The Wind Farm Simulator of Reflected Signals in Primary Radar System

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***Abstract*—The spreading of the renewable energy especially wind farms, increases possibilities of negative influence on the detection capabilities of primary radar systems. The paper deals with modelling of a simulator for reflected signals from wind farms. The developed simulator enables echo simulation from wind farms, with many variable input parameters, that helps with analysis of influence. The simulator simplifies and speeds up the development of wind farm mitigation techniques, on primary radar systems. The paper describes characterization of the model of the simulator that includes multipath reflection and a brief analysis.**

Keywords—wind turbine; power plant; primary radar system; clutter; reflection, Radar Cross Section, wind farm, Doppler shift

I. INTRODUCTION

The impact of an individual wind turbine or large wind farm is a very well-known serious problem that can negatively affect the functionality of different kinds of radar systems (primary and secondary radar systems, surveillance and weather radar systems or passive radar systems) [1], [2] and [3]. For the analysis of impact of a wind turbine or wind farms on radar systems (RS), it is necessary to collect a lot of real data in the different scenarios, for the developing of the universal mitigation techniques. The collecting of data is a very time and money consuming activity. The developing of a simulator of reflected signals from a wind turbine or wind farm, it is necessary for higher effectiveness. In the first part of our work [4], we developed a simulator for a single wind turbine influence, which can generate reflected signals in dependency on input variables. A simulator was used for verification of the developed model. The next step is developing of the „universal“ simulator for a wind farm, including multipath reflection. This paper deals with the description of a wind farm model and subsequent brief analysis of wind farm influence.

The impact of wind turbine on RS is primarily in wide Doppler shift and in a large Radar Cross Section (RCS) that can cause “blindness” of the RS or masking of targets located behind wind farm. The maxima of Doppler shift and RCS mainly depends on strength of wind turbine, number of blades, blade rotation speed, length of blades, azimuth and elevation of RS with respect to wind farm, and distance between RS and wind farm. The base parameters of primary radar systems that were used for the simulator are shown in Table 1.

TABLE I. PARAMETERS OF THE PRS

Parameters of Primary Radar System	
Detection distance D	12-150 km
Pulse intermodulation	P4
Carrier frequencies f_c	2,7 – 2,9 GHz
Antenna gain G_a	33,7 dB
Antenna rotation speed f_{rot}	12,5 rpm
Beam width θ_{ant}	1,4°
Pulse repetition period T_{op}	1 ms
Long pulse length τ	80 µs

The neighbourhood of maximum of Gaussian antenna characteristics is approximated by the formula

$$G_a(\Delta\Phi)[\text{dB}] = -3.\left(\frac{\Delta\Phi}{\frac{\Phi_{3dB}}{2}}\right)^2, \qquad (1)$$

where $G_a(\Delta\Phi)$ is antenna gain in direction of $\Delta\Phi$ from the axis of antenna (direction of central azimuth β_c in Fig. 1), and Φ_{3dB} is beam width in -3dB.

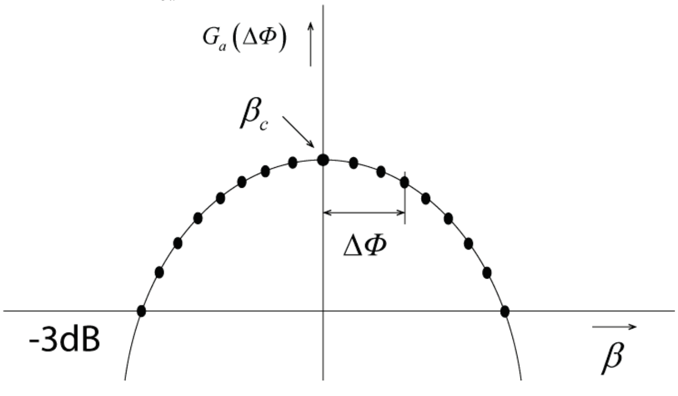

Fig. 1. The Gaussian aproximation of antenna characteristics

II. MODEL OF REFLECTED SIGNALS FROM WIND FARM

The model of reflected signals from wind farm is derived from the model for one wind turbine described in [4]. The model is extended for an unlimited number of wind turbines and is suitable for simulating the impact of the wind farm on a Primary Radar System (PRS). The extensions of the model in comparison to the model for one wind turbine are:

- Antenna characteristics of PRS
- Antenna rotation speed of PRS
- Multipath propagation of reflected signals (up to 3 reflections)
- Unlimited number of wind turbine

The output of one wind turbine simulator is reflected signal received by radar [4], defined by formula

$$s_R\left(i,b,t_r\right) = As_T\left(t-\tau(i)\right) + \\ +\sum_{b=1}^{B}\sum_{i=0}^{L} As_T\left(t+\tau(i,b,t_r)\right)e^{-2\pi f_{dop}(i,b,t_r)t}, \qquad (2)$$

where B is total number of blades in wind turbine,

L is total number of elements in blade,

A is attenuation of signal (constant for all blades),

b is b-th blade $1,2,...B$,

i is i-th element of blade from the $\langle 0;L\rangle$,

$s_T\left(t\right)$ is transmitted signal from PRS,

t_r is pulse repetition period,

$\tau(i,b,t_r)$ is time delay of reflected signal,

$f_{dop}\left(i,b,t_r\right)$ is Doppler shift,

t is time.

The simulator in the first stage detects azimuth of interests i.e. areas where the wind farm or standalone wind turbine is located. Reflected signals are computed only in the area of interest. This limitation is done for reason of high computing complexity of reflected signals in the simulator. The typical geometry of the area of interest included within the wind farm is shown in Figure 2.

In the right part of figure is the start point – the endpoint defined by azimuth (maximal distance is defined by base parameters of PRS). The dark shadow area presents antenna beam width with anticlockwise rotation. The computation of the antenna rotation after one pulse repetition period ϕ_{op} is defined by the formula

$$\phi_{op} = 6T_{op}f_{rot}. \qquad (3)$$

The azimuth of interest, i.e. β_{com} is defined by the formula

$$\beta_{com} = \theta_{ant} + \Delta\beta,$$

where θ_{ant} is beam width of antenna,

β is azimuth between PRS and individual wind turbines,

$\Delta\beta$ is angle range between maximal and minimal azimuth $\Delta\beta = \left(\max\left(\beta\right)-\min\left(\beta\right)\right)$.

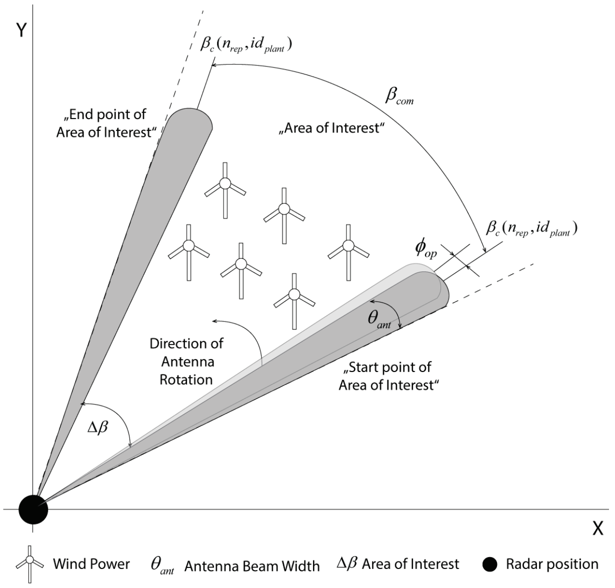

Fig. 2. Geometry of the wind farm and PRS with related parameters

The next step is computation of the central azimuth β_c for all pulse repetition periods T_r of an individual wind turbine defined by the formula

$$\beta_c(n_{rep},id_{plant}) = \min\left(\beta(id_{plant})\right) - \frac{\theta_{ant}}{2} + \left(n_{rep}-1\right)\phi_{op}, \qquad (4)$$

where T is number of total wind turbines,

n_{rep} is index of repetition period from set $n_{rep} \in \left\langle 1, N_{rep} = \left\lceil \beta_{com}/\phi_{op}\right\rceil\right\rangle$,

id_{plant} is index of power turbine from the set $id_{plant} \in \langle 1,T\rangle$.

For the individual repetition period, the beamwidth position is calculated (first position dark shadow, second position light shadow in Fig.1). The visible number of wind turbines depends on beamwidth position. The visibility of the wind turbines for individual beamwidth positions $M\left(n_{rep},id_{plant}\right)$ is defined by the formula

$$M\left(n_{rep},id_{plant}\right) = \begin{cases} 10^{-0.3\left(\frac{2\left|\beta_c\left(n_{rep},id_{plant}\right)-\beta\left(id_{plant}\right)\right|}{\theta_{ant}}\right)^2} & \left(\beta_c\left(n_{rep},id_{plant}\right)+\theta_{ant}/2 \geq \beta\left(id_{plant}\right)\right)\wedge \\ & ,\wedge\left(\beta_c\left(n_{rep},id_{plant}\right)-\theta_{ant}/2 \leq \beta\left(id_{plant}\right)\right) \\ 0, & other \end{cases}. \qquad (5)$$

The exponent in (5) corresponds to $\Delta\Phi = \left|\beta_c\left(n_{rep},id_{plant}\right)-\beta\left(id_{plant}\right)\right|$ shown in Fig.1. For visible wind turbine(s) with corresponding beamwidth, the function value of $M\left(n_{rep}, id_{plant}\right)$ is computed by formula (5) in the interval $\langle -3,0 \rangle dB$. If computed value is lower than $-3dB$ then the value of $M\left(n_{rep}, id_{plant}\right)$ is equal to zero (wind turbines are not visible).

The simulator computes multipath propagation of transmitted signals between individual wind turbines in the windfarm. The maximum of considered reflections are $K = 3$. The higher number of reflections is not considered due to small influences of "higher" reflections and increasing of computation complexity. The number of combinations for multipath propagation depends on the number of wind turbines and considered number of reflections. The example of possible combinations for three wind turbines and two reflections is

$$ref_2 = \begin{bmatrix} 1 & 1 & 2 & 2 & 3 & 3 \\ 2 & 3 & 1 & 3 & 1 & 2 \end{bmatrix}, \tag{6}$$

where each individual column corresponds to the multipath combination. The number represents the identification number of the wind turbine.

The distance between PRS and wind turbines $R_K\left(i_K\right)$ with consideration of multipath propagation (up to $K = 3$) is defined by the formula

$$R_K\left(i_K\right) = R_{RW}\left(ref_K\left(i_K,1\right)\right) + R_{RW}\left(ref_K\left(i_K,K\right)\right) + \sum_{k=1}^{K-1} \left\| Cor_{XYZ}\left(ref_K\left(i_K,k\right)\right) - Cor_{XYZ}\left(ref_K\left(i_K,k+1\right)\right) \right\|, \tag{7}$$

where R_{RW} is the direct signal from PRS to individual wind turbines,

$ref_K\left(i_K,k\right)$ is an individual combination of signal propagation between considered wind turbines.

k is row index in matrix in ref_K, $k \in \left(1,K\right)$,

i_K is column index of total number of combinations T^K,

K is number of reflections,

Cor_{XYZ} is Cartesian coordinates of selected wind turbines for individual combinations.

The total azimuth for each combination $\beta_K\left(i_K\right)$ (each column in (6)) and all considered number of reflections is defined by the formula

$$\beta_K\left(i_K\right) = \beta\left(ref_K\left(i_K,1\right)\right) + \beta\left(ref_K\left(i_K,K\right)\right) + \sum_{k=1}^{K-1}\left(\arctan\left(\frac{Y\left(ref_K\left(i_K,k\right)\right) - Y\left(ref_K\left(i_K,k+1\right)\right)}{X\left(ref_K\left(i_K,k\right)\right) - X\left(ref_K\left(i_K,k+1\right)\right)} \right)\right), \tag{8}$$

where X, Y is $\left[x, y\right]$ Cartesian coordinates of wind turbines. The computation of the total azimuth with multipath propagation for $K = 3$ and combination of wind turbines $ref = \left[1 \quad 2 \quad 3\right]$ is shown in Fig.3.

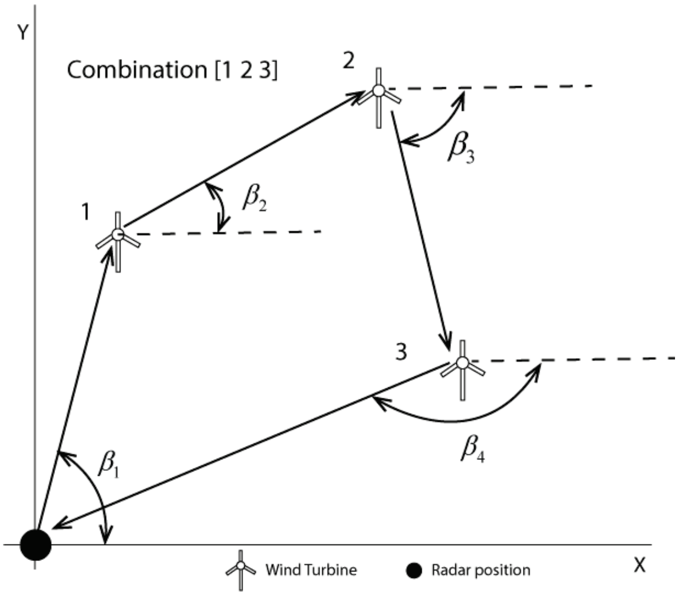

Fig. 3. Geometry of the wind farm for computation of the azimuth

The total elevation for each combination $\alpha_K\left(i_K\right)$ and all considered number of reflections is defined by the formula

$$\alpha_K\left(i_K\right) = \alpha\left(ref_K\left(i_K,1\right)\right) + \alpha\left(ref_K\left(i_K,K\right)\right) + \sum_{k=1}^{K-1} \arctan\left(\frac{Z\left(ref_K\left(i_K,k\right)\right) - Z\left(ref_K\left(i_K,k+1\right)\right)}{\left\| Cor_{XY}\left(ref_K\left(i_K,k\right)\right) - Cor_{XY}\left(ref_K\left(i_K,k+1\right)\right)\right\|} \right), \tag{9}$$

where Cor_{XY} is Cartesian coordinates of selected wind turbines for individual combinations in $\left[x, y\right]$,

Z is z Cartesian coordinate of wind turbines.

The next step is computation of the Doppler shift or Doppler velocity. The Doppler shift depends on rotation speed of blades, number of blade elements, pulse repetition period, and combination of signal propagation between individual wind turbines (one column i_K in (6)). The rotation speed of blades for individual elements is defined by formula (for each wind turbine)

$$V\left(id_{plant}, i\right) = \frac{2\pi f_{rot}\left(id_{plant}\right)}{60} i, \tag{10}$$

where i is i-th element of blade from the $\langle 0; L \rangle$,

L is number of element in one blade.

The angle of blades is defined by formula

$$\varphi\left(id_{plant}, id_{blade}, n_{rep}\right) = 2\pi\left(\frac{\left(id_{blade} - 1\right)}{B\left(id_{plant}\right)} + \frac{f_{rot}\left(id_{plant}\right)}{60} n_{rep} T_{op} \right) + \varphi_{inc}\left(id_{plant}\right), \tag{11}$$

where φ_{inc} is initialization angle of wind turbine blades.

The Doppler speed formula with consideration (10) and (11) is computed by the formula

$$Vdop_K\left(id_{plant}, id_{blade}, i, i_K, n_{rep}\right) =$$
$$V\left(id_{plant}, el\right)\cos\begin{pmatrix} \left|\pi-\alpha_K\left(i_K\right)\right|+\frac{\pi}{2}- \\ -\varphi\left(id_{plant}, id_{blade}, n_{rep}\right) \end{pmatrix}\cos\left(\beta_K\left(i_K\right)\right). \quad (12)$$

The total reflected signal received by the radar is computed by a sum of individual reflected signals that depends on the number of multipath reflections, computed distance (7) and Doppler speed (12), and all input parameters described in (2).

III. Analysis of Reflected Singnals from Wind Farm

The output from the simulator was verified on a real scenario – two wind turbines in Janov [6]. The position of the wind turbines and PRS simulations are shown in Table 2. The parameters of the PRS are the same as in Tab.1.

TABLE II. Parameters of the Simulations I.

Position of Wind Turbine 1	49°50'04.6"N 16°22'18.5"E
Position of Wind Turbine 2	49°49'56.3"N 16°22'08.4"E
Position of the PRS	49°49'52.3"N 16°05'26.2"E
Number of blades	3
The height of Wind Turbines	120 m
The length of blade	40 m
Avg. distance between PRS and WT	20,1 km
The maximal number of reflections	3

In Fig. 4, the position of the PRS (left) and positions of the two wind turbines (right) close to Litomyšl city, is shown. The zoom circle presents the detail of wind turbines.

Fig. 4. The simulation scenario (position of radar and two wind turbines) [6]

The results from simulations are shown in Fig. 5. The asterisk presents the exact positions of the wind turbines and the radar is placed in the center of the Cartesian coordinate system. The simulation does not contain any additional clutter. The feature will be added to the simulator in future. The surface unevenness has not been added to the simulator. The simulator uses only a free-space path loss (FSPL).

The simulated simple scenario was used only for evaluation of the reflected signal from wind turbines (or wind farms). The detailed analysis is presented in [7].

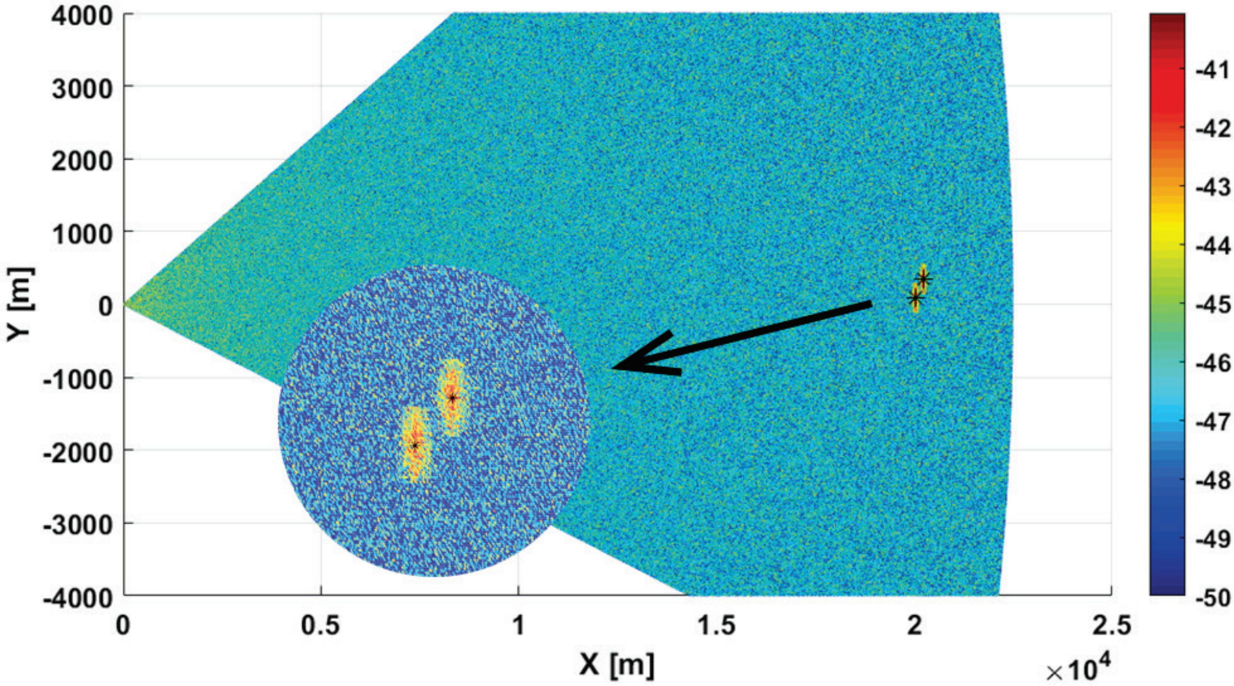

Fig. 5. The simulation scenario (position of radar and two wind turbines)

IV. CONCLUSSION

The paper presents an extension of the model of wind turbine reflected signals received by a PRS. The developed model includes antenna rotation of the PRS, pulse compression of the PRS, an unlimited number of wind turbines with variable parameters, and multipath propagation (up to 3 reflections between wind turbines). The preliminary simulation results were evaluated on the scenario with two wind turbines. The future work will focus on the Doppler shift and other simulations of real scenarios.

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