Scatter and Doppler Effect of Wind Power Plants to Land Radars

Derya Sozen  
Institute of Informatics  
Istanbul Technical University  
Istanbul, Turkey  
deryasozen@gmail.com

Mesut Kartal  
Department of Electronics and Communication  
Istanbul Technical University  
Istanbul, Turkey  
mkartal@ehb.itu.edu.tr

Abstract—Wind power plant installations at different scales are in an increasing pattern starting from year 2000. A curiosity has been raised about 4-5 years ago for if wind turbines interfere with radars. The interference occurs when wind turbines reflect radar waves and cause missing targets and blind regions on radar images. Doppler radars are most used to discriminate between the return from a desired target and that from undesired objects, usually ground clutter [1]. There are so many resulting effects of interference such as shadowing, damage to radar equipment, larger radar cross section (RCS) and missing desired targets, etc. Both radar and wind power plant mitigations are available. But still, there is no overall solution, only case by case treatment. RADAR is an acronym for RAdio Detection And Ranging, it will be used as “radar” throughout this paper.

Keywords—clutter; Doppler; radar; scatter; turbine; wind

I. INTRODUCTION

The most effected types of radars are defence, weather and air traffic control radars. There are methods for modelling the impact of wind turbines on radar returns. It is important to simulate the magnitude and Doppler shift that would occur in order to take corrective actions. Not only the growth of the number of wind power plants, but also the increasing size of wind power plants and the use of taller turbines, which can impact radars from a greater distance, are the factors increasing the interference.

Since the blades are moving, the echoes will have a velocity and can be mistaken for real weather. Since weather is always in motion and most clutter targets such as buildings are stationary, the basic clutter removal schemes filter targets that essentially have no or very little motion.

Radar clutter is defined as unwanted echoes, typically from the ground. The designer of a Doppler radar is generally interested in discriminating against these unwanted returns; hence, the properties of those unwanted echoes must be understood to provide an effective radar design.

Visibility of a target increases on radar display when its RCS increases. RCS changes according to the shape of the target and its movement with respect to the target.

The performance of radar describes how far it can see (range), how accurately it can measure the position of an object (accuracy), how well it can solve objects near each other (resolution) and how well it can see objects against a background (clutter improvement).

Radar issues have stalled so many projects all around the world for a while until the impact was realized and understanding of the impact with solutions emerged.

II. PULSED DOPPLER RADARS

A Doppler radar is defined by the IEEE standard radar definitions as one that uses the Doppler Effect to determine the radial component of radar target velocity or to select targets having particular radial velocities. When a Doppler radar uses pulse transmissions it is called pulsed Doppler (PD) radar.

A general objective in Doppler radar processor design is to maintain a linear response over the full dynamic range of the clutter and design the processor with an improvement factor sufficient to reduce the clutter residue to the receiver noise level. The residues of large clutter echoes exist because their amplitude is greater than the improvement factor.

\[
I_f = \left( \frac{C_{\text{out}}}{C_{\text{in}}} \right) \frac{G_{\text{av}}}{G_{\text{out}}} \frac{G_{\text{in}}}{C_{\text{in}}}
\]

where:

- \(C_{\text{in}}\) is the strength of clutter at clutter input,
- \(C_{\text{out}}\) is the strength of the clutter at clutter output,
- \(G_{\text{av}}\) is the average filter gain for moving targets.

![Figure 1. Improvement factor flow diagram](image1)

1 S/N is the Signal to Noise Ratio (SNR), e.g. -30 dB means the signal strength is 1/1000 of the strength of the noise
Radar can be calibrated to neglect stationary objects within its line of sight (LOS). Signal processing is for identifying moving targets and plot processing is for stationary ones.

What computers do is analysing the strength of the returned pulse, time it took to travel to the object and back, and Doppler shift of the pulse.

Velocity and reflectivity are two main types of radar reading data. The strength of the energy, which is returned to the radar after it bounces off targets, forms the reflectivity data. The Doppler shift of the returned energy forms the velocity data [2]. The change in frequency is called the Doppler frequency and it is approximately [3]:

\[
f_d \approx \frac{(2f_v v)}{c}
\]  

(2)

where:
- \(f_d\) is the frequency difference between the transmitted and returned signals,
- \(f_t\) is the frequency of the transmitted signal,
- \(v\) is the velocity of the target toward the transmitter,
- \(c\) is the speed of light (~300000 km/s).

\[
f_d = \frac{(2 \times 10000 \times \frac{1}{60})}{300000} \approx 0.001 \text{ MHz}
\]

Thus, the frequency of the returned signal is 0.001 MHz different from the transmitted frequency. If the target was approaching the transmitter; the Doppler would be added, in otherwise it would be subtracted.

III. WIND POWER PLANTS

A wind power plant is an area including more than one wind turbine to generate electric [5]. Wind power plants have both point clutter and a Doppler component. Most of the energy is scattered from the stationary parts of the turbine and its supporting structure. RCS of corner reflectors, flat plates, single curved surfaces, doubly curved surfaces, straight edges and curved edges can all be calculated separately [6]. The overall result would be the amount of point clutter.

The returned microwaves change their wavelength when they hit a moving object away or toward the radar. Red colour points a target moving away from the radar and green colour points a target moving toward the radar in distinguishing velocity data, see Fig. 4.

Turbine blades turning toward to radar creates positive Doppler shift. Turbine blades turning away from the radar creates negative Doppler shift.

Figure 2. Simple illustration of what happens inside radar equipment.

Figure 3. Doppler velocity interpretation.

Figure 4. The rotation of the blades resulting in a Doppler shift that varies sinusoidal with time [4].
Another property of wind turbines is their reflectivity; what they are made of. Most of the turbine blades are made of glass reinforced plastic that is 30% reflective to microwaves.

Other factors such as the pitch and yaw angles of the turbine and the individual pitch of the blades may also affect the RCS.

RCS of a wind turbine can be calculated with the below equation:

$$\sigma = \lim_{r \to \infty} \left[ 4\pi r^2 \frac{|E_i|^2}{|E_s|^2} \right]$$  \hspace{1cm} (3)

where:

$E_s$ is the power density that is stopped by the target,

$E_i$ is the power density in the range $r$,

$r$ is radius of the sphere, where RCS propagate in a spherical form.

IV. SIMULATION

Wind turbine model used in this paper is a horizontal axis type and has standard three blades. The radar type mentioned throughout this paper is monostatic (which means both the receiver and the transmitter are at the same place, not at different locations) and on a stationary platform. AGI STK9 is used to design the main simulation. Separate calculations on radar systems are driven with MATLAB.

Using Pythagorean Theorem:

$$D_l = \sqrt{(R + h_i)^2 - R^2} \approx \sqrt{2Rh_i} \hspace{1cm} (4)$$

where:

$D_l$ is the distance between the objects tangent to the local horizon of a smooth round Earth,

$R$ is the radius of the Earth,

$h_i$ is the height of the object above mean sea level.

Let us assume $h_1$ is 15 m and $h_2$ is 91 m, multiply $R$ it with $4/3$ because of the refractivity of the atmosphere, we get;

$$D_l \approx 55.28 \text{ km}$$

which means that there will be negligible effect of a wind turbine on a radar if they are approximately 55.28 km apart from each other.

Each turbine rotates at a steady rate in the simulation, but the rates of each of them are different and blade rotation is started from a random angular position. It would be unrealistic if all the turbines start to rotate from the same position with same blade speeds.

V. RESULTING EFFECTS

1. RCS with 90° yaw angle to the radar creates the bigger interference. For radar operating at 3 GHz the RCS is steady around 58 dB, whereas, RCS changes from 52 dB to 57 dB with 0° yaw angle to the radar, see Fig. 7. Clutter occurring when yaw angle is 0° can be filtered with classical methods such as Moving Target Indication. The situation of 90° yaw angle over limits these classical methods and needs to be dealt with improved methods such as Doppler analysis.

2. The distance between the wind power plant and the radar has the biggest impact [7].
3. Turbines may also reflect signals on each other and if they are so close to each other this effect will increase. In such case, radar may not be able to correctly detect turbines’ coordinates.

4. When it is a wind turbine case, the partial shadow area increases, and the total shadow area is a blind region for radar.

![Blind regions occurring behind the clutter source](image)

5. Classic radar equation [8]:

$$R = \frac{4 P_g g^2 \sigma}{P_g (4\pi)^3}$$

(5)

where:
- \( R \) is range (m),
- \( P_g \) is the transmitted power (W),
- \( G \) is the antenna gain,
- \( \sigma \) is the RCS of clutter (m²),
- \( \lambda \) is the wavelength (m),
- \( P_r \) is the received power at the radar antenna (W).

As the RCS of a clutter increase the range decreases so false range readings occur at the radar display.

6. For a target at point \( p \) which is located in the shadow region of the turbine, the decibel reduction in the power of the radar return is

$$\text{Power reduction of radar return} = 40 \log \left( 1 - \frac{D_{tp}^2 S^2}{D_{tp} D_{tp} \lambda^2} \right)$$

(6)

Where
- \( D_{tp} \) is the distance from the transmitter to a point \( p \)
- \( D_{tpw} \) is the distance from the transmitter to the wind turbine
- \( S \) is the typical width of the wind turbine

Let us assume that the radar operating at 2.8 GHz is 5 km away from a wind turbine with a width of 3 m and there is a target located 15 km away from the wind turbine inside its shadow region.

$$\lambda = \frac{c}{f_{radar}} = \frac{3 \times 10^8 \text{ m/s}}{2.8 \times 10^9 \text{ 1/s}} = 1.07 \times 10^{-1} \text{ m}$$

$$D_{tpw} = 5 \times 10^4 \text{ m}$$
$$D_{wp} = 1.5 \times 10^4 \text{ m}$$
$$D_{tp} = D_{tpw} + D_{wp} = 2 \times 10^4 \text{ m}$$

7. Wind turbine heights can reach hundreds of meters. This results in large RCS and potential for detection at long ranges.

8. With rotor diameters between 40 and 120 meters spinning at 10 to 35 rounds per minute, blade tip velocities can look like a desired target such as an aircraft or weather

9. Radars’ receiver protectors prevents damage from strong reflected signals, however standard upper limit is 53dB. Wind power plants constructed very near the radar (within a radius of 3 km) have the potential to return signals that exceed the limit of receiver protector and render the radar inoperable.

10. All the body parts of a turbine and a bunch of turbine together in an area can block the beam of radar sight completely.

VI. MITIGATIONS

There are two main ways of modifications. One of them is from radars’ perspective and the other is from wind power plants’ [9].

A. Radar Mitigations

1. Low frequency long-range radars can be used casting a wider area. But still turbines can have an impact on the transponder data.

2. The cost of a single radar installation is very much less than a single wind turbine construction. On the other hand, the cost of hundreds of wind turbines is very much higher. Under these circumstances, moving an impacted radar site to another place is much more efficient and cost effective [10].

3. When a wind farm has caused an unacceptable loss of coverage, supplementary gap filler radar could be installed.

4. Holographic radar systems can be used. A clutter map can be maintained for the stationary parts of a turbine on radar’s memory. Processing over many scans with radar memory in order to get the behaviour of the moving target and see the changes clearly may help in defining the target.

5. Radars can look at higher elevations to see over wind farms, see Fig.10. But this can result in the loss of low-altitude information crucial in some forecast situations, such as a tornado.
6. It would be hard to differentiate between wind turbines if there is more than one turbine in a radar resolution cell. That is why radar resolution should be higher if turbines are close to each other [11].

7. Antenna with low side lobes or higher altitude radars can be used to reduce the effects of all ground clutter including wind farms. Only the main lobe can be the point of interest. But again, in this situation so many low altitude targets will be lost.

B. Wind Power Plant Mitigations
1. Sudden change in the electrical property of the medium constitutes the target (conductivity, permittivity and permeability). Reduction of RCS by 99% about 20 dB is possible with stealth technology. However there will be a blind region for the radar behind the turbine. This may cause undesired results if there is a desired target in that region.

2. Telemetry transmission can be used to supply real time data of wind turbines into radar system. This data can be determined according to the direction of the wind (because the change in wind direction affects the yaw angle of turbines) or can be supplied from the wind power plant control centre.

3. Wind farms can be constructed far from radar sites as far as possible. This brings two utilities:
   a. The greater the distance between the radar and the turbine, the shadow region will get smaller.
   b. If radar sites and wind power plants are far enough from each other, then because of Earth’s curvature there will be no ground data loss for radar readings and no interference with wind power plants. Because they will be under horizon, not in radar’s LOS.

4. Construction of wind power plants can be restricted with law near defence or weather radar stations for the safety and security of the nation.

5. Multiple navigation radars, along with centrally located high elevation scanning radar, sited within the wind power plant, can provide improved elevation coverage above and around the wind farm itself.

6. Transponders can be used in wind power plant sites to supply signal info to the radars that will express its presence.

7. Turbines could be located in a way that the radar would only see one of them within its LOS. Turbines in a linear pattern can be preferred.

C. Both Way Mitigations

There will be no case like; a wind power plant and a radar site are constructed at the same time in a near-field area. If there is already a wind power plant in the area, then radar mitigations should be applied and if there is already a radar site in the area, then wind power plant mitigations should be applied.

VII. CONCLUSION

The wind power plants interfere with land radars. Short term strategies consist of creating awareness of the problem, collaborating with other National Agencies and supporting experimental signal processing investigations. Development of modelling software that produces estimated radar impacts and signal processing technology that eliminates wind turbine clutter, building additional radars for an alternate view of impacted areas, building taller radar towers to see over wind turbines and moving existing radars to other locations can all be done by radar funding. Besides, moving a wind power plant to another location is unlikely. Wind power plant funding is needed to help developing radar-friendly, stealthy wind turbine blades and towers. However, the cost of making turbine blades almost invisible to a radar is 10% to 20% more than standard cost.

The best solution might be to replace the aging radar stations with modern and flexible equipment that is more able to separate wind turbine clutter from desired objects. This would be a win-win situation. Radical actions should be taken.

The effects from individual turbines could be combined linearly. However, the interactions can be random and chaotic sometimes. Multipath effects are worthy of further investigation. Effects of wind power plants on mobile radars are complex situations, as well. This topic can be further investigated, too.

Software patches, used to filter clutter out, works better with offshore wind power plants, because there are less variables around.

Wind turbine towers can be conic other than cylindrical. But the endurance of the design should be investigated.
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