ESTIMATION OF RADAR CROSS SECTION OF A SAVONIUS WIND TURBINE

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ABSTRACT
The aim of this paper is to estimate the interaction between a Savonius wind turbine and a radar by means of simulation using Comsol Multiphysics 4.3a. Radar interference depending on each major part of a horizontal axis wind turbine is overviewed and studied. These results are then qualitatively compared with radar interference caused by the S-shaped Savonius wind turbine. It is shown that the S-shaped Savonius wind turbine causes noticeable interference on radar performance, compared to horizontal axis wind turbine.

KEY WORDS
wind turbine, radar, Doppler shift, radar cross section

1. Introduction
There is currently a strong focus on renewable energy production and wind energy is one of the most promising sources. As wind energy technology continues to develop, the physical size of the turbines is increased, causing interference with radar performance. Wind turbines have a considerable potential to reduce radar visibility of targets within the vicinity of a wind farm, such as marine and defense radar as well as air traffic.

There have been several studies about the interaction between horizontal axis wind turbines (HAWT) and different types of radar, based on both experimental data [3] and simulations [4, 5, 6, 12]. It has been shown that the level of interaction between a wind turbine and radar depends on the shape and dimensions of the wind turbine as well as the radar’s signal characteristics. The turbine’s moving parts and their velocity must also be considered as contributors to the total radar interference. To the best authors’ knowledge, there are no similar studies related to the Savonius wind turbine.

In this paper, the interaction between a monostatic radar and a S-shaped Savonius wind turbine is simulated using Comsol Multiphysics 4.3a. The interference between the different parameters of the S-shaped Savonius turbine and radar was then qualitatively analyzed.

2. Wind Turbines Interaction with Radar

2.1 Radar Cross Section
The radar’s operational principle is based on the analysis of the emitted and received waves. Two factors are considered when estimating the target’s influence on the radar system performance: radar cross section (RCS) and Doppler shift effect.

RCS is defined as a limit of a ratio of the dissipated by the target power in a given direction to the incident electric field, when the distance from the scatterer to the measurement point of the scattered power approaches infinity [2]. It is the measurement of a target’s ability to reflect radar signals back to the receiver. RCS is referred to as monostatic or bistatic, depending on the relative position of the transmitter and receiver. In the case of monostatic RCS, the same radar both transmits and receives the signal. Bistatic radar uses one radar to transmit the signal and another, to receive the signal, as shown in Figure 1. Monostatic RCS is considered in this research, since the majority of the currently operational systems are monostatic.

![Figure 1. Monostatic (a) and bistatic (b) radars](image)

2.1.1 HAWT interaction with radars

Radar interaction with the HAWT is more frequently investigated in literature since this type of wind turbine is much more widely used than Savonius wind turbines.

The nominal capacity and physical dimensions of HAWTs are continuously increasing. With the development of HAWT technology, future turbines up to 20 MW are expected to have a rotor diameter up to 250 m and a hub height of more than 150 m [9]. With some rotor
diameters (from 40 m to 126 m) and rotational frequencies (from 12 rpm to 34 rpm), blade tip velocities can exceed 150 Knots, which is comparable with a slow aircraft [5].

A typical HAWT for radar interference studies is the Vestas V82 turbine with 40 m blades and an 80 m hub height. Because of the moving parts of the wind turbine, time should be considered when performing scattering and diffraction investigations. The level of the turbine interference depends on several parameters, such as hub height, rotor diameter and rotational frequency. Because of its distinct parts, a HAWT is divided into the following components: tower, blades and nacelle. In the subsequent sections, each component is briefly analyzed.

2.1.2 Tower RCS

The turbine tower is usually manufactured from either concrete or, more often, from rolled steel. The large physical size of the turbine tower is the reason that it contributes to about 75% of the total turbine RCS [6].

If we consider turbine tower as consistent of a number of cylinders, the complex target scattering method can be applied to each of these sections. The integrated result through the tower height is the tower RCS. As can be seen from the equation, the RCS of the tower is proportional to its height and radius:

\[ \sigma_{\text{cylinder}} = \frac{2\pi r^2}{\lambda}, \]  

where \( \sigma_{\text{cylinder}} \) is cylinder RCS, measured in \( m^2 \), \( r \) - cylinder radius and \( l \) is cylinder height, \( \lambda \)-wave length [2].

Increased size of the turbine and, hence, tower increases the total turbine RCS.

2.1.3 Blades RCS

The turbine blades are found to be the next contributor to the total turbine RCS. Two turbine positions are investigated by Pinto et al.: when the blades are rotating in parallel or perpendicularly to the plane of the radar signal. Three blades are estimated to constitute about 15% of the total turbine RCS [6]. It is found by Pinto at al. that the turbine RCS is nearly independent of the blade rotation angle when blades rotate towards and away from the signal direction of propagation. As the blades rotate, the main shape of the turbine does not drastically change.

In the case where the radar signal direction of propagation is in parallel with the long axis of the turbine hub, RCS changes considerably depending upon the blade position. The RCS fluctuates from the average by approximately 2%. [6]

2.1.4 Nacelle RCS

The nacelle contains mechanical and electrical equipment for power generation and is able to rotate 360º, allowing the turbine to directly face the wind and perform with maximum efficiency. The physical size of the nacelle and relative orientation to the radar signal are the primary parameters that contribute to the turbine RCS. This contribution is estimated to be near 10% of the total turbine RCS [6]. The nacelle rotates relatively slowly which is why the radar considers the nacelle as a virtually stationary object [10].

2.2 The Doppler Effect

The Doppler effect is a change in the phase between consecutive pulses, reflected by a moving target.

A Doppler radar uses the Doppler effect to detect moving targets and to obtain data on its velocity. The basic principle of Doppler radar is the comparison of two successively received signals. The transmitted and received signals from a stationary object are nearly identical, while successive signals from a moving target have a change in the phase. Therefore, the difference between the signal phases, which is the Doppler frequency, is nonzero.

Moving parts of the wind turbine can cause a visible Doppler effect to the radar. For this reason, the blades should be considered during analysis.

2.2.1 Doppler frequency by the blades and nacelle

The biggest contribution to the total Doppler frequency of the turbine is made by the turbine blades. Each part of the blade has its own rotational velocity depending upon the distance from the center of the hub. Therefore, the rotating blades produce a continuous spectrum of the Doppler frequency in the range of the Doppler limits that air surveillance radars are able to detect. As it is investigated by Lok at al. [4], the Doppler frequency dependence from the blades rotation is characterized by the nearly constant value near the zero and the frequency peaks, which correspond to the specific blade position. Blades rotated towards and away from the signal direction of propagation in this study.

The strongest Doppler frequency is created when one of the blades is orthogonal to the radar signal. The nacelle and the section of the blade nearest to the hub contribute to the Doppler frequency values, which are near zero.

2.3 Savonius Turbine Interaction with Radar

The Savonius is a drag and lift type wind turbine. Dimensions of these turbines can vary in height, from 0.5 m to 4 m, and in rotor diameter, from 0.3 m to 1 m.
The Savonius turbine has a number of advantages compared to HAWT, such as low cut-in speed and low noise level. One promising implementation of the Savonius turbine is energy generation in an urban area. A common location would be the roof of a building.

Currently there are a number of modifications of the Savonius wind turbine. The gap between the turbine blades, blades overlap ratio as well as blade shape could be changed. Among these parameters the Savonius turbine blade shape has more significant influence on the radar with the wind turbine interaction. Since it changes the reflecting surface more significantly compared to other parameters.

This paper considers an S-shaped Savonius turbine with a rotor height of 4 m and an outside rotor diameter of 1 m. The S-shaped Savonius turbine without base or tower is studied. If it is mounted onto a tower, the tower should also be considered when determining the turbine RCS.

The Doppler frequency of the Savonius turbine is not expected to be considerable when compared to the HAWT. Since the tip speed ratio of the Savonius turbine is much lower than that of the HAWT (1-2 and 5-10 respectively). If we consider the operational tip speed ratios, the Savonius turbine blade rotation corresponds to the rotation of those sections of the HAWT blades, which are closest to the hub. Hence, the Doppler frequency of the reflected signal from the Savonius turbine will be near zero. The Doppler frequency is expected to be of second order importance in comparison to the RCS value.

2.4 The S-shaped Savonius Turbine Model Simulation

The 3D model of the S-shaped Savonius wind turbine is simulated using the Comsol Multiphysics 4.3a. The interaction between the S-shaped Savonius turbine model and the monostatic radar is calculated next.

The top view of the 3D model of the S-shaped Savonius turbine, studied in this paper, is presented on Figure 5. The height of the rotor is 4 m. The material chosen for the turbine model is aluminum.

![Figure 1. The top view of the studied model. The dimensions are in meters](image)

Perfect electric conductor (PEC) boundary condition was applied to the turbine surface in modeling. PEC acts as a perfect reflector and so does not allow any transmission through the material. The model is surrounded by a centered sphere and sphere layer. The close sphere with the radius of 3 m around the turbine is a far-field domain. The electric field is calculated in this domain. A perfectly matched layer (PML) covers the far-field domain around the model to minimize unphysical reflections of scattered waves when they leave the Far-Field domain. The thickness of the PML is 1 m.

The majority of aviation and marine radars are considered to operate over two frequency values: 3 and 10 GHz. As the frequency increases, the RCS of the turbine tends to increase. The high signal frequency is computationally demanding for simulation. The signal frequency of 100 MHz is chosen in order to satisfy the condition of the maximum mesh element size. At least five mesh elements per wavelength should be built. Mesh consists of 41,000 elements.

An assumption for this research is that a target is located at a long distance from the radar, allowing the radar wave to be considered as planar. In practice, this assumption can be regarded as an acceptable approximation [6]. In the plane, the signal, which is coming from the positive X ordinate direction and propagating in the negative X ordinate direction, corresponds to the 0º angle of incidence. The RCS was obtained for the angle of incidence ranged from 0º to 360º with the step of 1º.

The interaction between the turbine and radar is calculated by means of the relative electric field. This field describes changes in the resulting field, caused by the turbine presence. The RCS is measured at the angle of incidence of the coming wave:

\[
\lim_{r \to \infty} \frac{E_{rel}^2}{E_{b}^2} = \sigma (m^2)
\]

\[
\sigma \text{(dBsm)} = 10 \log_{10} (\sigma (m^2)),
\]

where \( E_{rel} \) is the relative field, \( E_{b} \) is the background field [13]. The abbreviation dBsm means dB per square meter.

2.4.1 Simulation Results

As a result of the performed simulation the RCS of the S-shaped Savonius wind turbine model is obtained.

The RCS varies between 9.3 dBsm up to 15.5 dBsm. The geometry of the turbine results in the symmetrical RCS graph, as it is shown in Figure 2. The RCS peaks around 20º and 200º angles appear because the bigger surface of the blades is perpendicular to the signal. Hence, a bigger share of the waves is reflected back to the radar. Meanwhile, for 90º and 270º angles of incidence the reflecting surface of the turbine blades is minimal.
3. Results

In this study, the interaction between HAWT, as well as an S-shaped Savonius turbine, with radar is investigated and overviewed. The influencing factors and their importance are considered below.

Static parts of the turbine:

- **HAWT.** The turbine tower is the biggest contributor to the total turbine RCS, at an estimated value of 75%.
- **Savonius turbine.** In comparison to HAWT, the dimensions and shape of the Savonius turbine base is not dependent upon the Savonius turbine itself. However, the chosen base can have a strong influence on radar interference.

Moving parts of the turbine:

- **HAWT.** Blades are the second contributor to the total RCS (up to 15%) and first to the Doppler frequency. The turbine nacelle has the least impact on the total RCS compared to the tower and blades.
- **Savonius turbine.** The Doppler frequency is expected to be less significant than RCS on the total radar interference.

Blade rotation frequency:

- **HAWT.** The high tip speed ratio causes significant Doppler frequency.
- **Savonius turbine.** Due to low tip speed ratio, the rotor causes lower Doppler frequency.

The turbine shape variation due to the blades rotation:

- **HAWT.** The RCS fluctuates from the average when the direction of propagation of the radar signal is in parallel with the nacelle long axis. The Doppler frequency obtains maximum value when the blades rotate towards and away from the signal direction propagation and one of the blades is perpendicular the this direction.
- **Savonius turbine.** Because of the geometry of the turbine, the radar interference varies depending on the signal angle of incidence. The RCS obtains a maximum value when the direction of propagation of the radar signal is perpendicular to the flat plane of the turbine (ZY plane on Figure 2) and a minimum value when it is in parallel with this plane.

The higher is the frequency of the signal, the greater is the RCS value of the turbine.

4. Conclusion

In this paper the interaction between a Savonius wind turbine and radar is simulated using Comsol Myltiphysics 4.3a. The RCS of the Savonius wind turbine is calculated. It is shown that the Savonius wind turbine can cause considerable influence on the radar ability to detect targets in the vicinity of the wind turbine. The RCS is expected to be of first order importance in comparison with the Doppler frequency, when the radar interference by the Savonius turbine is estimated. Hence, these interactions should be carefully considered when a Savonius turbine is planned at the beginning stage of the turbine project.

For the future work, the accurate prediction of the Doppler frequency, caused by the Savonius wind turbine will be done. In addition, the influence of the Savonius turbine configuration and different types of towers on the radar interference will be investigated.

References


