

Review

The Impacts of Terrestrial Wind Turbine's Operation on Telecommunication Services

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Abstract: This paper presents a compendious review for the evaluation and description of the mathematical modelling of the affected components in wind turbines which cause the scattering of communication signals. The impact of an adjacent wind farm operation on telecommunication signals is that it induces electromagnetic interference (EMI) in radar, television and radio signals, resulting from the complex rotating blade's geometry of the wind turbines. Thus, altering the quality of the reflected signal, especially the capability of the radar detection. In all the modelling studies, the radar cross section (RCS) model of a wind turbine's blade is found to be the most complex, due to its huge computational burden. However, clutter filtering is another interesting technique, which employs the Doppler signal processing to obviate the huge computational task in RCS. In this case, the rotating blades of the wind turbine produce Doppler echoes, which in turn are used to estimate the model of the blade by modelling the echo of the scattering points. Therefore, this review succinctly compiles the basic steps of theoretical analysis and simulations of the impact of wind turbines on communication signals, and the remedies to minimize the impact.

Keywords: electromagnetic interference; radar cross section; radar; wind turbine; blades; communication signals



Citation: Abubakar, U.; Mekhilef, S.; Mokhlis, H.; Seyedmahmoudian, M.; Stojcevski, A.; Rawa, M. The Impacts of Terrestrial Wind Turbine's Operation on Telecommunication Services. *Energies* **2023**, *16*, 371. <https://doi.org/10.3390/en16010371>

Academic Editor: Oscar Barambones

Received: 31 October 2022

Revised: 9 December 2022

Accepted: 22 December 2022

Published: 28 December 2022



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1. Introduction

The exponential growth in the number of wind turbine installations has resulted in a series of environmental problems, with one of them being electromagnetic interference, which is the potential blockade, scattering, and modulation of signals emanating from the communication (television or radio), radar (surveillance), and navigation systems by the rotating turbine's blades [1]. The RCS simulation is crucial for assessing signal reflections caused by the wind turbines [2]. The electromagnetic interference analysis of wind turbine structures and radar cross section modelling are both complex mathematical undertakings. Wind turbines (WT) initiate EMI via three basic processes: reflection/scattering, diffraction, and near field effects [3]. Therefore, the EMI from wind turbine operation can be classified as part of the technical power quality problem from an environmental perspective. Some of the impacts of wind turbines on radar systems include beam blockade, clutter returns due to scattering, and the Doppler effect generated from the blades' rotation [4,5].

Clutter refers to the echoes, which are reflected to the radar, originating from the body contrary to the aimed target. Clutter, in this case, is because of power reflected by wind

turbines. This power is mostly characterized by its RCS, which is in turn reliant on the wind turbines' size, shape, and materials. This could result in the energy missing its target direction entirely [6], and this is considered to be a severe technical glitch in countries such as the UK and the Netherlands, due to their large installed wind farms and heavy aviation traffic.

As outlined earlier, the radar cross section is an important factor for evaluating the impact of a wind turbine on a system's performance. The radar can be monostatic/bistatic. Determining the RCS of a complex object such as wind turbines is quite challenging due to its use of Maxwell's equations and high frequency estimations in differential/integral forms [7]. More accurate techniques to do so include finite difference time domain (FDTD), solution of the differential equations in the time domain [8], and the method of moments (MoM) solution of integral equations in the frequency domain [9]. The finite element method are also applicable in both the frequency and time domains [6,10].

When wind turbines are located near telecommunication installations, service quality might degrade. Owing to their huge dimension and continuous motion, wind turbines can interfere with radio-electric signals, such as those emitted by television broadcasting [11]. Distorted television signals are usually the result of two independent mechanisms: the shadowing effect and time dependent multi-path due to signal scattering by wind turbines. The scattered broadcasting signals are mostly attenuated, time-delayed, and phase shifted copies of the actual signal, which differs based on the blade rotation and orientation of the rotors [12,13]. The reflected signals on the metallic parts of the wind turbine caused static ghosts in transmission of analogue television service. More often than not, the rotating blades resulted in variations in brightness [14,15]. A number of software simulation tools can be used to analyze models and predictions of the impacts of wind turbines on digital television signals, some of which are mentioned in this paper.

Section 1 introduces the subject, while Section 2 details the background of the model components associated and affected by the telecommunication signal interference. The effect of wind turbine rotation on television broadcasting, with the subsequent mathematical models and analysis, are introduced in Section 3, while Section 4 discusses the interaction of wind turbines with radio signals and equations involved in their evaluation, which is the RCS analysis, and the radio-communications devices, such as the Radio Detection and Ranging (RADAR) in the monostatic and bistatic arrangements. In addition, the experiment due to the impact of lightning on wind turbines, which was observed to induce significant electromagnetic interference in the wind turbine as a result of an impulsive transient, was reviewed briefly. The future trend for prospective research in the field of wind turbine models for electromagnetic interference assessment and mitigation techniques will be discussed in Section 5, and Section 6 concludes the review.

2. Techno-Environmental Issues Due to Wind Turbine Installations

There are environmental factors that can be caused by wind turbine operations from a technical perspective. Its impact is specific to the telecommunication industries, broadcasting services, and civil and military aviation industries. In addition to that, the scheme military radar network, most often experiences the effect of cluttering, in a setting with sizable wind farms. This problem causes false information to be read or reflected from the radar, because of the severe distortion of the signal and the consequent EMI. The design of a coplanar antenna with a high-gain, was carried out in [16,17], which indicates to offer resistance to the effect scattered reflected signals. This compactness property shows the potential to mitigate the radar detection capacity issue, and also finds application in military radar design.

The examination of electromagnetic scattering pattern of communication signals, in wind turbine's blades, is the basis for tackling the issue of EMI. Usually simulation software is applied, especially in the case of radar signal interference, due to the limitation of the conventional simulation technique of super positioned model, with respect to scattered points. Authors in [18] put forward an upgraded simulation software, which can use the

Doppler echoes, based on the principle of electrical field scattering. This technique was implemented using the assumption of continuing induction of current on the complex geometrical blade's surface.

2.1. Components Models for Wind Turbines Electromagnetic Interference

The electromagnetic interference of a nearby broadcasting radio receiver could lead to distorted signals in the receiving circuit due to the rotating blades of wind turbines and hub of the turbine. It is therefore essential to understand the mathematical models of the relevant/active components responsible for this interference and consequent malfunctioning of the communication circuit, and potentially misleading information from radars [19].

2.1.1. Hub Model of the Wind Turbine

The negative impacts of wind energy to the environment include noise generation and electromagnetic interference. Wind turbines also initiate electromagnetic interference by scattering electromagnetic waves from navigational and telecommunication systems [20,21]. The strength of television and radio-communication signals facilities, within 2–3 km of the largest wind farm development, can be affected due to the diffracting effect of the rotating turbines. Nowadays, microwave satellite broadcasting employing the line-of-sight technique or digital cable networks eliminate the wind turbines' interference effects [22].

The crucial components of wind turbines affected by electromagnetic field are the control units within the hub and nacelle. The pitch control system is among the most important element, which offers essential control services to the wind turbine rotor. The electromagnetic model of the wind turbine is detailed in Figure 1. The general features of EMI relative to the wind turbines are introduced alongside its measuring techniques and means of protection [23,24].

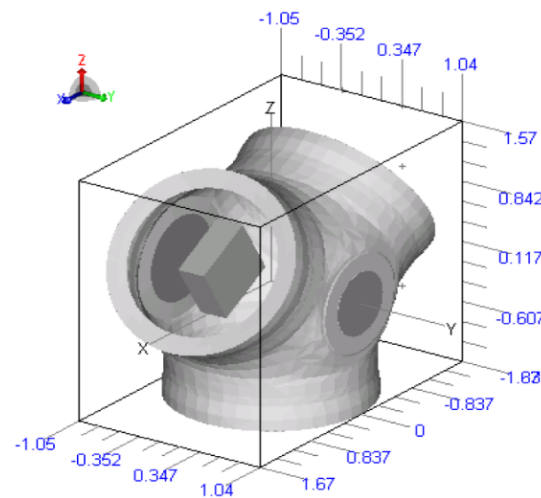


Figure 1. Wind turbine's hub electromagnetic model [23].

For example, the EMI radiating from the turbine are induced by a GSM 900 MHz transmitter, installed on the hub of the wind turbine and examined using the method-of-moments. The communication back-up for the control system of the hub is commonly offered by the transmitter. Applying the commercial method-of-moments (MoM) simulation software FEKO, an overall replicated model of a several megawatt wind turbine can be generated [25–27].

The Hertzian dipole approximation in Equation (1) was applied to energize the hub model with a frequency based on GSM of 900 MHz [28,29], polarization P_0 , and the radiated power P ;

$$\Pi(x) = \frac{e^{-jkr}}{4\pi\epsilon_0 r} \int_V P_0(x') dV' \quad (1)$$

where $P = \Re\{2\pi \int_0^\pi T_r(r, \vartheta)\} r^2 \sin\vartheta d\vartheta$ and the pointing vector T_r [30], $T_r = \frac{1}{2} (E_\varpi H_\varphi^* - E_\varphi H_\varpi^*)$

With the electric and magnetic field components of E_φ , E_ϖ , H_φ and H_ϖ [23].

The process where the wind turbines can negatively affect communication signals were classified in [31], by evaluating the repercussions of these effects in the case of various types of signals (e.g., television, radio, microwave, and navigation). The mathematical models that can be used to forecast the dimensions of possible interference zones within the immediate vicinity of wind power plants were also devised. The work was a preface to initiating the background to examine the effect of wind turbines on electromagnetic interference emitted by telecommunication industries.

2.1.2. Blades Scattering Model

Electromagnetic interference classification and detection caused by the slowly rotating blades of a MOD-2 wind turbine generator (WTG) were examined in [32]. The work was validated by field data measurement, during which at the ground level, the near field scattered components were observed to be a secondary signal and amplitude modulated [33]. A forecasting technique to detect zones of interference to television broadcast reception was presented therein. An electromagnetic interference that bedeviled the Bonneville Power Administration in the (BPA) was found to be caused by the metallic rotating blade of the huge machineries, which can also interfere with nearby VHF television signals. The case where the incident radiation is dispersed in a sloping orientation of the blade was also considered, as depicted in Figure 2.

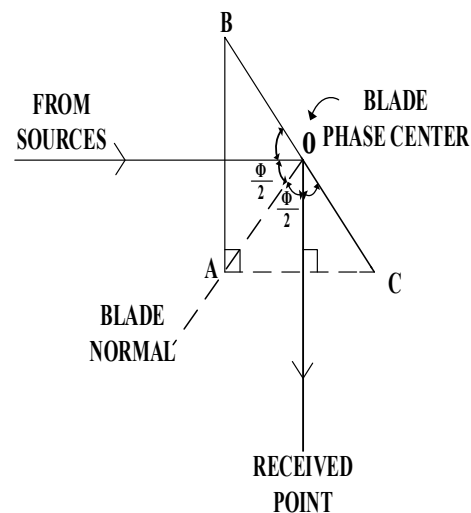


Figure 2. Electromagnetic scattering by wind turbine blade [32].

The application of the double angle formula leads to relation (2);

$$A_e = LW \left[\frac{1 + \cos \Phi}{2} \right]^{1/2} \quad (2)$$

where A_e represents the actual scattering quarter of the blade focused by the receiver at point R. The relation of Equation (2) draws the shape of an area of equal interference level, the MOD-2 machine at its hub height.

The received signal can be considered as modulated by the scattered (wind turbine blade) at a precise modulation index m_0 . The modulation S_m , in dB, is defined in Equation (3);

$$S_m = 20 \log \frac{1 + m_0}{1 - m_0} \quad (3)$$

where m_0 is subject to judgement as it varies with the ambient signal level.

The ITU-R (International Telecommunication Union-Recommendation) recently researched the latest models and computational techniques to determine the signals reflected by the wind turbines and its impact on the quality of digital television reception [26].

2.1.3. Radar Cross Section Modelling Methodology

The modelling technique introduced in [26,34] stipulated that the turbine be sectionalized into smaller portions in order for the radar in the far-field of each portion to appear to be in the near field of the generic structural configuration. The radar cross section of each portion can then be determined on the basis of the expected scenario. Figure 3a depicts the 2 MW turbine model, coordinates the scheme of the model, and its partitioning.

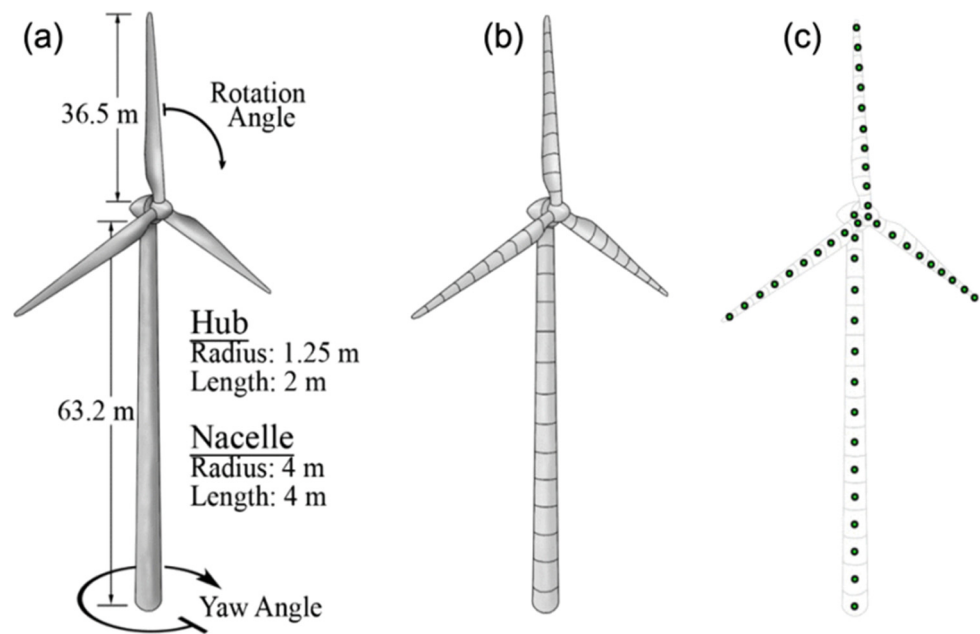


Figure 3. (a) CAD geometry of the basic 2MW turbine employed in the RCS modelling; (b) portioned turbine for RCS modelling; (c) the RCS point positioned at the center of each portion [34].

Each facet is regarded to be an ideal electric conductor (IEC). If it is required in the model, a complex and amalgamated material can be estimated by manipulating the reflection coefficients of each facet. The RCS of the portion σ_n was modelled by the computation and summation of the scattered signal from each facet, as per Figure 3b, on the portion using the physical optics formulation [35,36]. In a similar study [37,38], the combination of physical and geometrical optics techniques was employed to undertake the issue of several interaction among the wind turbine's facet.

In order to compute the overall RCS of the turbine component parts (blade, tower or nacelle), σ_{TOTAL} , the impacts from the portions can be summed using Equation (4). The point of reference of each segment's phase were at its core, as per Figure 3c. After identifying the turbine's orientation and the position of the radar point, the distance to each section d_n was determined from the geometry of the scene. It was then applied to calculate each phase's segment impact. The overall/total RCS of a turbine component, with

$$\sigma_{TOTAL} = \left| \sum_{n=1}^N \sqrt{\sigma_n} \exp\left(j \frac{2\pi d_n}{\lambda}\right) \right|^2 \quad (4)$$

N segment, was computed by applying the relative phase technique [39].

In the case of larger objects where the RCS is marred by surface reflection, the relative phase technique offers a better estimation of the absolute RCS. Although, the relative phase

technique ignores second order effects such as joint coupling among various components of the turbines [33].

2.1.4. Doppler Signature Modelling

The Rectangular Meshing for RCS estimation, (ReMeRA) model, is a division of the WinR (Wind turbine RCS) model, which is a dedicated wind farm modelling costume designed and manufactured at the University of Manchester [34]. This model was employed to estimate the Doppler signature due to the blades' rotation, and can be obtained by calculating the magnitude of each facet and velocity vector on the rotating blade [40]. Nevertheless, since the ReMeRA model sectionalizes the blade into smaller portions along its axis, the facets in each portion are mostly considered to shift in line with the velocity vector while the blade rotates. First, the mid-point of each blade section was computed as the point at the core of the section, as depicted in Figure 4.

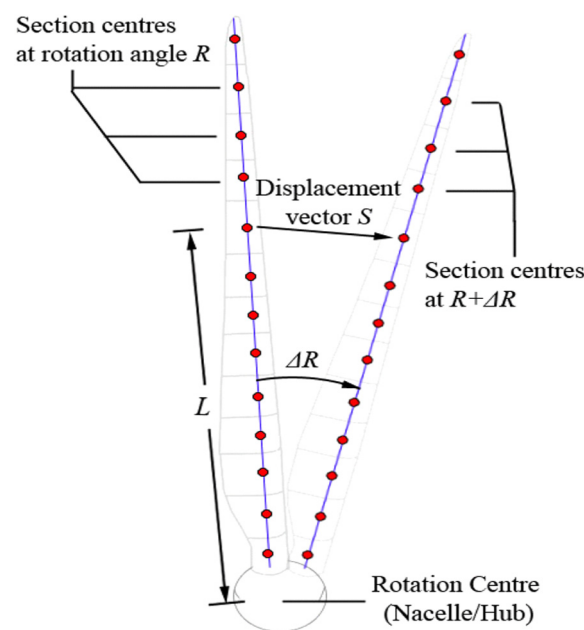


Figure 4. Blade portion centers for Doppler modelling of the transposition vectors [34].

The complete description of the Doppler signature modelling relies on the length of the portion in relation to the blade length and roughness needed for the Doppler computing. Given a Doppler frequency resolution Δf , the section length must not surpass ΔL . This is crucial for turbines, as it is illuminated sideways and its worst-case scenario is when V_r is equal to T_s . ΔL was deduced from the equation relating T_s and f_d , as shown in Equation (5).

$$f_d = 2V_r / \lambda \quad (5)$$

f_d is the Doppler frequency shift, V_r is the velocity vector. The tangential speed T_s L meters away is given in Equation (6), where RPM is the blades' rotation rate per minute.

$$T_s = 2\pi L(RPM)/60 \quad (6)$$

Therefore, from Equations (5) and (6), the Doppler frequency resolution becomes: as Tangential speed becomes the same as velocity vector.

$$\Delta f = \left[\frac{2}{\lambda} \right] \left[\frac{2\pi \Delta L (RPM)}{60} \right] \quad (7)$$

$$\Delta L = \frac{15 \Delta f \lambda}{(RPM) \pi}$$

3. Wind Turbine Interference Impact on Television & Communication Signals

The International Telecommunication Union (ITU-R) stated in Recommendation ITU-R BT.805 described a common scattering model in 1992 and 2011, which can be used to analyze the distortions affecting analog television reception due to wind turbines [41]. Nevertheless, the standard recommendation is applicable to analogue television. Henceforth, the ITU-R researched the negative impacts of signals reflected by wind turbines on digital television reception, taking into account the inconsistency of the reflected signals [42]. The empirical assessment of the effect of wind turbines on DVB-T quality of reception was conducted in [43], entailing a complete briefing of the various propagation channel in wind farms by recognizing and classifying the conditions where a substantial deterioration of signal quality can be seen. The transmission regulations/modulation were found to be independent of the report of the propagation channels, and therefore authorized for any wireless communication and broadcasting system.

The EMI in wind farms allowed us to understand EMI in the context of MW wind turbines. The three mechanisms it causes resulting from EMI are near field effects, diffraction, and reflection/scattering [32,44,45]. The probability of a wind turbine interfering with radio signals due to electromagnetic field radiated by the generator is referred to as near field effects.

An overall model was developed in [46]. Figure 5 shows the circumstances under which wind turbines can generate the EMI effect. A transmitter (T) passes a signal directly to a receiver (R) and to a wind turbine (WT) with either vertical-or horizontal-axis construction (VAWT or HAWT). Due to the rotation of the turbines' blades, it produces and transmits a scattered signal. The receiver then concurrently intercepts dual signals, with the scattered signal initiating the EMI due to it being delayed and/or distorted. The analogy of signals reflected in a similar fashion to mirror reflection is referred to as being back-scattered. As shown in Figure 5, almost 80 per cent of the area surrounding the turbine is the backward scattered zone. In other words, a scattering of the signal that is analogous to shadowing is often referred to as forward scattering and ~20 per cent of the precinct of the turbine is regarded as the forward scattered zone.

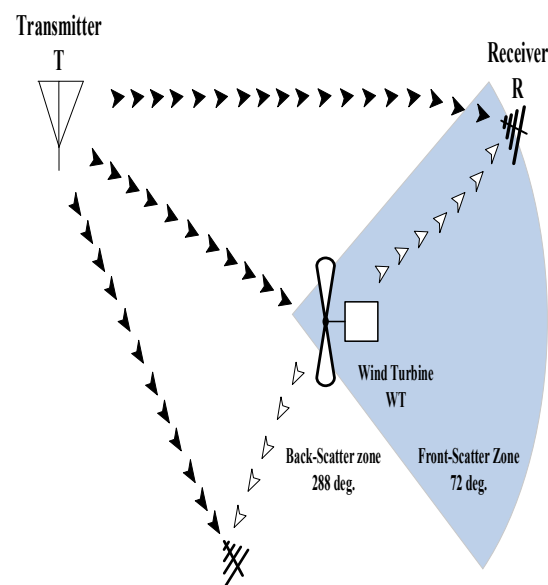


Figure 5. Visualization of the propose relative position of the transmitter, receiver and a wind turbine that may generate EMI [47].

The reception of both direct and scattered signals mostly resulted in interference and distortion and delay of the scattered signal. The envelope of the absolute electric field strength of the ambient signal, E , around the receiving point, R , is shown in (8a) and (8b);

$$|E_R|_{envelop} = |E_{R,D}|[1 + m_E f_m(t)] \quad (8a)$$

$$m_E = \frac{|E_{R,S}|}{|E_{R,D}|} \quad (8b)$$

where E_R = field strength at the receiver of the total signal (mV/m).

$|E_{R,D}|$ = amplitude of the field directly from the transmitter impinging on the receiver (mV/m).

$|E_{R,S}|$ = peak amplitude of the scattered field (from the wind turbine) during rotor revolution (mV/m).

m_E = modulation index of the ambient field.

f_m = time-varying modulation shape function; $-1 \leq f_m(t) \leq 1$. t = time (s).

The modulation index, m_E , is the parameter used to measure the extent of the interference with the signal field. The magnitude of the interference impact was expressed mostly by the modulation shape function f_m . The envelope of $|E_R|$ denotes the field of the overall signal that were really monitored, while the modulation shape function represents the time dependence of the envelope for the scattered signal generated by the blade rotation. The equations introduced were based on the available test data and models applicable to electromagnetic interference, but the field test data from several wind turbines are restricted to measurements close to the 3 MW capacity horizontal axis wind turbines (HAWTs) with metal blades.

A comparative study comparing values predicted with experimented data collected from a Digital Television (DTV) assessment in Spain was conducted in [48]. The signature information was merged into the applicability of these methodologies after corroborating the scattered model vs. the measured data. In the event of possible interference resulting from wind turbines operation, five theoretical scattering models for the comparative study were adopted.

1 Recommended ITU-R BT.805

The ITU-R Recommendation consists of the conventional model, which only accounted for the scattered signal from the blades that were assumed to be rectangular metallic plates [41]. Figure 6 shows the two scattering zones denoted as the general scatter region and forward scatter region.

2 New Recommended ITU-R Draft

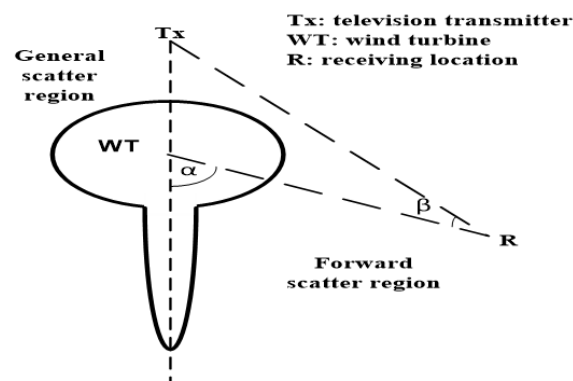


Figure 6. Plot outlook of the Rec. ITU-R BT.805 model [41].

The Draft New Recommendation for the evaluation of poor quality signal reception of digital television caused by the rotation of wind turbines [49] proposed tackling shortcomings characterized by the trivial ITU-R BT.805. First, the scattering model was designed on

the basis of the triangular blade, and a hypothesis closer to the original shape of the modern blades than the rectangular estimation, was applied in the Rec. ITU-R BT.805. Second, the scattered model relies on the incident and scattered angles of the signal with respect to the plane rotation of the blades, taking the wind turbine orientation opposite to that of the wind direction. Figure 7 illustrates the proposed view of the overall wind turbine.

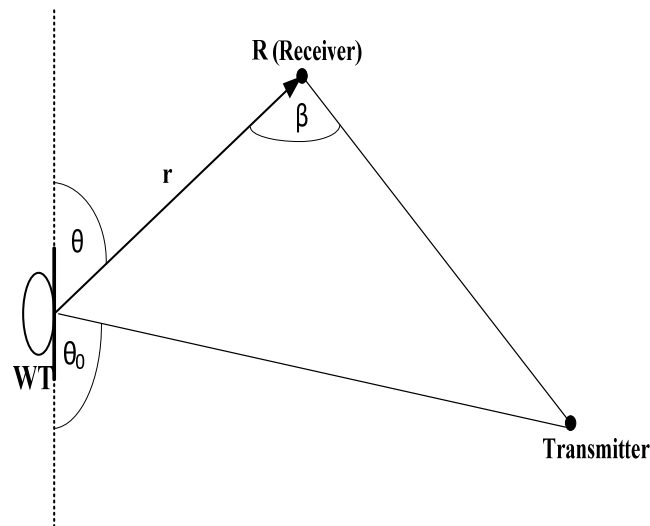


Figure 7. Plot outlook of the Draft New Rec. ITU-R model [49].

A “scattering coefficient”, ρ , consists of the free-space path loss, from the wind turbine location to the point of reception, is expressed in Equation (9):

$$\rho = \frac{A}{\lambda r} g(\theta) \quad (9)$$

where:

$$g(\theta) = \sin^2 c^2 \left(\frac{\overline{W}}{\lambda} (\cos \theta - \cos \theta_0) \right) \sin \theta$$

and $\overline{W}$ is the mean width of the blade (m), A is the blade area in (m^2), λ wavelength (m), r is the distance from the blade of the wind turbine to the point of reception in (m), θ_0 is the signal incident angle at the blade, and θ is the scattered signal angle originating from the blades’ surface.

The scattering coefficient ρ entails only the backscattered signal from the blades. As per the proposed view in Figure 7, this reflects a condition when the receiver and transmitter are positioned at the same side of the semi-plane restricted by the rotating plane of the blades. Therefore, the receiving point can be obtained in the forward/backward areas of the blades, pending the direction of the wind. In terms of the Draft New Recommendation, the metallic mast also considerably impacts the backscatter.

3 Sengupta

Sengupta hypothetically determined the scattered field via the application of physical optics estimation to compute the moments of the electric dipoles induced on the surface of the blade [50].

For practical methodology, Sengupta adopted the “idealized signal scatter ratio”, Z_I . This variable is defined as per the ratio in Equation (10), assuming that the blades of the wind blades were oriented for maximum signal reflection (or shadowing) from the transmitter [46,47] given in relation (10). The “idealized signal scattered ratio” is shown in Figure 8.

$$Z_I = \frac{\eta_S D}{2 \xi} \cos(k\Phi_S), \quad (10)$$

where

$$k = \begin{cases} 0.5 - 0.8\pi \leq \Phi_S \leq 0.8\pi & (\text{Backward Zone}) \\ 2.0 - 0.8\pi \leq \Phi_S \leq 1.2\pi & (\text{Forward Zone}) \end{cases}$$

and η_S is the efficiency of the scattered signal from the blade relative to the flat metallic plate ($\eta_S = 0.27$), empirically determined for fiberglass blades [50], D is the rotor diameter (m), ξ is the distance in (m) from the wind turbine to the receiver, and Φ_S is the azimuthal scattered angle (rad).

4 BBC Research Unit

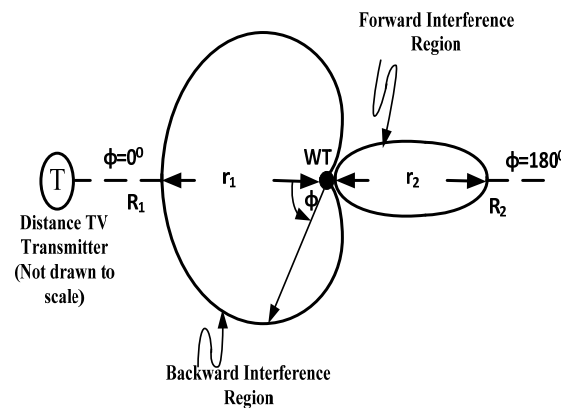


Figure 8. Proposed interference zone by Sengupta [51].

The model adopted by the British Broadcasting Corporation (BBC) research unit was based on a flat conducting plate model for the blades and a possible suggestion of mirror kind reflection condition [52]. Simplifying it, the value of the re-radiated free-space field E_r (V/m) is obtained as per Equation (11).

$$E_r = \frac{EA \sin \Phi}{\lambda D_2} \times 10^{-3} \quad (11)$$

where E is the incident wave strength (V/m), A is the area of the plate (m^2), λ is the wavelength (m), and D_2 is the distance from the observer to the wind turbine in (km). The path geometry is demonstrated in Figure 9, where S is the source (transmitter), V is the viewer (observer), and R is the wind turbine.

5 Van Kats

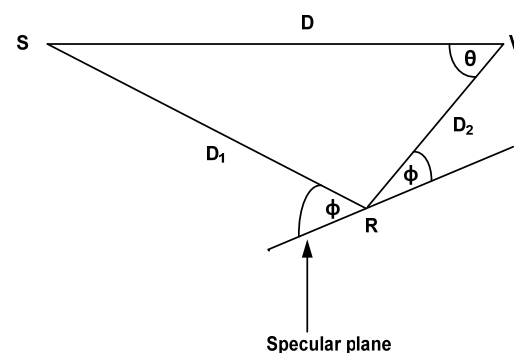


Figure 9. Adopted path geometry by BBC R.D [52].

Van Kats employed the RCS perception [53] in order to classify the scattered signal reflected from the wind turbine [54].

A “co-ordination area” was outlined to demarcate an area around the wind turbine, where signal strength of television could be weakened. The geometry of the “co-ordination area” is shown in Figure 10.

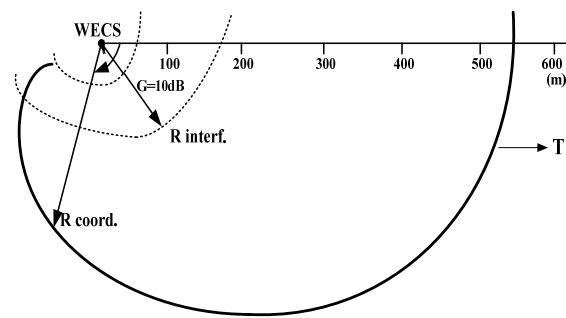


Figure 10. Adopted geometrical arrangement for the zone of co-ordination by Van Kats [54].

In terms of the co-ordination region, the blade was estimated using a rectangular ideal conducting screen, and the worst-case scattering condition of the wind turbine was considered as well. The RCS of the wind turbine is detailed in Equation (12).

$$\sigma(\alpha) = \left[\frac{4\pi}{\lambda^2} A^2 \left(\frac{1 + \cos\alpha}{2} \right) \right] \quad (12)$$

where A is the blade effective area (m^2) and λ is the wavelength in (m). As per [51], the applicable area of the blade is related to the elongated geometrical area A_p in Equation (13), with the scattering efficiency η_s ;

$$A = \eta_s \cdot A_p \quad (13)$$

The empirical calculations of the scattering models show that they do not yield the actual estimations of the scattered signals from the wind turbines. Due to the high magnitude of the forecasting errors (6 dB to 32 dB) and standard deviations (6 dB to 24 dB), it was concluded therein [48] that the lack of accuracy was due to the shortcomings of the theoretical model.

It was stated in [55] that any motion or standing structure within the vicinity of television or radio station interferes with the signals. The towers of the wind turbine can produce undesirable EMI, thereby deteriorating the performance of nearby transmitters and receivers [56]. In [57], the possible effect on wind turbines on the telecommunication networks was reviewed. They summarized the main impacts and techniques that can be implemented in order to predict fault occurrence and remedial strategies.

Technique for Mitigations

The software tool W_i^2 detailed in [58] was developed in the University of Basque County (UPV/EHU). It comprises of several models and algorithms that can approximate the possible effect of a definite wind farm within the coverage of telecommunication service. In an effort to prepare for alternative solutions beforehand and ensure a faultless coexistence between the wind farm and telecommunication installations, it is paramount to determine the best location of wind farm development near the radar and radio-communication installations. The W_i^2 software tool is made up of four basic modules: a database containing all the fundamental data regarding the wind farms and the radio communication service under consideration, data set of external altimetry, a graphic user interface, and the basic module.

4. Wind Turbine Interference with Radar Signals

Radar (Radio Detection and Ranging) is an electromagnetic system for sensing the location of objects and recognizing target patterns. It operates by sending electromagnetic signals aimed at the target and reflected signal from the target object within its coverage area, thereby pinpointing the position of the object and other data information from reflected/echo signals [59]. In summary, a wind turbine could scatter signals that are both amplitude- and frequency-modulated due to the continuing rotation of the blades. The characteristics of time and frequency of this scattered signal depend on several factors,

some of which are constant, such as the distance from the transmitter and the materials of turbines and its dimensions, while others are time-dependent, such as the angular velocity of the blades and orientation of the nacelle [57,60].

When airport radar receives reflected signals from a wind turbine structure, it could result in the radar malfunctioning as the rotation of the blades can pass a substantial Doppler shift onto the received radar signal, which is comparable to that from an aircraft [61]. The Doppler spectral signature of a wind turbine echo is similar to that of a helicopter. Therefore, a consistent scheme is needed to clarify/discern the wind turbines plots as air “target or as helicopter” [62]. In order to determine if a wind turbine can be erected within the vicinity of radar installations, air space navigation service providers (ANSPs) issued stringent requirements, such as the barring of wind turbines from within a 10 km range of primary surveillance radar (PSR) or secondary surveillance radar (SSR) [62].

Despite the contribution of wind energy towards the production of green energy, a major setback of this system is the huge metallic structure of the rotating blades, which could interfere with a collection of radars for civilian air-traffic-control. A survey carried out by the office of the Undersecretary of Defense for Space and Sensor Technology recognizes the effect produced by wind turbines when positioned in-line-of-sight of air-traffic-control or airborne radars [63]. Thus, most research on wind turbines interference with radar signals are funded by the defense sector, such as the Defense Evaluation Research Agency (DERA) and the US Department of Homeland Security. A number of wind turbine projects across the globe have been stopped due to the seriousness of the potential threat it poses, particularly with regard to the aviation industries.

RCS and Doppler spectra of wind turbines for large electrical power generation gathered by the Air Force Research Laboratory and Mobile Diagnostic Laboratory (AFRL/MDL) were analyzed at Fenner, New York. A small proportion of the MDL practical measurement data set was compared with the theoretically modelled Doppler signatures using an XPatch computer model. Additionally, a radar simulation of a commercial passenger airliner signature, incorporated into a measured windmill data file, was presented. The work was limited to a few comparisons over 400 of the four discrete frequencies L-, S-, C-, and X-band data files at different elevation and yaw angles were collected by the MDL during the deployment to Fenner, NY, in a fortnight [64].

Processing four hundred data files is time consuming, due to each calibration constant needing to be determined for each windmill, frequency, polarization and MDL location site. The general data processing procedure is illustrated in Figure 11. The standardization operation makes the data scaling detect the range to the target and radar response as a function of frequency and polarization. The calibration offers data in dB that is a unit of RCS for the RCS vs. time format.

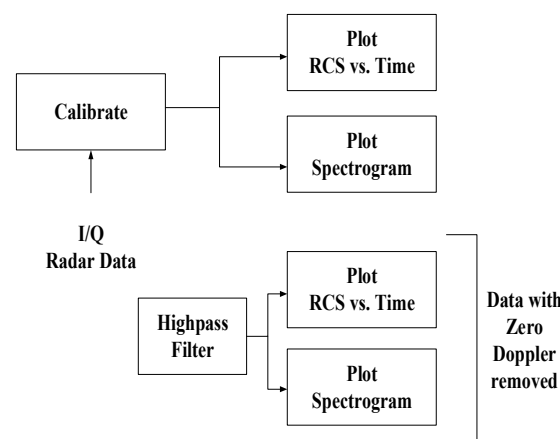


Figure 11. Calibration and scattering processing [64].

Radar parameters were quantitatively modelled with respect to a wind turbine by [65]. It is a rather complicated task, owing to its numerous (electrical degrees) of freedom, large

electrical scale, and complex shape. Moreover, different terrain and atmospheric conditions can result in irregular propagation and multi-path effects, making it rarely possible to forecast the effects of interference due to the rotating wind turbine. The paucity of relevant knowledge to analyze wind turbine interference (WTI) on the current radar networks and alleviate the impacts of clutter has resulted in the moratorium of 100 s of MWs capacity of wind farm projects, thereby hampering the effort of green energy campaign.

Owing to the motions of the return power of a wind turbine, it oscillates from pulse to pulse. Thus, it is imperative to model the probability density function (pdf) of the oscillations, for the purpose of assessing the effect of WTI on the radar performance. The wind direction was used to determine the aspect angle as in Equation (14), which usually varies within a restricted range, it was then assumed that:

$$\varphi = \varphi_0 \pm \Delta\varphi \quad (14)$$

where $\Delta\varphi$ describes the variation.

The standard measure used to determine the extent to which the EM energy is captured by the radar target and scattered to the radar receiver is referred to as the RCS model. It relies on the nature of the target and radar variables, as per Equation (15).

$$R_m = \frac{pL^2}{\lambda} \quad (15)$$

where L is the radar/target antenna of the largest dimension, λ is the wavelength of the radar, and ρ is the determinant factor for the largest phase difference of the incident/scattered spherical wave over the whole radar target/antenna. $p = 2$ yields $\frac{\pi}{8}$ maximum phase difference, which is the recommended value for the majority of RCS measurements according to [66]. Due to space constraint in the chamber, the wind turbine model was set to ~4 m distance from the radar antennas, which is less than the standard required distance.

Wind farms are increasingly erected in the path of radar signals, which consequently degraded its performance due to interference. Bistatic RCS method can be applied by employing an electromagnetic wave frequency solver tool known as the XGtd, and illuminating the geometrical shape with a plane wave will allow us to compute the RCS mathematically using Equation (16).

$$RCS = \lim_{r \rightarrow \infty} \left[4\pi r^2 \frac{|E_s|^2}{|E_i|^2} \right] \quad (16)$$

where E_i is the field impinging on the target, E_s is the electric field scattered found by incorporating the individual contributions of the ray paths, and r is the observed distance from the target. RCS output comprises of the magnitude and phase values co-and cross-polarized field components in terms of the incident plane wave polarization [67].

The power received from a wind turbine reflection has been reported in [62], and is detailed by Equation (17)

$$P_{WT} = \frac{P_{peak} G_r G_t G_{PC} \lambda^2 \delta_{WT} f^4}{(4\pi)^3 R_{WT}^4 L} \quad (17)$$

With P_{peak} as the peak power transmitted in (W), G_r , and G_t power gain of the receiver and transmitter antenna, respectively, G_{PC} as the pulse compression gain, λ as the wavelength in (m), δ_{WT} the near field [68], RCS of the wind turbine, f as the pattern propagation factor that includes the dimension of the antenna pattern and the radar environment, R_{WT} the slant range to the wind turbine, and L is the number losses.

4.1. Radar Range Link Equations

It has been stated in [69] that the rotor-induced Doppler effect can cover targets in motion or be misconstrued as weather echoes. Due to its characteristics, the wind turbine section of the return might not be differentiated and treated as clutter by radar. The RCS of a point target (i.e., a disproportionate size ratio of target to the radar resolution cell) was determined for a wave plane incident using the limit Equation of (18) [70,71].

$$\sigma_{pq}(f, \theta_i, \Phi_i, \theta_s, \Phi_s) = \lim_{R \rightarrow \infty} \frac{4\pi R^2 |E_p^s(\theta_s, \Phi_s)|^2}{|E_q^i|^2} \quad (18)$$

where R is the distance from the target, f is the frequency, the subscript/superscript i symbolizes the incidents, s scattered, and $p, q = \theta$ or Φ are components in the spherical polar coordinate geometry, as illustrated in Figure 12.

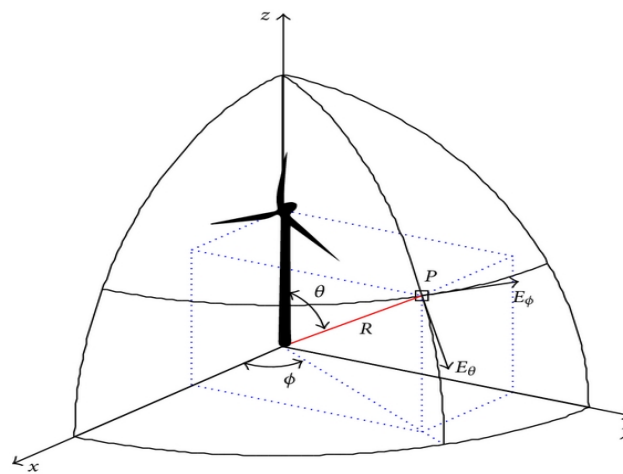


Figure 12. RCS patterns and their associate coordinate geometry [69].

The limit equation ensures that the scattered signal remains inversely proportional to R . The co-polarization signifies the situation when $p = q$, while the cross-polarized RCS is $p \neq q$. Generally, σ is expressed as a scalar, with the unit m^2 .

4.1.1. Monostatic Radar Range Equations

The power detected from a target for the monostatic radar at a range R was given by the traditional radar range;

Equation (RRE) in (19) [72].

$$S = \frac{P_t G_t^2 \lambda^2 \sigma_t}{(4\pi)^3 R^4 L} |F_t|^4 \quad (19)$$

where P_t is the transmitter power, G_t is the antenna gain in the target course, λ is the wavelength, σ_t is the target.

RCS (m^2), and L is the assorted loss factor of the system. The factor F_t is the single path propagation factor and it is squared twice in order to determine the power and one complete trip, respectively, thus rising to the fourth power.

A performance evaluation of radar and telecommunication systems is usually based on the signal-to-noise ratio (SNR).

However, [69] ignored the effect of noise when comparing it with the clutter of wind turbine, while the signal-to-clutter ratio (SCR) was applied as a factor for performance

assessment. The clutter power reflected from a wind turbine's target point with RCS σ_w at the range R_w is represented in Equation (20);

$$C = \frac{P_t G_w^2 \lambda^2 \sigma_w}{(4\pi)^3 R_w^4 L} |F_w|^4 \quad (20)$$

The wind turbine and target RCSs varies with time. In the case of the former, it was due to the motion of the rotor and the multipath variations characterized by the rotor motion, while in the case of the latter, it was due to the varying aspect angle, multi-path, and the velocity.

From the Equations (18) and (19), the SCR for the monostatic case can be determined using the ratio in Equation (21).

$$\frac{S}{C} = \left(\frac{G_t^2}{G_w^2} \right) \left(\frac{\sigma_t}{\sigma_w} \right) \left(\frac{R_w^4}{R^4} \right) \left(\frac{|F_t|^4}{|F_w|^4} \right) \quad (21)$$

It can be seen that increasing the transmitter power will not cause the SCR to increase due to the clutter power increasing in proportion to the target power.

4.1.2. Bistatic Radar Range Equations

Bistatic geometry increases when the transmitter/receiver are as far apart as possible in angular distance. Bistatic radar is not as regular as monostatic; nevertheless, the overall bistatic case encompasses the broadcasting systems, cellular radio, and GPS. The direct signal from the transmitter to the receiver is represented by Equation (22) [73] and Figure 13.

$$S = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2 L} |F_d|^2 \quad (22)$$

where R is the distance from the straight path of the transmitter to the receiver, G_t is the transmit antenna gain along the receiver path, G_r the receive antenna gain along the path of the transmitter, and F_d is the propagation factor for the one-way voltage. As per the bistatic configuration illustrated in Figure 13, the incoming clutter power to the receiver from the wind turbine is shown in Equation (23) [74].

$$C = \frac{P_t G_{tw} G_{rw} \lambda^2 \sigma_{bw}}{(4\pi)^3 R_t^2 R_r^2 L_t L_r} |F_t|^2 |F_r|^2 \quad (23)$$

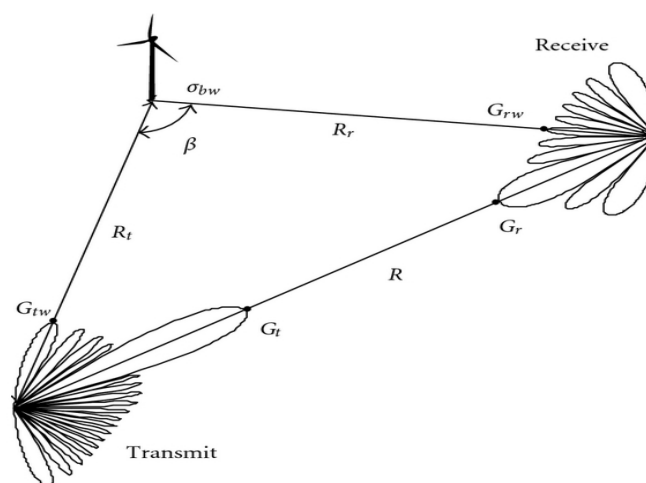


Figure 13. Parameters of the Bistatic Case [69].

The subscript w signifies the parameters associated with the wind turbines, where the subscript t and r denotes transmit and receive, respectively, σ_{bw} is the bistatic RCS of the wind turbine when the incident path originates from the transmitter and the viewing side is from the receiver, as demonstrated in Figure 13.

For the special case of SCR, the line-of-sight propagation path and ideal situation ($L_t, L_r, |F_t|, |F_r| \approx 1$) resulted in Equation (24).

$$\frac{S}{C} = \frac{G_t G_r}{G_{tw} G_{rw}} \frac{R_t^2 R_r^2}{R^2} \frac{4\pi}{\sigma_{bw}} \quad (24)$$

The side lobe levels of the two antennas were positioned as low as possible in order to increase SCR, in addition to mitigating the wind turbine RCS. The majority of the EMI cases occur in the near-field zones due to the size of the wind turbine structure. Thus, the far-field assumption applied previously by the EM solvers lead to inaccurate results. The RCS standardization and EMI study of wind turbine structures is rather complex. The scaled-model-based technique allows for the fast characterizations of the complete turbine structures and recognition of its key aspects. One of the simplest approaches for radar EMI modelling is the laboratory-based measurement of scaled wind turbine models, consisting of the scattering mechanisms [75]. During radar operation, the target is used to scatter the power expressed in relation to its RCS, which is defined as the elongated area needed to intercept and radiate an equal amount of power as the target scattered toward the receiver in an isotropic manner.

Wind turbines are large signal reflectors that are bigger than the target object the radar is focused on, hence their presence could obstruct weaker signal from smaller targets, as demonstrated by [57]. Furthermore, it was shown that the rotation of the blades induced a Doppler shift that can also be sensed and observed by the radars. As current radar technology does not recognize patterns and filter out signals from the wind turbine, information could be lost. When scattering is directed toward a radiating source, it is called monostatic scattering, while if it occurs in the retro-direction with respect to the monostatic, it is called bi-static scattering. An exceptional case, known as forward scattering, occurs when the bi-static angle is $\sim 180^\circ$ [76]. For instance, Figure 14 illustrates the scattering pattern, which displays a high variability due to the complicated design of blades and nacelle.

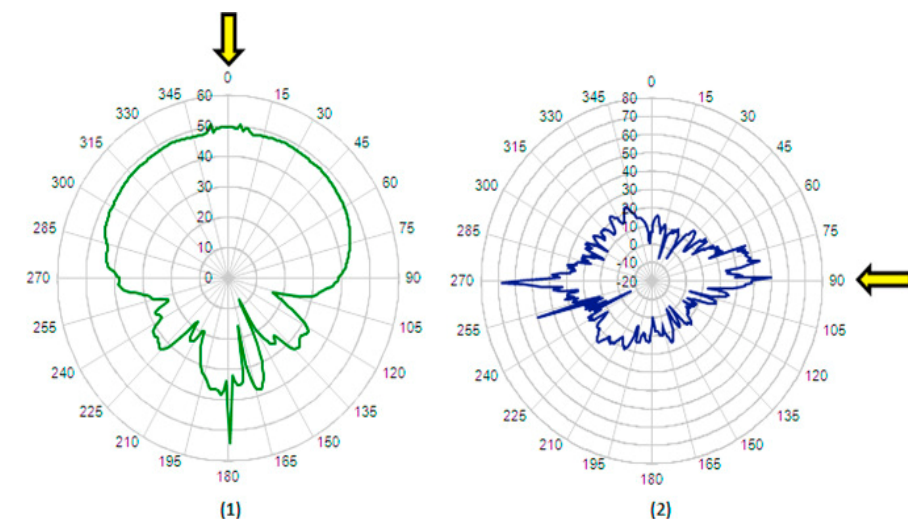


Figure 14. Illustration of the scattering outline by a particular case of the incident signal on a rotating turbine, showing the conditions and the coordinates of the blades, in which yellow arrows indicates the incidence direction. (1) Horizontal plane; and (2) the scattering arrays of the vertical plane [57].

Generally, (Figure 14), forward scattering from a blockade is greater than the backward scattering effect. The former is almost out of phase with the direct field, which resulted in a shadow at the back of the wind turbine [76].

4.2. Lightning Induced Electromagnetic Interference on Wind Turbines

The discharge due to lightning is one of the two natural occurrences of electromagnetic interference. Electric and magnetic fields induced by lightning poses a significant danger to a number of systems, especially those associated with sensitive electronic devices. As the proliferation of wind power generation system is experienced, the destruction of wind turbines due to lightning needs to be taken seriously. This study has been restricted to the lightning surge propagation in wind turbines. The current front of the first stroke is detailed by Equation (25);

$$I = At + Bt^n \quad (25)$$

where

$$A = \frac{1}{n-1} \left(0.9n \frac{I_{max}}{t_n^n} - S_m \right)$$

$$B = \frac{1}{t_n^n (n-1)} (S_m t_n - 0.9 I_{max})$$

To study transients in large proportion or random electrical networks, EMTP is employed. This work utilizes the latest version of EMTP-RV. The complete software is called EMTP Works, where EMTP is an acronym for Electro-Magnetic Transient Program, designating the computational engine. The current tail equation is represented by Equation (26) [77,78].

$$I = I_1 e^{\frac{-(t-t_n)}{\tau_1}} - I_2 e^{\frac{-(t-t_n)}{\tau_2}} \quad (26)$$

The equation was employed at the time when EMTP enters the tail zone at $t \geq t_n + t_{start}$. It has been observed in [79] that the steepness of the current is an essential variable in relation to the EMI that exposes crucial electronic devices, such as the control unit to potential danger. Thus, a distributed sensor network was developed to enable online localization and classification of lightning impact. The major shortcoming of utilizing distributed sensors for lightning measurement is EMI due to the electromagnetic transient, which could damage sensor elements or upset the stream of communication data. Fiber optic sensors are often used to mitigate or tackle the aforementioned challenge due to their immunity to EMI and robustness against external disturbances for application in communication over long distance.

The study on how wind turbines interact with the downward lightning strike was reported in [80,81], stating that the common downward lightning discharge is mostly initiated with a weak luminous lightning stepped leader, stemming from the columbia cloud and spreading from the air downward to the terrestrial installations and facilities. A lightning stepped leader model was recently applied in many simulations works [82,83] to forecast electric fields generated by lightning strikes. The distance of the lightning strike from the lightning-stepped leader to the wind turbine is usually computed by the application of rolling sphere technique [84,85], as per Equation (27).

$$R = 0.6 \cdot I_{peak}^{1.46} \quad (27)$$

where I_{peak} is the peak current (in kA) and R is the lightning strike distance (in m), as proposed by the lightning protection standard [86]. The blade model of the wind turbine with a static electric field around it due to the lightning stepped leader can be solved using finite element analysis. The equations of electrostatics shown in Equations (28a)–(28c) were applied to calculate the electric field due to the given vertically-charged lightning-stepped leader.

$$\nabla \times E = 0 \quad (28a)$$

$$\nabla \cdot E = \rho_v / \epsilon_0, \quad (28b)$$

$$E = -\nabla \phi \quad (28c)$$

where E is the electric field tensor, ρ_v is the electric charge source, $\rho_v = \lambda / \pi r^2$, λ is the line charge density, r is the radius of the vertical cylindrical lightning-stepped leader channel, $r = 1.5\text{m}$, ϵ_0 is the permittivity of the free space, and ϕ denotes the electric potential. The

FEA software COMSOL Multiphysics was employed to solve Equations (28a) to (28c), characterizing the lightning stepped leader. The computational domain was $4000 \text{ m} \times 4000 \text{ m} \times 4000 \text{ m}$, with an outline of the created high-fidelity wind turbine model, as illustrated in Figure 15.

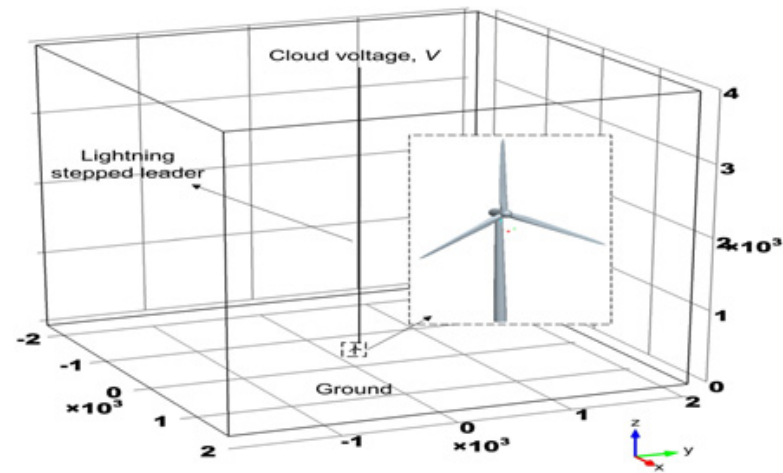


Figure 15. Problem setup in COMSOL Multiphysics [80].

Wind Turbines Electromagnetic Interference Alleviation Techniques

A methodology was explored for the application of active radar absorbing structures on the idea of a phase switched screen (PSS). PSS is one of the strategies that can be used to control the effects of tracking errors in radar systems induced by undesirable reflections from wind-farm installations. The results obtained from the experiments on a calibrated model windmill with PSS blades working concurrently with a 10 GHz Doppler radar system were reported in [61].

A cutting-edge radar system provides an effective means of tackling wind turbine clutter and obsolete radars. Radar with resolution in altitude is normally considered to be less sensitive to the impacts introduced by wind turbine clutter than 2D radar. In addition to the Range-Azimuth-Gating (RAG) and Track Initiation Inhibit (TII) as mitigating strategies, an entirely different and efficient method is to utilize sensor fusion, as illustrated in Figure 16 for two 2D primary surveillance radars (PSRs).

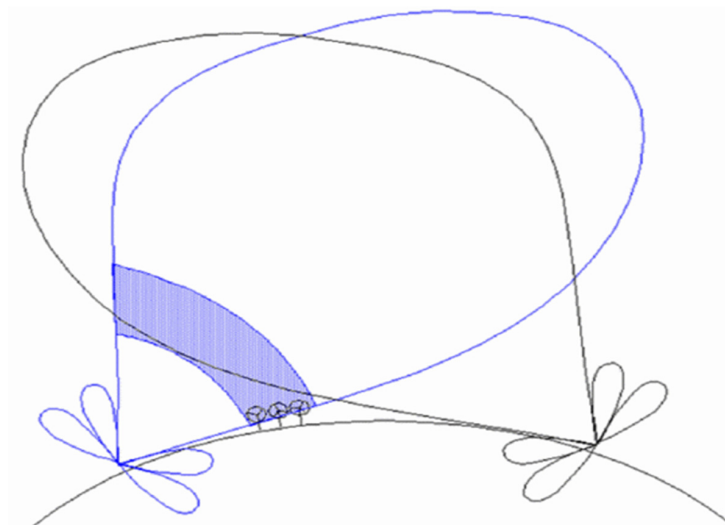


Figure 16. Illustration of sensor fusion as mitigation strategy against wind turbine clutter [62].

It can be observed that the radar is unaffected by wind turbine clutter. Lightning Strike Protection were elaborated upon in [62].

5. Discussion

The primary environmental issue from wind turbine structures in an onshore environment is EMI with terrestrial signals originating from telecommunication and radar systems (transponder). Therefore, the installations of radar, radio, and television broadcasting facilities in a location within a few kilometers of wind farms requires an elaborate modelling and analysis in order to avoid the degradation of the quality of transmitting and reception signals. Digital technology with specially-designed antennas somewhat mitigates this, especially in broadcasting corporations.

It can be deduced that the effective remedy of television broadcasting signals interference with the wind turbine blade is total switching to the digital broadcasting system and phasing out of the analog television transmission system, which is susceptible to signal distortion and consequent appearance of ghost pictures when the facilities are within the vicinity of wind farm development. On the other hand, the International Telecommunication Union (ITU) stated in recommendation ITU-R BT.2142-1 stated that digital television signals can still experience scattering due to wind turbines unless a standard TV aerial is employed, which would then be able to resist the interference from the rotating wind turbine blades.

The calculation of the RCS of wind turbine's blade, to analyze and model the distortions caused to communication services, e.g., military, meteorological radar or aerial navigation of radio systems, requires a number of methodologies. The RCS modelling of a wind turbine requires a super computing environment due to its immense size and the complex geometry of wind turbines. It is therefore recommended that preventive measures that are feasible and cost effective be adopted, especially with the application of Lucernhammer software for predicting the suitable location of the radar deployment relative to the wind farm development prior to its installations. Advancements in radar technology and software upgrade can offer effective means for encouraging the coexistence of radar stations and wind farms.

The most auspicious mitigating strategy for the EMI of the wind turbines with radar and communications signals that has been presented is stealth technology, similar to that of a raptor (radar evading aircraft), needs to be developed and incorporated in the aerodynamic design of the wind turbine, particularly in the leading and trailing edges of the blades. Stealth technology is designed to absorb signals instead of reflecting it to induce the clutter effect, due to the fact that it is made up of radar absorbing material (RAM). Wind turbine manufactures Qinetiq and Vestas are leading the research on stealth technology for wind turbines in order to make it commercially viable. Furthermore, research on the general design of wind turbines that can be immune to both signal reflection and lightning that induces electromagnetic transient can be pursued.

6. Conclusions

Prior to the construction of windfarm in a given site, it is imperative to pursue an assessment of EMI with respect to the immediate environment of the erected wind turbines, to avoid signal distortion that the wind turbine operation may cause to a nearby telecommunication networks. Thus, the wind turbine scattering of telecommunication signals has been classified as techno-environmental impact. To analyze and forecast the possible EMI, owing to the wind turbine rotation, three different parameters, are usually studied, i.e., RCS, scattered field and the Doppler echo. Therefore, this paper presents an in-depth review of mathematical modelling and simulation, as well as the basic equations involved in evaluating the scattering effect of wind turbine rotations in the path of communication systems such as the radio, television, and radar signals, with the subsequent mitigation techniques via preventive or corrective measures. The interactions of wind turbines with these signals were analyzed in the context of scattering the signal and induce EMI, thereby degenerating its quality en route to the reception network. The impact of these reflected signals, which are distorted, most often affect the detection performance of the radar. It can be noticed that there are mainly two types of techniques employed in the modeling of

the wind turbine. One is to model the wind turbine echo, on the basis of high-frequency estimations, that is the RCS of the blade, and the other uses the estimated relation that is equivalent to the whole blade of the wind turbine. This kind of review will serve as a guide to assess the technical feasibility, on whether to erect a windfarm in a given site, with nearby telecommunications hardware, especially radar schema.

Funding: This work is supported by the Universiti Tenaga Nasional grant no. IC6-BOLDREFRESH2025 (HCR) under the BOLD2025 Program.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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