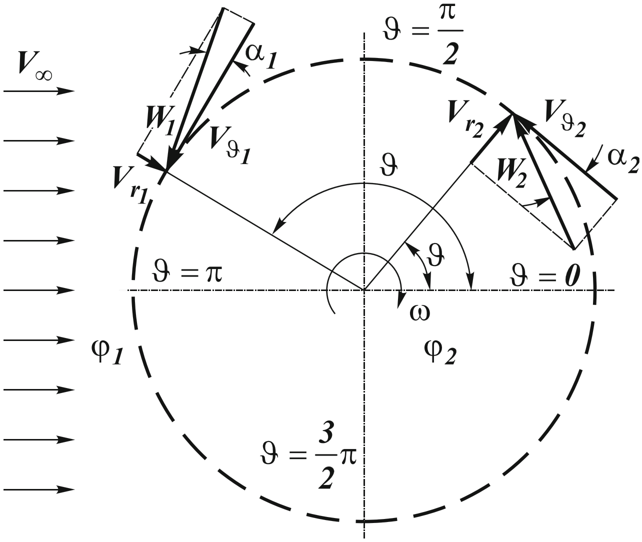

Fig. 3. Determination of velocity and angles of attack on the windward and leeward parts of the rotor.

On the swept circles of the rotors, knowing the velocity at each point of the surface, it is possible to determine the angles of attack and the resulting velocity approaching the blade from the expressions:

$$\alpha(\vartheta) = arctg\frac{V_r(\vartheta)}{V_\vartheta(\vartheta)},$$

$$W(\vartheta) = \sqrt{(V_r(\vartheta))^2 + (V_\vartheta(\vartheta))^2}.$$

In Figs. 4–7 show the dependences of the angles of attack $\alpha(\vartheta)$ and the relative resultant speed $\overline{W}(\vartheta)$ for an isolated rotor and two rotors of a wind turbine with a vertical axis, operating synchronously at a speed coefficient $z = 2, 5$.

The angles of attack were obtained for three-blade rotors with a vertical axis, having a diameter $D = 1\ M$, a chord of the blade $b = 0, 1\ M$, a height of the rotor $H = 0, 7\ M$, and an angle of installation of the blade $\varphi_\pi = 0°$.

1 and 2 - rotors 1 and 2 with a distance between them equal ***2D***; 3 - rotors 1 and 2 with a distance between them equal ***5D***; 4 - rotors 1 and 2 with a distance between them equal ***10D***; 5 - rotors 1 and 2 with a distance between them equal ***60D*** and an insulated rotor.

1 and 2 - rotors 1 and 2 with a distance between them equal ***2D***; 3 - rotors 1 and 2 with a distance between them equal ***5D***; 4 - rotors 1 and 2 with a distance between them equal ***10D***; 5 - rotors 1 and 2 with a distance between them equal ***60D*** and an insulated rotor.

From Fig. 4 and 5, it can be seen that with the synchronous operation of two rotors of a wind turbine with a vertical axis, both when arranged sequentially along the axis ***0x*** and along the axis ***0y***, the range of variation of the angles of attack on the swept surfaces is narrowed in comparison with an isolated rotor.

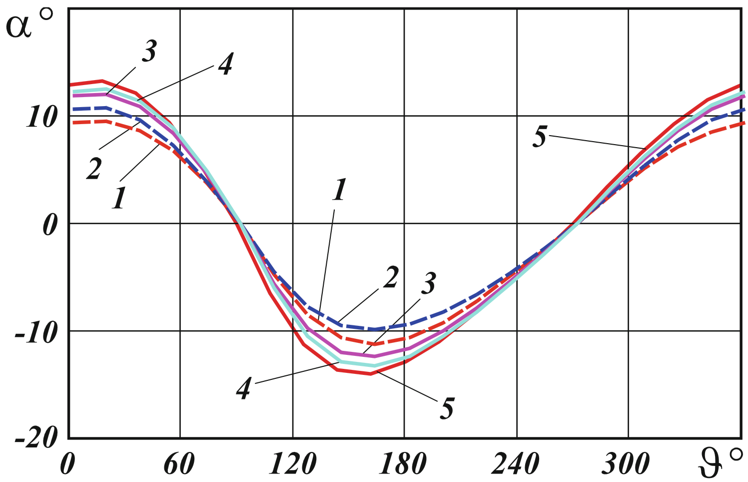

Fig. 4. Comparison of dependencies $\alpha(\vartheta)$ for isolated and synchronously operating rotors when they are located along the axis ***0x***.

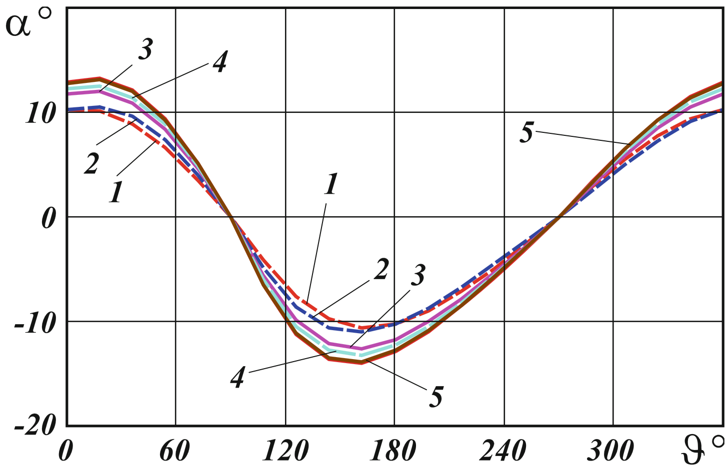

Fig. 5. Comparison of dependencies $\alpha(\vartheta)$ for isolated and synchronously operating rotors when they are located along the axis ***0y***.

When the distance between the centers of the rotors is from ***2D*** to ***5D***, the dependences $\alpha(\vartheta)$ for the first and second rotors differ significantly. Starting from a distance of equal ***5D*** dependences $\alpha(\vartheta)$ practically merge, but the range of variation of the angles of attack on the swept circles remains smaller than for an isolated rotor up to a distance ***(50...60) D*** where the mutual influence of the rotors on each other decreases. When the distance between the centers of the rotors is equal ***(50...60) D***, each of the rotors works as an isolated one.

1 and 2 - rotors 1 and 2 with a distance between them equal ***2D***;

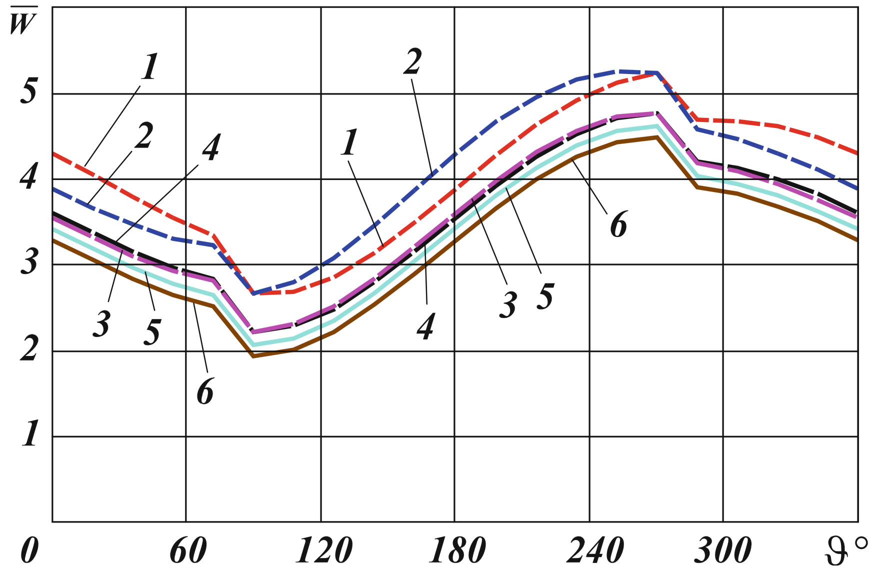

Fig. 6. Comparison of dependencies $\overline{W}(\vartheta)$ for isolated and synchronously operating rotors when they are located along the axis ***0x***.

3 and 4 - rotors 1 and 2 with a distance between them equal ***5D***; 5 - rotors 1 and 2 with a distance between them equal ***10D***; 6 - rotors 1 and 2 with a distance between them equal ***60D*** and an insulated rotor.

The narrowing of the range of variation of the angles of attack leads to the fact that in most of the swept surface of the rotor, the blades will operate in the range of angles of attack that are less than the angle of attack of the start of stall, which should improve the aerodynamic characteristics of the rotors.

With the synchronous operation of two rotors, the centers of which are located at a distance from ***2D*** to ***5D***, the relative net speed on the swept surfaces increases. Moreover, when the rotors are placed along the axis ***0x***, on the swept circle of the first rotor, the relative resulting velocities will be greater than for the second, on the leeward side, and smaller on the windward side. When the rotors are located along the axis ***0y*** on the swept circle of the first rotor, the relative resulting velocities are greater than on the second, in the range of azimuthal angles $0 < \vartheta < \pi$, and smaller for $\pi < \vartheta < 2\pi$.

The same regularities are preserved for the distances between the centers of rotors larger then 5*D*, but the mutual influence of the rotors on their kinematic decreases. At a distance from ***(50...60)D*** each of the rotors can be considered as working in isolation, and their kinematic parameters will fully coincide with the parameters of an isolated rotor.

1 and 2 - rotors 1 and 2 with a distance between them equal ***2D***;

3 and 4 - rotors 1 and 2 with a distance between them equal ***5D***; 5 - rotors 1 and 2 with a distance between them equal ***10D***; 6 - rotors 1 and 2 with a distance between them equal ***60D*** and an insulated rotor.

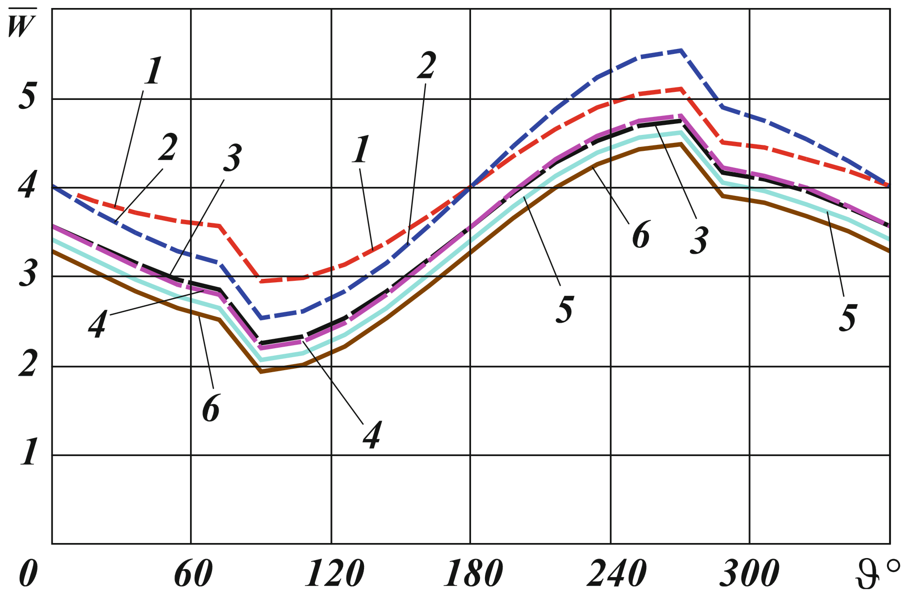

Fig. 7. Comparison of dependencies $\overline{W}(\vartheta)$ for isolated and synchronously operating rotors when they are located along the axis ***0y***.

Changes in the dependencies $\overline{W}(\vartheta)$ will affect the aerodynamic characteristics of each of the synchronously operating rotors.

The rotor torque coefficient is determined from the expression [3]:

$$c_m = \frac{\sigma_{o\kappa p}}{2} \int_0^{2\pi} c_x(\vartheta)\overline{W}(\vartheta)^2 d\vartheta,$$

where $c_x(\vartheta)$ – longitudinal force coefficient of the blade, determined depending on the angle of attack $\alpha(\vartheta)$.

In Fig. 8 shows the dependence of the longitudinal force coefficient on the angle of attack $c_x(\alpha)$ for the NACA-0018 profile. Experimental studies of an isolated blade were carried out at the Reynolds number $Re = 0,3 \cdot 10^6$, blade elongation $\lambda = 6{,}36$ [4].

The dependences show that the placement of two synchronously rotating rotors with a vertical axis gives an increase in the maximum value of the torque coefficient in comparison with the isolated one. There are some related studies [5–7] which confirm the positive effect of using several wind turbines, however, they are more aimed at studying the mutual arrangement on the self-starting torque.

Let us consider the dependences of the maximum value of the torque coefficient for two synchronously operating wind turbine rotors with a vertical axis, located along the axis ***0x*** and ***0y***, on the distance between their centers.

In order to check the analytical model results a numerical simulation for the case 1 (Fig. 2 a) was carried. Numerical model is based on Navier-Stokes equations describing the conservation of mass, momentum and energy.

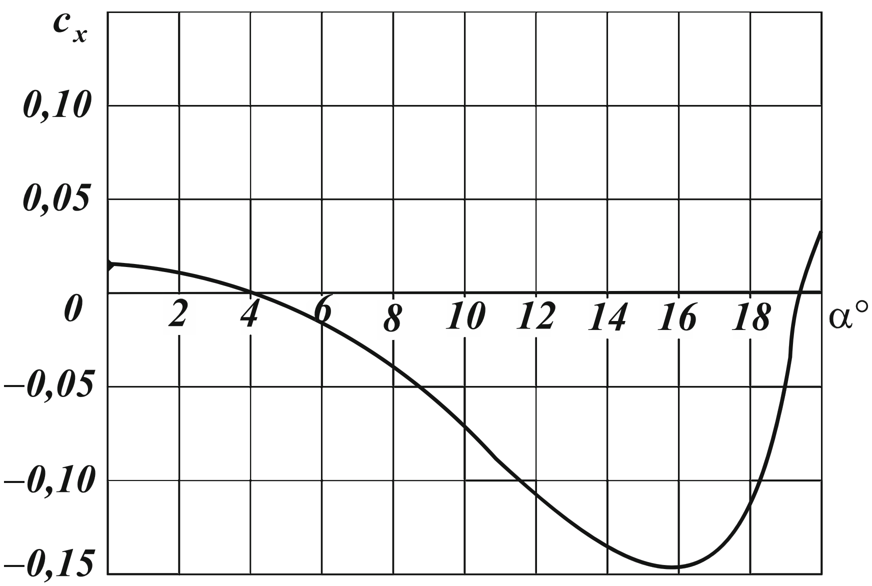

Fig. 8. Dependency $c_x(\alpha)$ for profile $NACA - 0018$

Figure 9 shows the comparative analysis of the results. As can be seen both approaches gives a very close results.

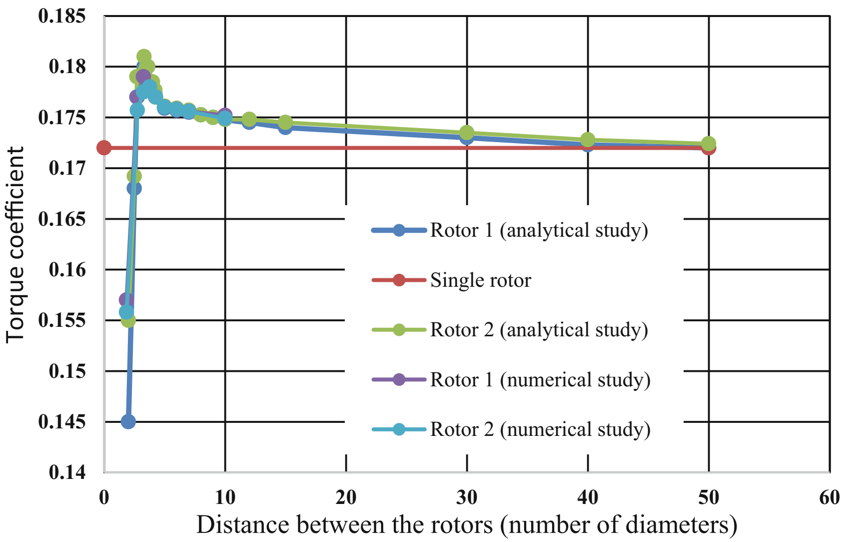

Fig. 9. Comparative analysis for analytical and numerical model for a set of rotors

3 Conclusions and Future Work

The specified research direction is rather promising. Obtained results shows a positive impact from optimum mutual position of wind turbines. It was found that the distance between rotors pattern equal to 5D gives an increase in power. Also mutual arrangement can reduce a torque required for self-start of a rotor. Initial comparative analysis of the analytical model and numerical shows good agreement between results. However further research is vital.

Several direction are left for the further research – parametric study on flow velocity vector angle effect on wind farm efficiency. Another important thing is desynchronization of the rotors which is also not studied, thus can give a positive boost in performance.

Promising results can be obtained with a combination of different geometrical parameters for individual turbine and their amount.

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