The Modelling of Wind Turbine Influcence in the Primary Radar Systems

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***Abstract*—Wind turbines or wind farms present a major source of renewable energy. The expansion of wind turbines across the world rapidly increases. Unfortunately, for radar systems, wind turbines are a big source of clutter that can negatively influence the behavior of the detection capabilities of radar systems, or even totally "blind" radar systems. The problematic of mitigation of the influence of the wind turbines on radar systems is highly variable and depends on parameters of the wind turbines and radar systems. The main negative parameters of wind turbines are large Radar Cross Sections and Doppler shift spread of reflected signals. For the determination of general mitigation techniques, it is important to make a deep analysis of the different types of scenarios using a developed simulator of reflected signals from a wind turbine. This paper describes developed simulator and wind turbine parameter analysis.**

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

I. INTRODUCTION

In the last three decades, the sources of renewable energy have started to play a key role in our lives due to increasing prices of the traditional sources of energy (such as oil, black/brown coal etc.) and because of protection of the environment from global warming. One of the most important sources of renewable energy is wind. The increased spreading of wind turbine usage started in the 1980`s [1], [2], [3]. At present, the power of installed wind turbine, achieves almost 500.000 MW worldwide [4]. In some countries, the amount of wind turbine energy exceeds more than 14% of total generated energy.

The increasing number of installed power turbines presents serious problems for detection capabilities of the primary radar systems (PRS) due to rotation of the turbine blades that causes reflection of a transmitted radar signal (clutter). The negative influence of the wind turbine or wind turbine farm on the radar systems is described in [5 - 11]. The bulk of the influence on the primary radar systems is highly variable and depends on the wind turbine parameters. The parameters are:

(1) The size of the wind turbine
(2) The number of the wind turbine (farm)
(3) The number of blades (typically 3-5 blades)
(4) The rotation of the wind turbine in the wind direction
(5) Variable Radar Cross Section (RCS)
(6) Doppler frequency shift due to rotation of the blades
(7) The several types of the wind turbine (Horizontal Axis Wind Turbine - HAWT, Vertical Axis Wind Turbine VAWT - Savonius/Darrieus [12], [13], [14].
(8) The variability of the active time of the wind turbine

Most of the installed wind turbines are a HAWT type and all the following analysis will be done only for this type. The typical parameters of HAWT wind turbine are (a) Number of blades 3-5 (typically 3), (b) height (30-140 m), (c) Rotor diameter (70-150 m). The examples of wind turbine parameters from different companies are shown in Table 1.

TABLE I. TYPICAL WIND TURBINE PARAMETERS

Model of Wind Turbine	**Aerodyn aM 5.0**	**Windey WD110-2000**	**Wobben E82/3000**
Rotor diameter [m]	139	110	82
Tower height [m]	100	80-100	78-138
Maximum rotor speed [rd/min]	11,8	13,4	6 (min) - 18 (max)
Power [kW]	5000	2000	3000
Pin speed [m/s]	310	278	93 - 278

Fig.1 shows the prediction of wind turbine dimension up to 2030 with highlighting of the base parameters. The rotor diameter and hub length will be increasing and consequently influence of wind turbine will be greater.

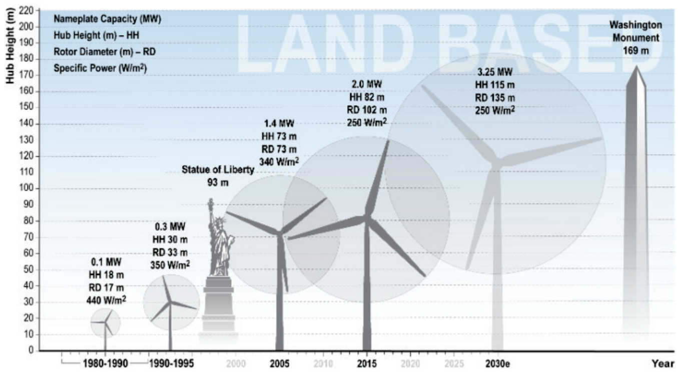

Fig. 1. The prediction of the win power dimension and base parameters [15]

II. Parameters of Primary Radar System

The parameters of Primary Radar Systems (PRS) use for a detection sequence of two pulses (1) short pulse – for detection targets below 12 km that do not have any intermodulation and (2) long pulse – for detection targets above 12 km to a maximum distance with P4 intermodulation described below. The PRS waveform sequence is shown in Fig. 2 and presents the transmitted signal $s_T(t)$.

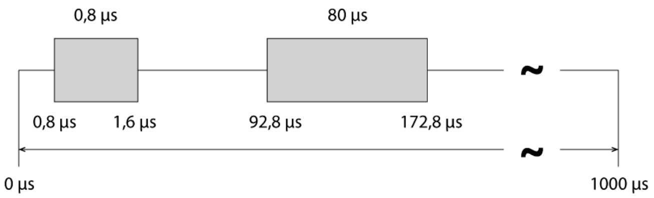

Fig. 2. The PRS waveform sequence

The parameters of based PRS used for analysis are:

- Carrier frequencies: 2,7-2,9 GHz
- Beam width: 1.4 deg
- Antenna gain: 33.7 dBi
- Antenna rotation speed: 15 rpm
- Min. detection of targets for long pulse length: 12 km
- Max. detection of targets for long pulse length: 150 km

The long pulse uses P4 polyphase coded pulse compression with parameters: long pulse length: $\tau = 80\mu s$, pulse repetition period: $T_r = 1ms$, number of phases $N = 100$. The phases of the P4 compression pulse are computed by the formula

$$P4_{\varphi}(id) = \frac{\pi(id-1)^2}{N} - \pi(id-1), \qquad (1)$$

where id is index of phase from interval $\langle 1; N \rangle$,

N is total number of phases in one pulse.

The phase function of P4 is shown in Fig.3.

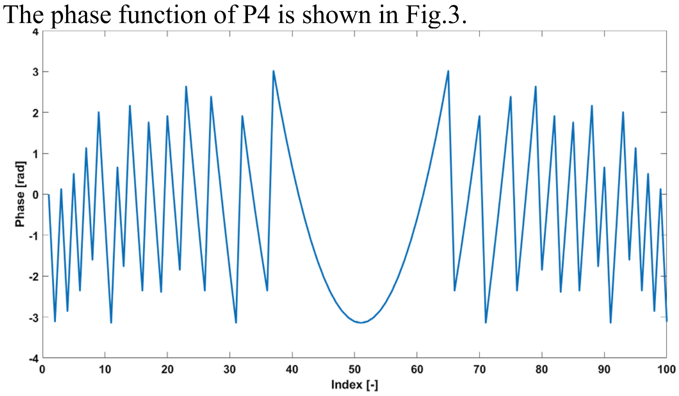

Fig. 3. The function of P4 phase

The autocorrelation function of P4 is shown in Fig.4. The properties of P4 pulse compression are described in [16], [17].

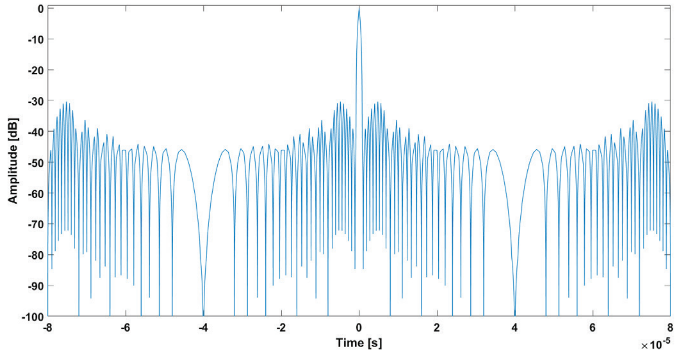

Fig. 4. The function of P4 phase

III. Model of Reflected Signal from Wind Turbine

The model of wind turbine can be divided into the static part of wind turbine as tower, nacelle, and movable parts that correspond to blades of wind turbine. The base geometry of the model includes one wind turbine and one radar system and it is shown in Fig. 5. The wind turbine speed is considered as constant speed due to the low dynamics of changes in rotation speed of wind turbine. The shape of blades is considered cylindrical.

The individual blades are divided into the elements. The number of elements is variable and depends only on demanding accuracy. The formula for the present angle of an individual blade is defined by the formula

$$\varphi(b, t_r) = 2\pi\left(\frac{(b-1)}{B} + \frac{f_{rot}}{60}t_r\right) + \varphi_{inc}, \qquad (2)$$

where: b is b-th blade $1, 2, \ldots B$,

B is total number of blades in wind turbine,

f_{rot} is rotation frequency of the wind turbine $[rpm]$,

t_r is repetition period of radar,

φ_{inc} is initialization angle of blades.

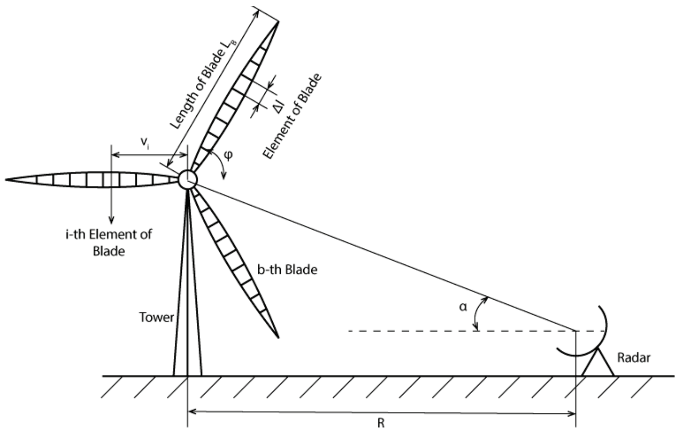

Fig. 5. The geometry of the wind turbine and radar

The distance between radar and individual blades elements (for all blades) is calculated by the formula

$$D(i,b,t_r) = R - v_i \cos(\alpha)\cos(\varphi(b,t_r)), \tag{3}$$

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

R is distance between radar and center of the wind turbine,

v_i is distance between center of rotor to individual blade,

α is elevation angle of radar corresponding to the wind turbine center of rotor, while b and t_r as in (2).

By the equations (2) and (3), it is possible to compute the time delay and Doppler speed of the individual element of any blade.

The time delay of reflected signal from individual elements of wind turbine is given by the formula

$$\tau(i,b,t_r) = \frac{2D(i,b,t_r)}{c}, \tag{4}$$

where: c is the speed of light and $D(i,b,t_r)$ is the distance between radar and individual element.

The Doppler speed of individual elements for all blades is computed by the formula

$$V_{dop}(i,b,t_r) = V_{PIN}(i)\cos\left(\frac{\pi}{2} - \alpha - \varphi(b,t_r)\right)\cos(\beta), \tag{5}$$

where: $V_{PIN}(i)$ is rotation speed for every i-th element of b-th blade (Rotation speed is constant for all blades. The rotation speed is zero in the center of wind turbine and maximal at the end of the blade),

β is azimuth of the radar in relation to the center of the wind turbine.

The Doppler shift is computed by the equation

$$f_{dop}(i,b,t_r) = \frac{-V_{dop}(i,b,t_r)}{V_{dop}(i,b,t_r) + c} f_c, \tag{6}$$

where: V_{dop} is Doppler speed computed in (5),

f_c is carrier frequency.

The Radar Cross Section is computed by the definition formula

$$RCS(\alpha,\beta) = \cos(\alpha)\left|\sin(\beta)\right|. \tag{7}$$

The reflected signal from the wind turbine received by radar is defined by the formula

$$\begin{aligned} s_R(i,b,t_r) &= A s_T(t - \tau(i)) + \\ &+ \sum_{b=1}^{B}\sum_{i=0}^{L} A s_T(t + \tau(i,b,t_r)) e^{-2\pi f_{dop}(i,b,t_r) t}, \end{aligned} \tag{8}$$

where: L is total number of elements in blade,

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

$s_T(t)$ is transmitted signal from PRS.

The rest of variables is explained in previous formulas.

IV. Simulator of Reflected Signal for Wind Turbine

The model of reflected signal from the wind turbine is developed in the Matlab environment [18]. The model includes one wind turbine and one PRS, without considering the rotation of the PRS antenna. The model outputs are received signal from the wind turbine and correlation of the transmitted and received signal.

The input parameters of the model are:

- $[x_w, y_w, z_w]$ Cartesian coordinates of wind turbine
- Number of blades
- The rotation speed of blades $[rpm]$
- The length of blades $[m]$
- The length of blade element $[m]$
- Initialization rotation of blades $[°]$
- $[x_R, y_R, z_R]$ Cartesian coordinates of radar
- Carrier frequency f_c of PRS
- Distance of radar to the wind turbine R $[m]$

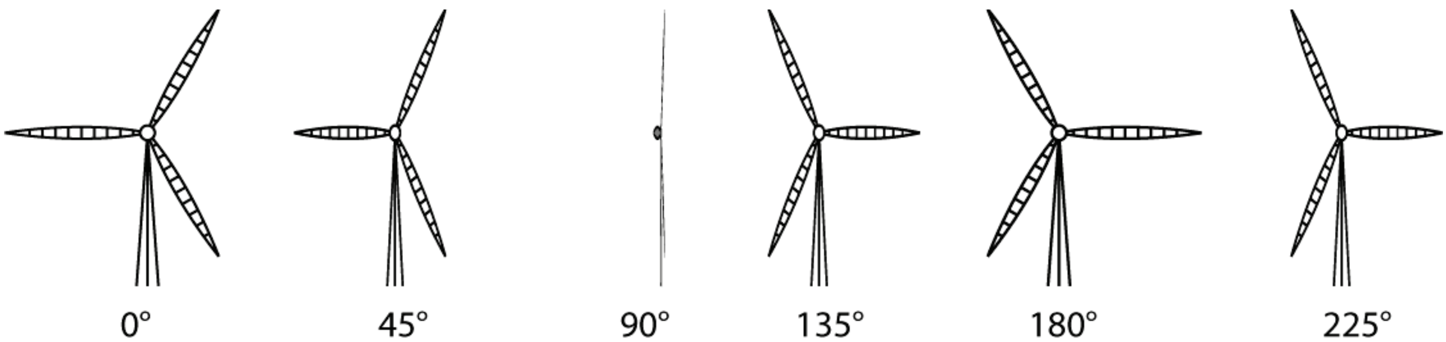

Fig. 6. The visibility of the wind turbine depending on the azimuth β

- Transmitted signal $s_T(t)$ - defined in Chapter II
- SNR $[dB]$ and A attenuation coefficient.

The Doppler shift and RCS of the received signal is very variable as will be shown. The size of the Doppler shift mainly depends on blade length, the rotation speed of wind turbine and azimuth (Fig.6) of wind turbine and PRS. The maximal Doppler speed occurs for azimuth angle 90° and 270°. The minimal Doppler speed occurs for 0° and 180°. The values of the RCS vary in reversal to Doppler shift (minimal RCS for 90° and 270°, maximal for 0°and 180°).

The next analysis will show wind turbine with selected parameters: blade length 50, number of blades 3, the rotation speed of blades 12,5 $[rpm]$, position of the radar is in $[0,0,0]$ and wind turbine position is defined by distance 20 km, $\alpha = 0°$, β=90° .

The blade position depends on time for $B = 3$ shown in Fig.7. The blade position is a function of rotation speed, number of blades and initialized blade angle.

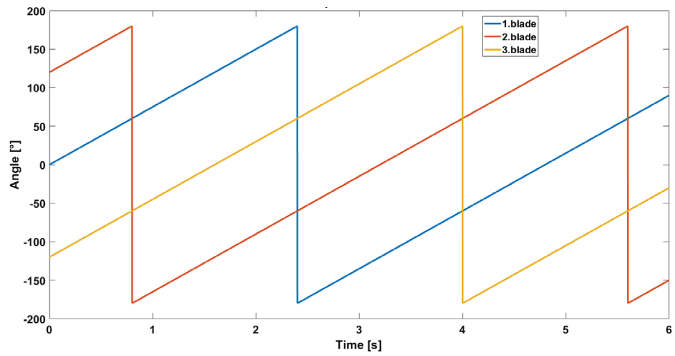

Fig. 7. The dependency of blades position on time for 3 blades

The Fig.8 shows “worst” situation of Doppler shift for azimuth $\beta = 90°$ for 3 blades.

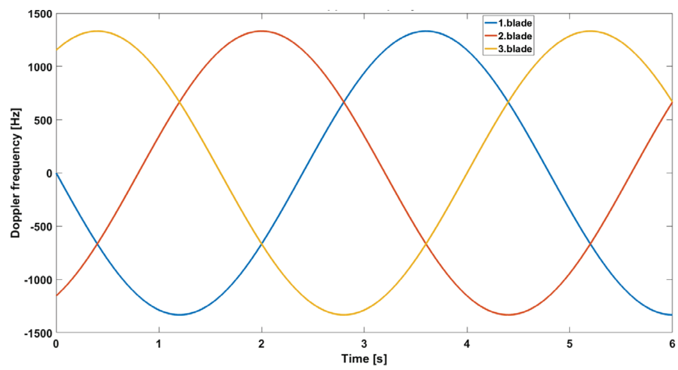

Fig. 8. The dependency of Doppler frequency on time for 3 blades

The Doppler shift is highly dependent on azimuth and blade position (rotation blade speed) and length of blades. The dependency of Doppler shift on length of blades is shown for one blade in Fig.9 and for three blades is shown in Fig.10 (for azimuth $\beta = 90°$).

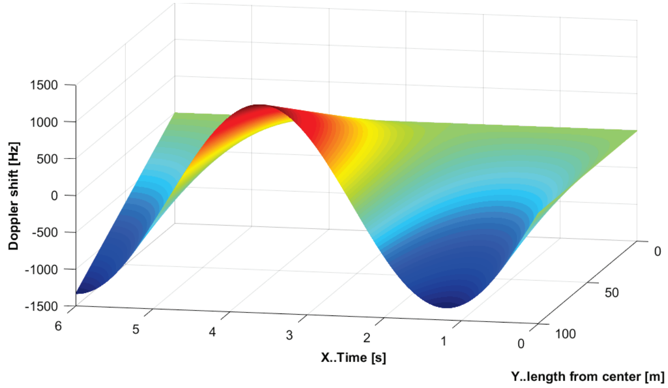

Fig. 9. The Doppler shift dependency in time and length blade for 1 blade

The Y axis presents distance from the center of rotor to the end of blade. In the rotor center, Doppler shift is close to zero. The Doppler shift is linearly increasing with distance from the rotor. The maximal Doppler shift occurs at the end of the blade.

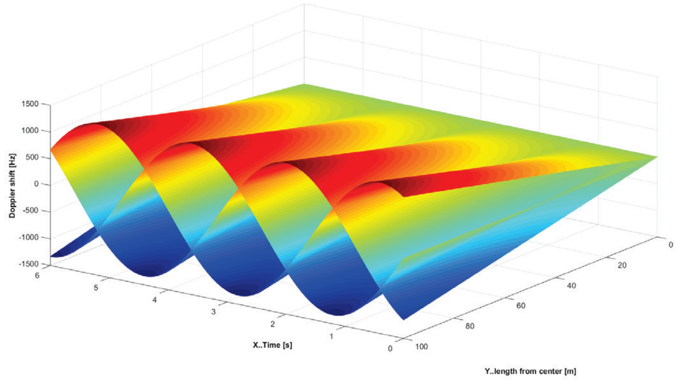

Fig. 10. The Doppler shift dependency in time and length blade for 3 blades

The dependency of Doppler shift on azimuth is shown in Fig.11. The function is symmetric, and maximal and minimal values of the function are always in the $k\pi$, $k \in \mathbb{Z}$ azimuth position. In time, maxima and minima position depends on the initialized angle of the blades.

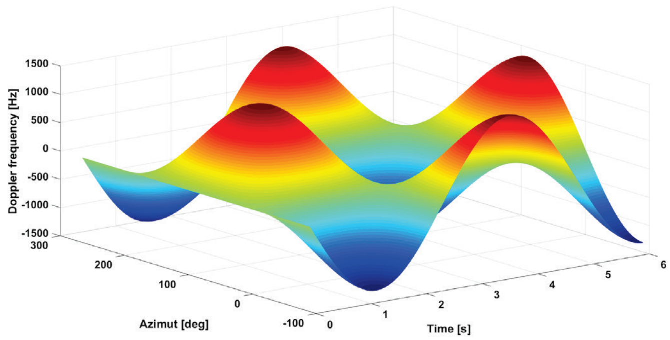

Fig. 11. The Doppler shift dependency in time and azimuth

V. Conclusion

The paper deals with description, analysis and modelling of a simulator of reflected signals from wind turbine in primary radar systems. The development of a simulator is important from the point of view of mitigation techniques of wind turbine influence. This first part of paper describes typical parameters of the wind turbine and their negative influence on the visibility and detectability of targets in the PRS. The next part describes a model of the reflected signals from one wind turbine, that includes many variable parameters (azimuth, position, elevation, number of blades, and parameters of PRS, SNR, attenuation). The model can simulate different scenarios suitable for development of new mitigation techniques, and comparison with real measurements of wind turbine clutter. The paper includes analysis of the negative wind turbine parameters, especially Doppler shift that is caused by blade rotation speed. The Doppler shift depends not only on blade rotation speed but also on azimuth, elevation, length of blades, etc. as is shown in paper.

The future work will be focused on extension of the wind turbine simulator to wind farms, multipath reflection of transmitted signals between them and subsequent analysis for the developing of the mitigation techniques.

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