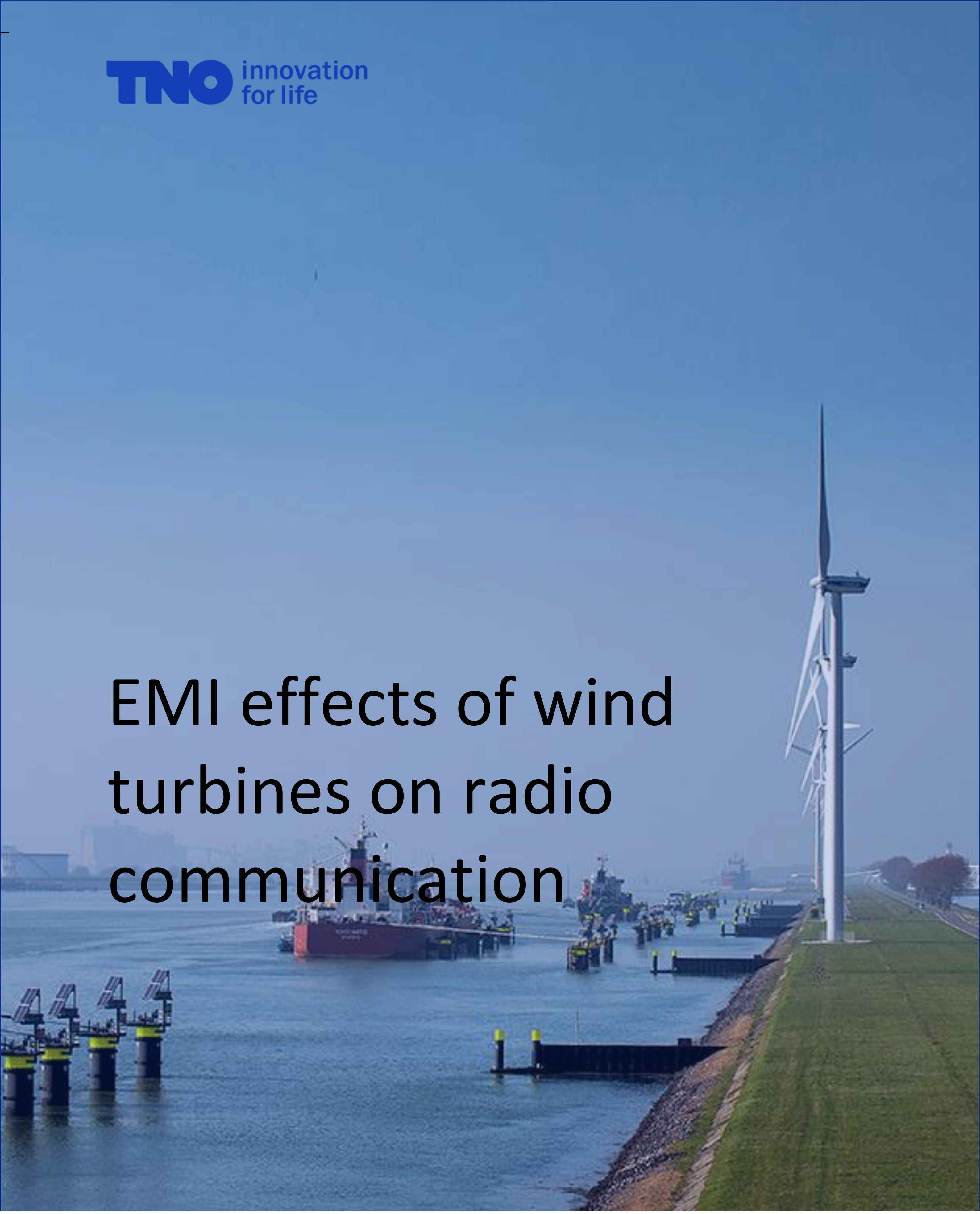

EMI effects of wind turbines on radio communication

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EMI effects of wind turbines on radio communication

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Summary

TNO has been commissioned by *Rijkswaterstaat (RWS)* to investigate the Electro Magnetic Interference (EMI) of wind turbine generators on their wireless communications along waterways.
Rijkswaterstaat runs numerous base stations which operate in the maritime VHF-band (156 – 162 MHz). For public order and safety, C2000 needs to cover similar areas as maritime radio do, hence the associated frequency band is also incorporated in this study.
Interviews and literature research have been conducted to estimate the influence of Electro Magnetic Interference (EMI) originating from wind turbines.

EMI data of wind turbines is scarcely available on the internet, only a few documents were found. Many attempts were made to contact various wind turbine manufacturers, but they showed reluctance to share actual data of EMI generated by wind turbines. However, based on the feedback from three manufacturers (Enercon, Vestas and Nordex), interviews with ASTRON, the VERON EMC-commission and the Dutch Authority Digital Infra Structure (RDI), it can be concluded that most wind turbines emit 15 to 20 dB less than ordained by CISPR11[1].

The International Council on Large Electric Systems[2] (Cigre) sets limits of EMI-levels for wind turbine generators at 3 to 10 dB lower levels than CISPR11 does for the class associated with high power wind turbine generators (WTG). The RDI provided insight in the somewhat obscure EMI-limit levels for wind turbine generators, revealing that “A product norm is under consideration by IEC88”.

Given the exposure of wind turbines in society, there is a strong incentive by this industry not to cause disturbances, hence to ordain itself to more strict EMI-limits than might be expected based on their power category. It is expected that a future product norm will be equal or less than the levels now set by Cigre.

Based on the interviews, available literature and calculations, it is safe to state that at present there is little harmful EMI to be expected from wind turbine generators. When actual EMI data of the wind turbine generators to be installed is not available, the values from Cigre should be used. For a single wind turbine this will result in a minimum separation distance of 275 metres to a base station (marine radio). In case of a complete windfarm, the separation distance may increase to 910 metres.
The separation distance between waterways and WTGs may be reduced to zero over a considerable stretch of the coverage range of a base station. Near the base station and at the far end (approximately > 65%), wind turbines should be located further away from the

[1] CISPR, EMC Standards | Academy of EMC. CISPR11 equalling the European standard EN55011, which defines EMI levels. 40 dBμV/m @ 30 metres distance for > 20 kVA generators. (The 2014/30/EU EMC-directive refers to CISPR11)
[2] Cigre is an independent organisation, established in 1921 in Paris, France, CIGRE is a global community committed to the collaborative development and sharing of end to end power system expertise. 8_1_CIGRE_Global_Profile_Ed2Aug22.pdf

waterway. In general it is recommended to apply minimum distances in line with the recommendations provided by the TNO report regarding radar[3].

[3] Effecten van windturbines op binnenvaartscheepsradars.
Een voorstel tot een nieuwe nationale regelgeving, TNO 2016 R10617 | 2.0, 16 september 2016

Samenvatting

In opdracht van Rijkswaterstaat heeft TNO een onderzoek uitgevoerd naar de effecten van Electro Magnetic Interference (EMI) door windturbinegeneratoren (WTG) op maritieme communicatie en navigatiesystemen in de 156-162 MHz band, maar ook C2000 gezien het belang van orde en veiligheid rondom waterwegen. Een literatuurstudie is uitgevoerd en interviews zijn gehouden om uit te zoeken wat de verwachte EMI is die wordt geproduceerd door wind turbines.

Op internet zijn bijna geen meetgegevens over de EMI-effecten van windturbines te vinden. Fabrikanten bleken zeer terughoudend over de werkelijke EMI van hun apparatuur. Op basis van interviews met drie windturbine fabrikanten (Enercon, Vestas en Nordex), ASTRON, de VERON EMC-commissie en de Rijksinspectie Digitale Infrastructuur kan echter worden geconcludeerd dat de feitelijke EMI van windturbinegenerators 15 tot 20 dB lager ligt dan men zou mogen verwachten op basis van de CISPR11 limieten voor hoog vermogen industriële apparatuur, waaronder de meeste windturbines vallen.

De organisatie voor hoogspanning elektriciteit "Cigre" (International Council on Large Electric Systems) hanteert EMI-niveaus die 3 tot 10 dB lager liggen dan die voor hoog vermogen industriële apparatuur. De RDI geeft aan dat er een productnorm in ontwikkeling is door IEC88.
De EMI van windturbinegeneratoren moet hoe dan ook voldoen aan de CISPR11 EMI-eisen die gelden voor hoog vermogen industriële apparatuur, maar de sector is zich bewust van de mogelijke effecten van EMI op de omgeving en legt zichzelf strengere normen op om storingen te voorkomen. Het ligt in de lijn der verwachting dat een toekomstige productnorm gelijk aan of strenger zal zijn dan de niveaus zoals nu gehanteerd door Cigre.

Gebaseerd op de interviews en internet data en berekeningen, kan worden gesteld dat de kans op ernstige interferentie klein moet wordt geacht t.g.v. de EMI van windturbinegeneratoren. Indien actuele informatie over de EMI van de te plaatsen windturbine generators ontbreekt zal moeten worden uitgegaan van de waarden zoals door Cigre gehanteerd. Voor een enkele wind turbine moet dan een minimale afstand van 275 meter worden aangehouden tot aan een basispost (gebaseerd op alleen marifoon en AIS). Indien er sprake is van een compleet windpark kan die afstand oplopen tot 910 meter.

Langs de vaarwegen mag de minimale afstand in principe tot nul worden gereduceerd, gerekend vanaf de minimale scheidingsafstand bij het basisstation tot ongeveer 65% van de reikwijdte van de basispost zender. Vanaf dat punt moet de afstand van een WTG tot aan de waterweg weer toenemen tot aan de minimale scheidingsafstand zoals ook geldt rondom het basisstation.
Verder wordt geadviseerd om een minimale afstand tot aan de waterweg aan te houden gelijk aan de waarde overeenkomstig de aanbevelingen uit het TNO rapport betreffende radar[4].

[4] Effecten van windturbines op binnenvaartscheepsradars.
Een voorstel tot een nieuwe nationale regelgeving, TNO 2016 R10617 | 2.0, 16 september 2016

Contents

Abbreviations

Abbreviation	Meaning
AC	Alternating Current
AIS	Automatic Identification System
ASTRON	Netherlands institute for radio astronomy
C2000	Communication 2000, A TETRA based closed network
Cigre	International Council on Large Electric Systems
DAB+	Digital Audio Broadcast
DC	Direct Current
DFIG	Double Fed Induction Generator
EMC	Electro Magnetic Compatibility
EMI	Electro Magnetic Interference
IEC88	TC88: Wind Energy Generation systems
IGBT	Insulated Gate Bipolar Transistor
LOFAR	Low Frequency Array
NEN-EN55011/A1	Industrial, scientific and medical equipment – Radio-frequency disturbance characteristics – Limits and methods of measurement (CISPR11:2015/A1:2016,IDT)
NTIA	National Telecommunications and Information Administration
PWM	Pulse Width Modulation
RDI	Dutch Authority Digital Infra Structure (formerly: Telecom Agency)
RF	Radio Frequency
RFI	Radio Frequency Interference
RWS	*RijksWaterStaat*: executive agency of the Ministry of Infrastructure and Water Management
SINAD	Signal Noise And Distortion
SNR	Signal to Noise Ratio
TETRA	Terrestrial Trunked radio
WTG	Wind Turbine Generator

Introduction

Sustainable energy has become a very important item in politics and society in view of climate change. Moreover, it will help to become less dependent on the import of gas and oil from countries with a dubious reputation. Wind energy plays a major role in the conversion to a carbon free society. By 2030 21 Giga Watt (GW) of energy will be available from wind parks situated in the North Sea. For land based wind parks the prognoses are aimed at 7 GW by 2030[5]

Generation and transformation of electric energy may introduce side effects like high frequency (RF) noise, denoted Electro Magnetic Interference (EMI). These high frequency signals may manifest itself as distinct signals or as wide band noise sometimes covering a large part of the RF spectrum.

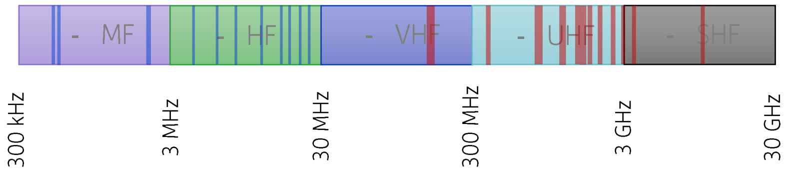


Figure 0.1 Frequency spectrum and designations[6]. The red bars indicates vital wireless infrastructure applications as relevant in for this document.

The European Union has issued the EMC-directive[7] which set limits to the maximum produced field strengths by electric and electronic equipment in the EU. Every electronic device and system purchased in the EU must comply to this directive, this includes wind turbine installations. However, even for systems compliant with the EU EMC directive, the field strength limits referred to by this directive are such, that communication systems operating on VHF through UHF may still be seriously hampered.

The Directorate-General for Public Works and Water Management (RWS) has commissioned TNO to investigate the actual emitted RF-fields and whether they pose a hazard for Marine radio, AIS, TETRA/C2000 and telecom providers to provide their service. All these communication and navigation systems operate in the red shaded area as depicted in Figure 0.1.

[5] Monitor Wind op Land 2019, Monitor Wind op Land 2018 (overheid.nl)
[6] Radio spectrum - Wikipedia
[7] Directive 2014/30/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to electromagnetic compatibility (recast)Text with EEA relevance (europa.eu)

1 Wind turbine technology

This chapter provides a basic introduction on high power wind turbines and associated wind parks. Small turbines for domestic use are briefly dealt with.

1.1 Kinetic to electric energy conversion

The conversion of wind energy to electricity is performed by transforming the kinetic energy from wind into motion of windmill blades which subsequently drive generators (turbines). The generators produce an AC- or DC-voltage at a relative low voltage level: 600 to 1000 V, which is too low for low-loss long distance transport. In case of DC-generators a conversion to AC must be performed first, which needs to be upconverted to minimise transport losses. On-land wind turbines use voltages between 10 kV and 36 kV, depending on the local situation. For offshore wind turbines 33 or 66 kV is used.

In practice wind turbines relying on DC-generators are only used for small scale industrial and domestic use, as they are available only up to a few kW. High power wind turbines use variations of synchronous and asynchronous 3 phase AC-generators.

High power wind turbines employ dedicated control electronics to synchronise the generator to exactly match the 50 Hz from the mains grid. The generator acts like an engine when 3-phase AC is supplied. Such wind turbines are carefully brought up to a blade revolution speed which matches the grid frequency of 50 Hz, after which they are connected to the utility network. The rotor blade pitch is then controlled to increase torque which initiates a swap in function of the turbine from an electrical Engine to power Generator. This type of turbine operates best under a limited range of wind speeds. A disadvantage of this type of synchronous generators is that the energy conversion efficiency drops as the rotor rotation speed has to be kept constant even if the wind speed increases.

Next generation wind turbines employ *Doubly Fed Induction Generators (DFIG)*[8] allowing much higher energy efficiencies at a large range of wind velocities than previous generation synchronous generators. The main change is related to the introduction of a variable rotor speed, up to +/- 30%, while maintaining frequency synchronicity. The details of this technique are explained in various publications and presentations[9]. A relevant aspect of this technique regarding EMI is the use of an AC-DC-AC converter, which is Pulse Width Modulated (PWM) at a frequency of a few kilo Hertz[10]. Earlier generation wind turbines based on synchronous technology did not employ switching technology (except for small scale DC turbines).

The latest generation of wind turbines do a full power conversion, with switch PWM frequencies between 1 and 3 kHz. The same power converter principal applies as for the earlier generation of WTGs: From AC to DC and back to AC. The last conversion exactly matches phase and frequency of the mains network.

[8] Induction Generator 6 - Double-Fed Induction Generator - YouTube
[9] Doubly-fed electric machine - Wikipedia
[10] Frontiers | Short-term frequency regulation of power systems based on DFIG wind generation (frontiersin.org)

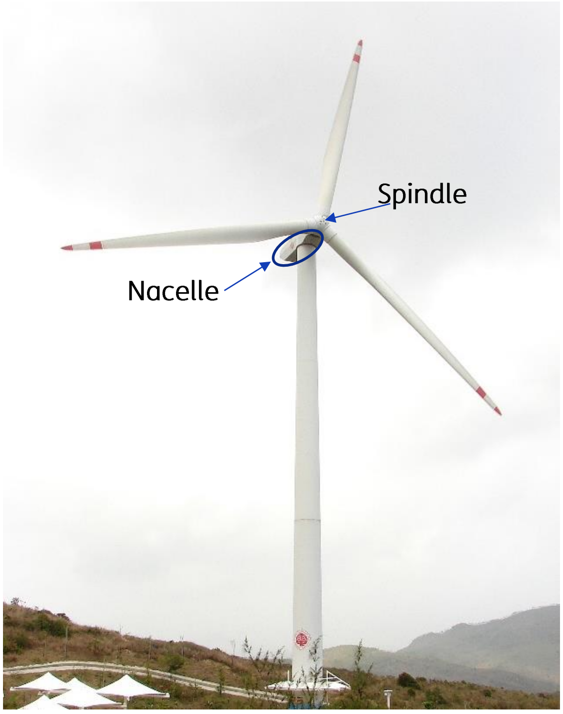


Figure 1.1 Wind turbine generator[11] and location of the nacelle and spindle. The nacelle is regarded as the main source of EMI.

Throughout this report references to the nacelle or spindle relate to the same position and height in the mast of a wind turbine.

1.2 Potential RF-noise sources

In DFIG technology the *rotor* generated electricity is fed directly to the grid, while the energy derived from the stator coils, obtained over 3 sliprings, is fed to an AC-DC-AC converter. This stator energy, is first modulated using PWM in order to provide exactly the same frequency and phase as the grid's and then supplied to it.
The PWM modulation from AC to DC and back to AC is performed using high power IGBT's (Insulated Gate Bipolar Transistors). IGBT-modules are capable of switching hundreds of Amperes at voltages over 1 kV in less than a microsecond[12]. Their maximum switch frequency is limited to some tens of kHz, but that suffices for PWM purposes in the AC-DC-AC converter.

The PWM causes harmonics and sidebands. The low frequency harmonics and sidebands have to comply to regulations in order to connect to the grid, but do not effect VHF communication, hence are out of scope. The higher order harmonics may reach into the VHF and UHF frequency range, hence EMC filters have to be applied at the AC-DC-AC in- and outputs, as well as control circuitry lines[13]. The systems in a nacelle must comply with the EU EN 61000-6-4 industrial standard.

The pitch of rotor blades is controlled using linear engines (hydraulic valves, actuators). The control circuitry is relatively low power, but uses a microprocessor for control, which is a potential source of EMI. Inside the rotor blades a metal conductor is incorporated to deal with

[11] By Patrickmak - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=3916580
[12] Datenblatt / Datasheet FF900R12ME7P_B11 (infineon.com)
[13] Page 13: EMC Compliance for Renewable Resource Power Systems - White Paper (intertek.com)

lightning strikes. Rotor blades are often struck by lightning, but not directly connected to the nacelle. An intended spark gap separates them. This gap reduces unintended antenna effects from inside EMI-sources to reach the outside world. In order to protect the electronics inside the control circuitry against the ingress of spike currents, EMC protection measures are taken which work in two directions, i.e. they also limit RF-noise to reach the outside world. Hence, it is envisioned that rotor blade pitch control potential may theoretically contribute to external EMI, but in practice will have limited impact.

Yaw control is a potential source of EMI due to its control circuitry, but not a likely source for a large contribution, since it is protected against EMC from the outside world (lightning strikes).

Warning lights based on LEDs, are often powered with switch mode power supplies. In some cases these power supplies proved to be a considerable source of EMI. Investing in suitable power supplies and EMI filters may be a simple and easy way to improve on the general EMI footprint of a wind turbine mast. Merely “Compliant with EU EMC-regulations” may not suffice as it only states that the device is not *over* the EMC limit.

Wind turbine masts are often fitted with additional sensor circuitry, like temperature, moisture and other meteorological equipment. Such sensors may be attached to low cost data processing equipment which may be sources of relatively high EMI. Similar as the earlier mentioned power supplies, measures should be taken to improve (i.e.: extra filters, metal enclosures) on their radiating properties more strictly than the EU EMC-regulations ordain.

Equipment which needs to comply to the EMI directives, is in most instances measured without cables attached. The device “as is”, needs to comply to the EU-regulations. In practice devices like temperature sensors will require long stretches of cable in order to transport data and electric power to the sensor outside. These wires act as antennas, hence the importance to properly filter all cabling, especially when fitted to sensors on the outside of a wind turbine mast.

2 Effects of electromagnetic interference on wireless communication

Radio communication in all its forms, relies on the ability to detect, decode and transform radio signals into useful information. Successful decoding depends on the ratio between the signal of interest and the radio frequency (RF) noise which is produced by the ambient environment. This “environment” encompasses the Sun, the Galaxy, lightning and man-made noise (man-made noise consists of all electric fields emanating from electric and electronic equipment, but also sparks from combustion engines). Over the last decades man-made noise has become a significant factor, often overruling the natural rf-noise contributions.
The effects of natural noise sources have been studied and elaborately documented by the International Telecom Union (ITU), amongst others. Clear distinctions could be made in the past between rural, residential and industrial environments. Planning of communication and broadcast networks could rely on the figures provided by the ITU[14]. The advent of sustainable energy has a large contribution changing this theatre in an adverse manner. The high numbers of devices which produce a significant amount of RF-noise (EMI) cause an electromagnetic smog which profoundly affects the communication range of wireless systems. EU “compliant” certificates do not provide a guarantee that this electro smog is reduced, on the contrary.
In this chapter the impact of man-made noise is explained, partially based on an earlier report from TNO written for RWS[15].

2.1 EMC classification and applicable EMI-levels

Electro Magnetic Compatibility encompasses the susceptibility of equipment to external electric fields as well as the RF-emissions. Strictly speaking relates EMC to the *susceptibility* and EMI to the *radiation* aspects of a device. However, the term “EMC” is often used to describe both phenomena’s.
Susceptibility to external electric fields is out of scope of this project, the radiating effects of electrical and electronic equipment is the prime subject.

[14] RECOMMENDATION ITU-R P.372-16 - Radio noise*, page 100

[15] Radio en visuele hinder door zonneparken naast vaarwegen, M.L. van Emmerik, P.C. Hoefsloot, K.P.H.M. van der Sanden, TNO 2022

Groups and classes as denoted in EMC standards EN61000-6-4/A1[16] and CISPR11/EN55011[17]:

- Class A: Industrial and high power applications, not intended for residential use.
  - Group 1: General purpose, not intended RF transmitters.
  - Group 2: ISM RF applications.

- Class B: Residential usage, has lower emission limits than class A.
  - Group 1: General purpose, not intended RF transmitters.
  - Group 2: ISM RF applications.

The emission limits applicable to industrial equipment designated by class A, group 1 and power level are provided in Table 2.1. For wind turbines the measurement distance is set to 30 metres[18], but independent of the power level, the ≤ 20 kVA emission limits seem to be applied by the industry.

Table 2.1 Maximum permitted radiated electric field strength in the EU for industrial and residential equipment, according to CISPR11. Values are scaled to a distance from the object of 30 metres and are applicable for test site ("laboratory) as well as in situ ("at location").

qp = quasi peak p = peak a = average		**Group 1, general purpose (scaled to a distance of 30 m) [dBµV/m]**				
		Class A Industrial				Class B Residential
Frequency range [MHz]	**Bandwidth [kHz]**	**≤ 20 kVA**			**> 20 kVA**	
		average	**quasi peak**	**peak**	**quasi peak**	**quasi peak**
30 – 230	120	**-**	**30**	**-**	**40**	20
230 – 1000	120	**-**	**37**	**-**	**40**	27
		Power level not defined				
		average	**quasi peak**	**peak**		
1000 – 3000	1000	**56**	**-**	**76**		
3000 – 6000	1000	**60**	**-**	**80**		
1000 – 3000	120 *)	**47**	**-**	**76**		
3000 – 6000	120 *)	**51**	**-**	**80**		

*) The measurement bandwidth for frequencies > 1 GHz is 1 MHz. Scaling emission levels to a smaller bandwidth may only applied on average noise.

The classification "Class B, residential" is applicable to other equipment, e.g. for weather related sensors, lighting, etc.

The EMI limit values for frequencies less than 1 GHz are based on Quasi Peak, while for frequencies higher than 1 GHz average or peak is used by the standard.

Electronic noise from devices can be measured in several ways. Ignition noise from combustion engines loses much of its energy at frequencies > 1 GHz, hence such type of pulse noise contributes little to the ambient noise. Computer controlled systems on the other

[16] Electromagnetic compatibility (EMC) - Part 6-4: Generic standards - Emission standard for industrial environments, (IEC 61000-6-4:2006/A1:2010)
[17] EMC Standards | Academy of EMC
[18] EMC IN WIND ENERGY SYSTEMS, WORKING GROUP C4.30, Nov. 2017

hand, use very high clock rates. Due to their very fast processing properties, short transmissions with harmonics into the GHz range may occur. These transmissions will present themselves as semi random repetitive peaks in the frequency spectrum. Such peaks may be harmful if they coincide with a reception band (e.g. 4/5G. Whether peak transmissions (peak noise) will be harmful to providers falls out of scope of this research. Whether peak or average noise levels must be used to evaluate the impact, depends on the actual noise which is emitted by a WTG. For this research both limit values are shown in two graphs for frequencies between 1 and 6 GHz (Figure 3.5 and Figure 3.6).

The value of the average noise more closely resembles "white" noise, if the contribution of peak noise is very low.
Quasi peak takes into account the repetition rate and duty cycle of peak noise. Depending on the occurrence rate of peak noise, it is a mix between average and peak noise.

Wind turbine generators generally produce electric power levels considerably in excess of 20 kVA and most modern turbines are in the range of 1 MW or more. Working group C4.30 has set the EMI-levels of wind turbines, measured at 30 metres, to a level as associated with ≤ 20 kVA. See Table 2.2. To date there is no product standard for wind turbines (see consultation with RDI, paragraph 4.8).

Table 2.2 Electric field strength limits for Wind Turbine Generators at 30 metres distance, according to the association[19]

Frequency range	Magnetic field (quasi-peak)
150 kHz – 490 kHz	13,5 dB(µA/m)
490 kHz – 3,95 MHz	3,5 dB(µA/m)
3,95 MHz – 20 MHz	-11,5 (µA/m)
20 MHz – 30 MHz)	-21,5 dB(µA/m)
	Electric field (quasi-peak)
30 MHz – 230 MHz	30 dB(µV/m)
230 MHz – 1 GHz	37 dB(µV/m)

For high power industrial equipment running at power levels of more than 20 kVA, an EMI-level of 50 dBµV/m @ 10 metres (which equals 40 dBµV/m @ 30 metres) is set as limit by the applicable EMC standards over a frequency range from 30 to 1000 MHz. The EMI-levels depicted in Table 2.2 proclaim a value which is 10 dB less in the marine radio band and 3 dB less for systems operating at frequencies higher than 230 MHz (e.g.: C2000*). If the EMI from Wind Turbines indeed complies to these levels, the risk for harmful interference to marine radio applications is significantly reduced.*

[19] EMC IN WIND ENERGY SYSTEMS, WORKING GROUP, C4.30, Nov. 2017, Table 5.3

2.2 Radio communication and navigation coverage

Marine radio and navigation network planning is based on the radio installations on both sides of the communication channel, also called a “radio link”. In particular the antennas and transceivers aboard vessels and the base station equipment and its antenna facilities play a prominent role. Added to this are environmental aspects like terrain and man-made noise. Regarding the ambient RF-noise levels that are relevant for marine applications, the terrain can often be qualified as “rural” and sometimes “urban” or even “industrial”. The latter mainly applies for main port environments. In a main port location one expects high RFI-levels due to the high numbers of cranes, lorries and small scale processing industry. Radio coverage and AIS navigation range is anticipated to be short in those situations, but is dealt with accordingly when setting up a base station.

In rural and suburban marine environments one expects low ambient noise levels, according to the ITU recommendations[20] and NTIA[21], as illustrated in Figure 2.1. The vertical scale denotes the logarithmic strength of the ambient radio noise relative to a virtual noise temperature of 290 Kelvin, which is set as “0 dB”. The region of interest for RWS starts at 154 MHz (marine radio) up to 3500 MHz for 5G applications.

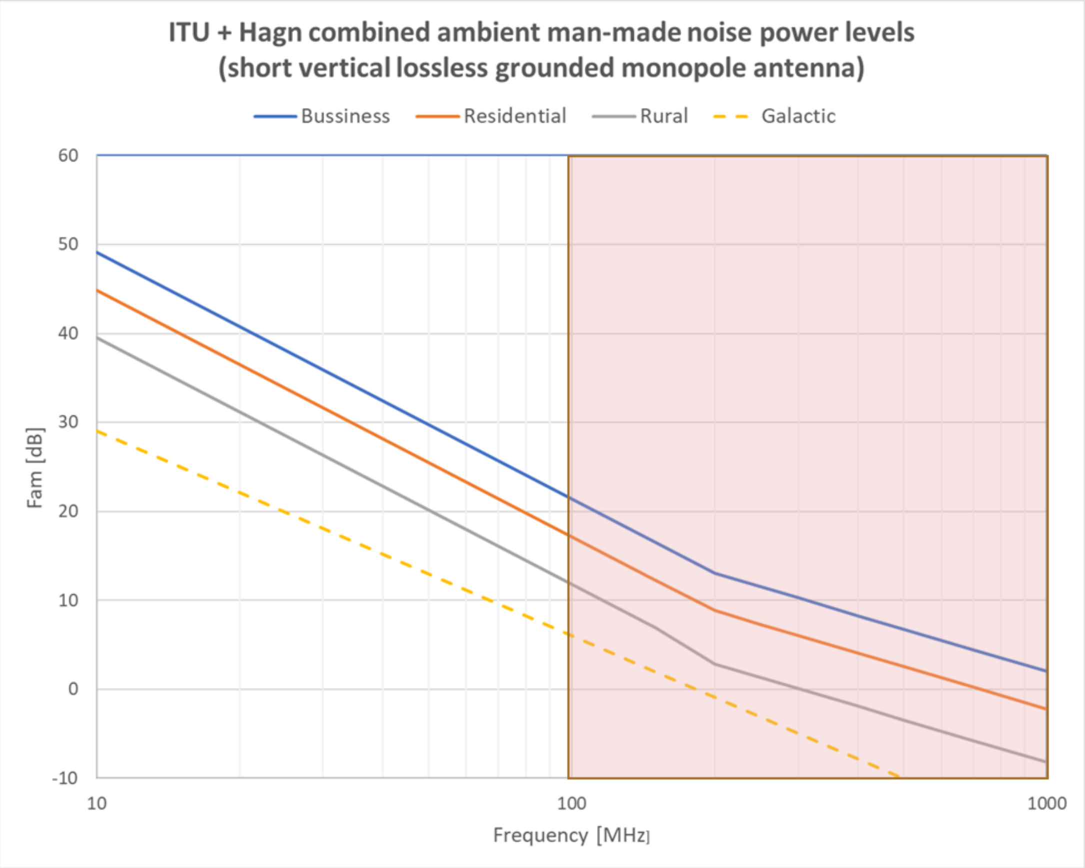


Figure 2.1 Ambient noise between 10 and 1000 MHz, combining ITU and NTIA (G.H Hagn).

[20] RECOMMENDATION ITU-R P.372-16 - Radio noise*
[21] NTIA Technical Report TR-11-478, Wideband Man-Made Radio Noise, Measurements in the VHF and Low UHF Bands, Jeffery A. Wepman, Geoffrey A. Sanders

The ITU provides one additional curve which represents quiet rural, a situation of complete absence of man-made noise (quiet rural). Figure 2.2 shows the ambient noise levels (rural and quiet rural) versus an extension of the frequency range up to 10 GHz. At frequencies over 1 GHz the assumption is that electric and electronic equipment contributes very little to raise the natural ambient background noise level, hence both lines merge.

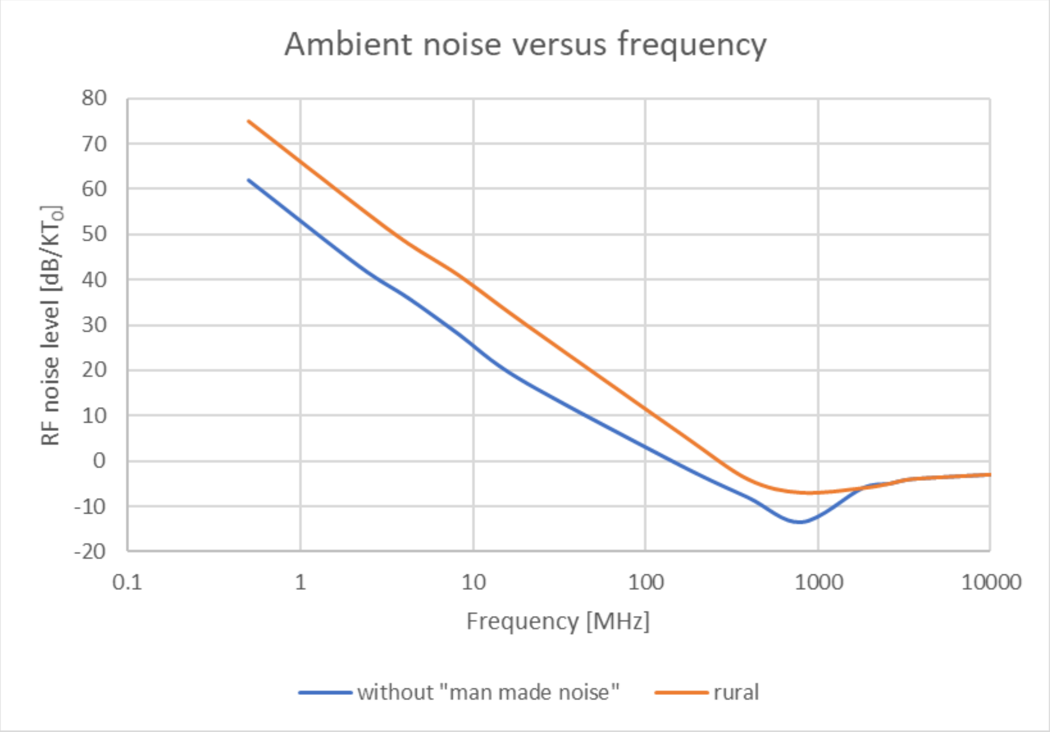


Figure 2.2 Ambient background noise in the absence of man-made noise (“quiet rural”) compared with “rural” (see Figure 2.1).

Locations not polluted by man-made noise (as represented by the blue line) have become virtually non-existent, except for remote places with very little human activity. The orange line resembles a situation with little additional man-made noise contribution. This slightly enhanced man-made noise situation (rural), is used in this document as a reference to calculate the impact of new RF-noise sources in the environment.

Calculations and assumptions regarding the background noise can be found in Appendix A.

3 Acceptable distances between wind turbines and receive installations

In this chapter wind turbines will be treated as RF-noise sources, either with a known emission level, or assuming that they exactly fit the maximum applicable emission level as dictated by the standards.
Based on an acceptable SNR decrease of a receive system by 3 dB, the separation distances between a wind source (wind turbine) and target (receiver) will be calculated and provided as curves.

3.1 Electromagnetic interference and impact on reception quality

The communication range of a radio link, whether it is marine radio, C2000, DAB+ or 4/5G, is specified by a defined minimum system signal-to-noise ratio (SNR) at its antenna. When the RF-noise at a receive antenna increases, the SNR will *decrease*, hence the reception quality (audio and data) will deteriorate. In ruling communication and navigation standards specific RF SNR values are agreed upon for which a system will perform according to its designation.

Raising the ambient noise by 3 dB does not imply that the receiver SNR decreases by the same amount. That depends on the receiver properties, i.e. the system noise floor. The more sensitive a receiver is, the more susceptible it will be to a rise of the ambient noise level. A sensitive receiver also has a larger reception range than an insensitive one.
Based on the required sensitivities, as specified by the appropriate system standards, the ambient noise is increased which results in a system (=receiver) SNR decrease of 3 dB. The associated field strength for this 3 dB decrease in RF SNR, is used to calculate the required separation distance between wind turbines and marine reception locations.

A 3 dB decrease in SNR at a receiver is a well-defined and measurable quantity. Such loss of quality will have a small impact at the fringes of the coverage area. For marine grade equipment a 3 dB loss of system SNR should be just acceptable[22]. However, any loss of sensitivity of a marine radio may pose a risk when emergency situations arise, as these may be accompanied by transmitter and antenna failures, e.g. if a vessel is in distress.

One should strive to limit the loss of system SNR to a value less than 3 dB.

All subsequent calculations in this document are based on a 3 dB system SNR decrease of targeted receivers, due to the rise of the ambient noise caused by man-made noise-sources.

[22] Radio en visuele hinder door zonneparken naast vaarwegen, paragraph 5.1.4, , M.L. van Emmerik, P.C. Hoefsloot, K.P.H.M. van der Sanden

Figure 3.1 describes the methodology of setting the acceptable level of interference for an external noise source. A rise of the *system noise* of 3 dB occurs when the external source has the same noise power as the system noise floor of the receiver (the noise floor of a receiver is comprised of all the contributing elements in the receiver chain, which can be translated to an equivalent noise floor at the antenna. This equivalent noise floor determines the basic receiver sensitivity).

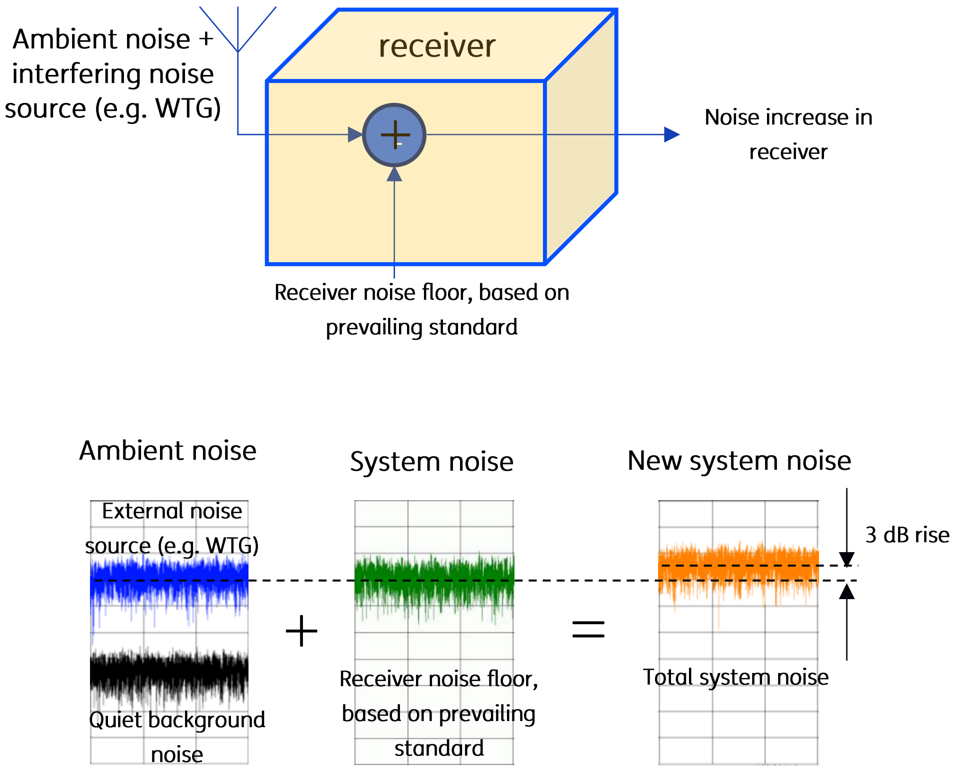
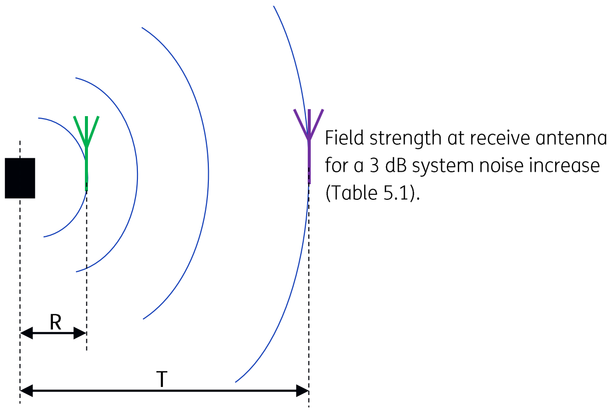


Figure 3.1 Ambient noise (quiet background + additional noise from an interfering source), and impact on a receive system with its sensitivity based on prevailing standard. In orange the 3 dB rise of the new system noise due to the interfering noise source is shown.

For an RF-noise source which may be treated as a single point, the impact on a receive installation is defined by:

- height of the RF-noise source;
- field strength of the RF-noise source at a specified distance (EMI-level);
- distance between RF-noise source and receive antenna;
- height of the receive antenna;
- physical obstacles;
- RF-properties of the receiver;
- required minimal sensitivity level of the system as defined by the applicable standard.



R = Reference measurement distance of 30 metres at which the EMI-levels are determined (table 2.1).

T = Separation distance between source and target for a 3 dB system noise increase

Figure 3.2 Reference measurement distance (30 metres) and targeted receive antenna. R and T are ratio's which are based on the maximum allowed field strength levels in Table 3.1 and the emissions at reference distance R.

Based on a 3 dB system noise increase, calculations have been performed which provide the interfering field strength levels for several communication systems (Table 3.1). The sensitivity levels (noise floor of the applicable receivers according to their standards) have been taken into account for each system.

Table 3.1 Interfering field strength levels which cause an increase of the receiver total system-noise by 3 dB.[23] BS = Base Station equipment, MS = Mobile Station equipment

Type of system		**Reception system noise temperature [K]**[24]	**Field strength level at reception antenna [dBµV/m]*) For 3 dB system-noise increase**
Marifoon/AIS (VDES)		4800	**11,1**
C2000[25]	BS / MS	578 / 1154	**9,6 / 12,2**
GNSS[26]		170	**17,1**
IMT2020:[27,28]			
800 MHz	BS / MS	81 / 222	**9,8 / 12,4**
900 MHz	BS / MS	81 / 222	**10,9 / 13,4**
1500 MHz	BS / MS	81 / 222	**15,3 / 17,9**
1800 MHz	BS / MS	81 / 222	**16,9 / 19,6**
2100 MHz	BS / MS	81 / 222	**18,2 / 20,8**
2600 MHz	BS / MS	81 / 222	**20,1 / 22,7**
3500 MHz	BS / MS	81 / 222	**22,7 / 25,2**

*) To date neither CISPR11 nor CISPR22 have released EMI limit levels for > 1 GHz. EN61000 6-4/A1 provides average and peak value emission limits for the frequency range between 1 and 6 GHz.

[23] Radio en visuele hinder door zonneparken naast vaarwegen, page 45, M.L. van Emmerik, P.C. Hoefsloot, K.P.H.M. van der Sanden, TNO 2022

[24] Gebaseerd op de vigerende applicatie standaarden.

[25] ETSI TS 100 392-2 V3.9.2 (2020-06), Terrestrial Trunked Radio (TETRA); Voice plus Data (V+D); Part 2: Air Interface (AI), par. 6.6.2.4

[26] Gebaseerd op diverse commerciële producten zijn de ruisgetallen << 2 dB

[27] ETSI 3GPP TS 36.101 V16.5.0 (2020-03), 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (Release 16), par. 7.3.

[28] ETSI TS 136 104 V15.3.0 (2018-07), LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception (3GPP TS 36.104 version 15.3.0 Release 15).

3.2 Separation distances between an EMI-source and receiver

Communication systems require a certain SNR at the antenna for which they will perform according to their purpose. Coverage and detection ranges are based on these SNR values. For a noise source that causes a system SNR decrease of 3 dB (see paragraph 3.1) an equivalent field strength can be calculated, which in turn will translate to a minimum distance between noise source and receive antenna.
The signal loss between the RF-noise source and the target is controlled by the way radio signals travel. Even when there is a clear direct sight (which is obviously often the case when it concerns wind turbines) radio waves will propagate both in a straight line and via a second reflection path via the surface to end up at the target antenna (two-ray reflection path). Specific rules determine whether a free space scenario or 2-ray propagation has to be applied. In these particular simulations however, the cross over point turned out to be outside the range of wind turbines. Hence, only the free space loss model was used.
In the next paragraph separation distances will be calculated, including the effects of multiple turbines, as encountered in wind farms.

3.2.1 Single wind turbine separation distances for fixed limit EMI-levels

The calculations presented in this paragraph show the distance at which wind turbines have to be placed from a receiver (base station) when the actual EMI-level of the individual wind turbine is unknown or cannot be provided by the manufacturer. In those situations the maximum EMC-limits should be used as referred to by EU-legislation (CISPR11 and IEC61000-6-4)[29]. However, based on the findings in paragraph 2.1 (Table 2.2) and interviews (chapter 4) the lower EMI-level applicable for ≤ 20 kVA industrial will be used.
For frequencies between 1 and 6 GHz the approach will be slightly different as no quasi peak limit values are available, but only “average” and “peak”. Hence for two separate graphs are presented.

Calculations have been performed for various heights of the reception antenna and the wind turbines. For the latter it is assumed that the noise source resides in the nacelle, i.e. in the top of the mast were the spindle is connected to the rotor blades. In practice the power converters may be installed at ground level as well, but for distances of more than a few hundred metres the nacelle situation is a worst case scenario.

For fixed emission levels of 30 and 37 dBµV/m (30-230 and 230 – 1000 MHz respectively) and antenna heights ranging between 2 to 30 metres, and nacelle heights of 30 and 100 metres, the effects on the required separation distance is marginal. Only for very low receive antenna heights (≈ 2 m) a significant change occurs, which is due to multipath effects which start to become important.

3.2.1.1 Separation distances for systems operating below 1000 MHz, based on fixed EMI-levels

For applications operating on frequencies between 30 and 1000 MHz, separation distances are provided in Figure 3.3 and Figure 3.4 based on a *single* wind turbine generator (EMI

[29] IEC-61000-6-4 2007 A1 2011

source). Due to the heights of the nacelle and the target receive antenna, there's little effect from the individual height changes. Only at very low heights of the target antenna the so called 2-ray propagation takes effect. For all other heights the free space propagation model suffices.

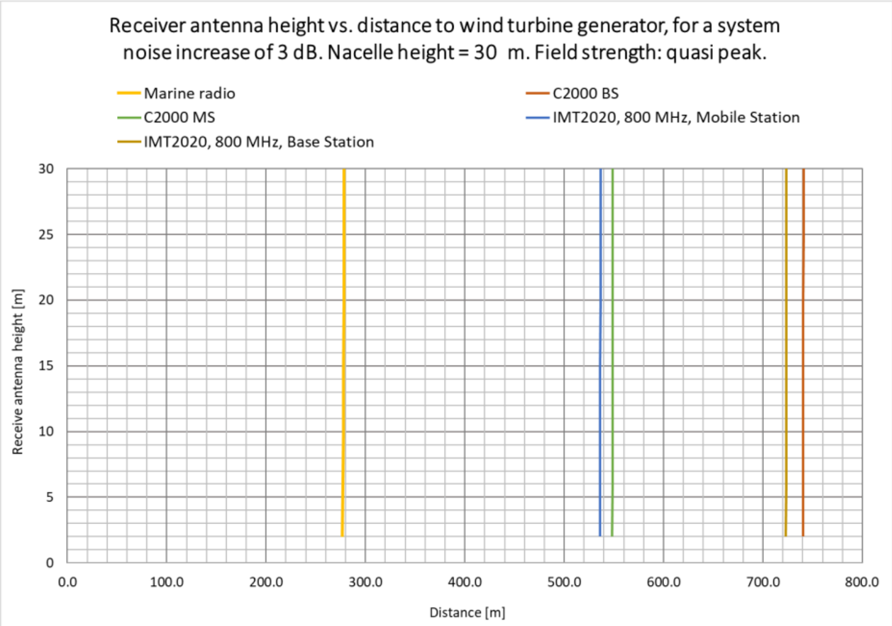


Figure 3.3 Separation distances versus applications and antenna height for a 3 dB increase of the system noise given EMI-levels of 30 dBµV/m (referred to 30 metres and < 230 MHz, i.e. marine radio) and 37 dBµV/m (referred to 30 metres, 230 – 1000 MHz). Nacelle height = 30 metres.

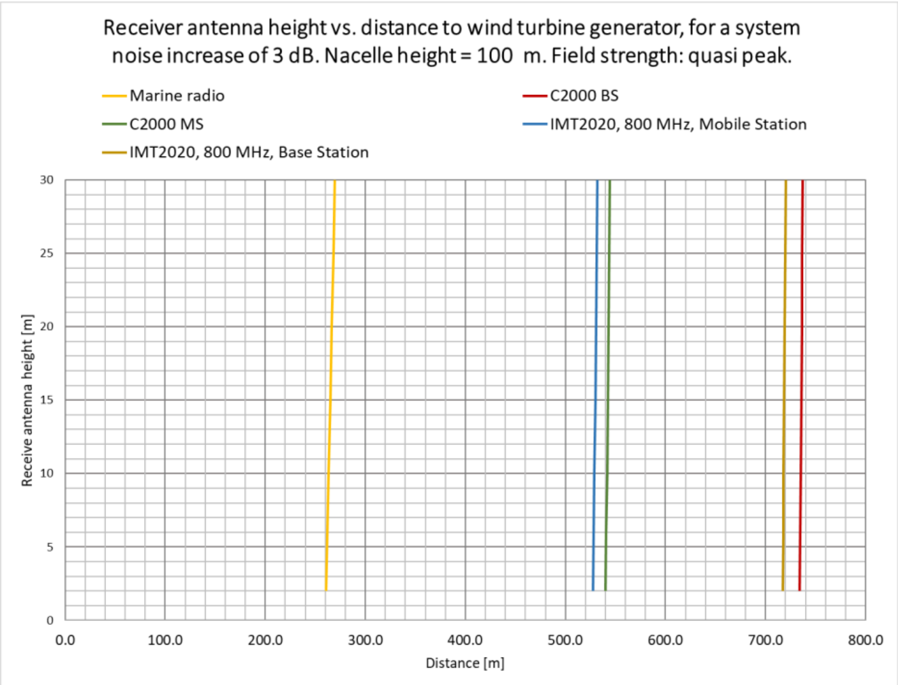


Figure 3.4 Separation distances versus applications and antenna height for a 3 dB increase of the system noise given EMI-levels of 30 dBµV/m (< 230 MHz, i.e. marine radio) and 37 dBµV/m (230 – 1000 MHz). Nacelle height = 100 metres.

Figure 3.3 and Figure 3.4 show little change in the required separation distances, with very little dependency on the antenna and nacelle heights. Hence the decision was made to use a fixed nacelle height of 75 metres and receive antenna height of 15 metres, for all EMI versus distance calculations in paragraph 3.2.2.

3.2.1.2 Fixed EMI separation distances for systems operating between 1 and 6 GHz

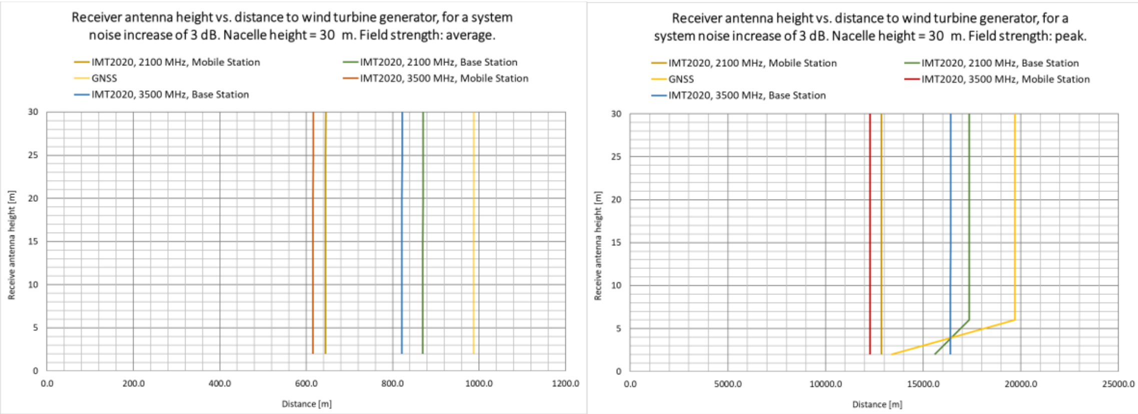


Figure 3.5 Average- and peak EMI-values, versus receive antenna height. Nacelle height = 30 metres

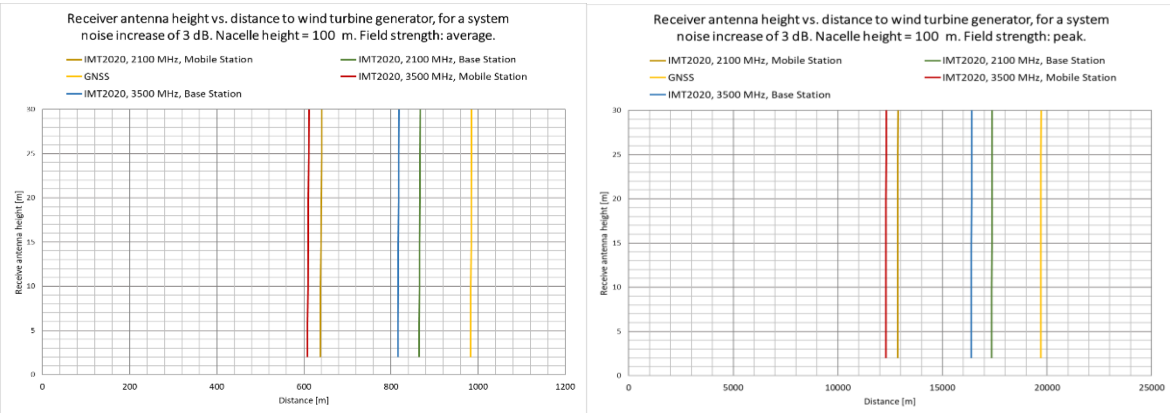


Figure 3.6 Average- and peak EMI-values, versus receive antenna height. Nacelle height = 100 metres

Similar to the calculations performed in the prior paragraph, the height of the nacelle and receive antenna have a minor effect on the required separation distances given a specific EMI-level.
For peak noise, neither the repetition ratio nor duration of the peak noise are specified as this is not “ignition noise”, but considered man-made. Sources may be computer clocks and peripheral equipment which carry out specific tasks. Hence, the peak noise is considered to be constant over a certain period of time, resulting in a decrease of receiver performance. In practice the situation may be more benign. Depending on the application there may be correction algorithms which correct for errors (e.g.: Forward Error Correction) and may completely eradicate pulse noise. If that is the case, only the average levels apply.

For instances where specific data regarding the emitted peak noise cannot be provided by manufacturers, it would be safe to utilize the peak curves, although this will result in long separation distances.

It is in the interest of the manufacturer to provide the peak and average EMI-values, as it may result in smaller separation distances between WTGs and receive locations.

3.2.2 Separation distances versus EMI-level

In many situations it is conceivable that a manufacturer is able to provide more details about the actual EMI-level which is generated by the complete wind turbine system (i.e.: including air traffic lights, etc). In those cases the actual values can be used to estimate a separation distance for which the system SNR of the targeted receiver is decreased by ≤ 3 dB.

For a range of field strength levels the minimum required separation distances are calculated. The heights of source and target are in theory variables which will influence the result. However, the calculations showed remarkable little differences in the outcome when source (nacelle) and target (receive antenna) heights were changed within a specific range. Hence, only calculations based on a nacelle height of 75 metres and reception antenna height of 15 metres are presented. The values can be applied for nacelle heights ranging between 30 and 100 metres and receive antenna heights from 10 to 30 metres (Figure 3.8). It is assumed that there are *no physical obstacles* between source and target.

In the Netherlands there is no legislation which sets a minimum physical separation distance between a wind turbine generator and domestic environments. In some west European countries a minimum separation distance of 4 to 10 x the tip height of a wind turbine generator is ordained and in some countries even larger minimum separations distances are ordained[30].

[30] Minimumafstand tussen windturbine(s) en woningen? - NWEA

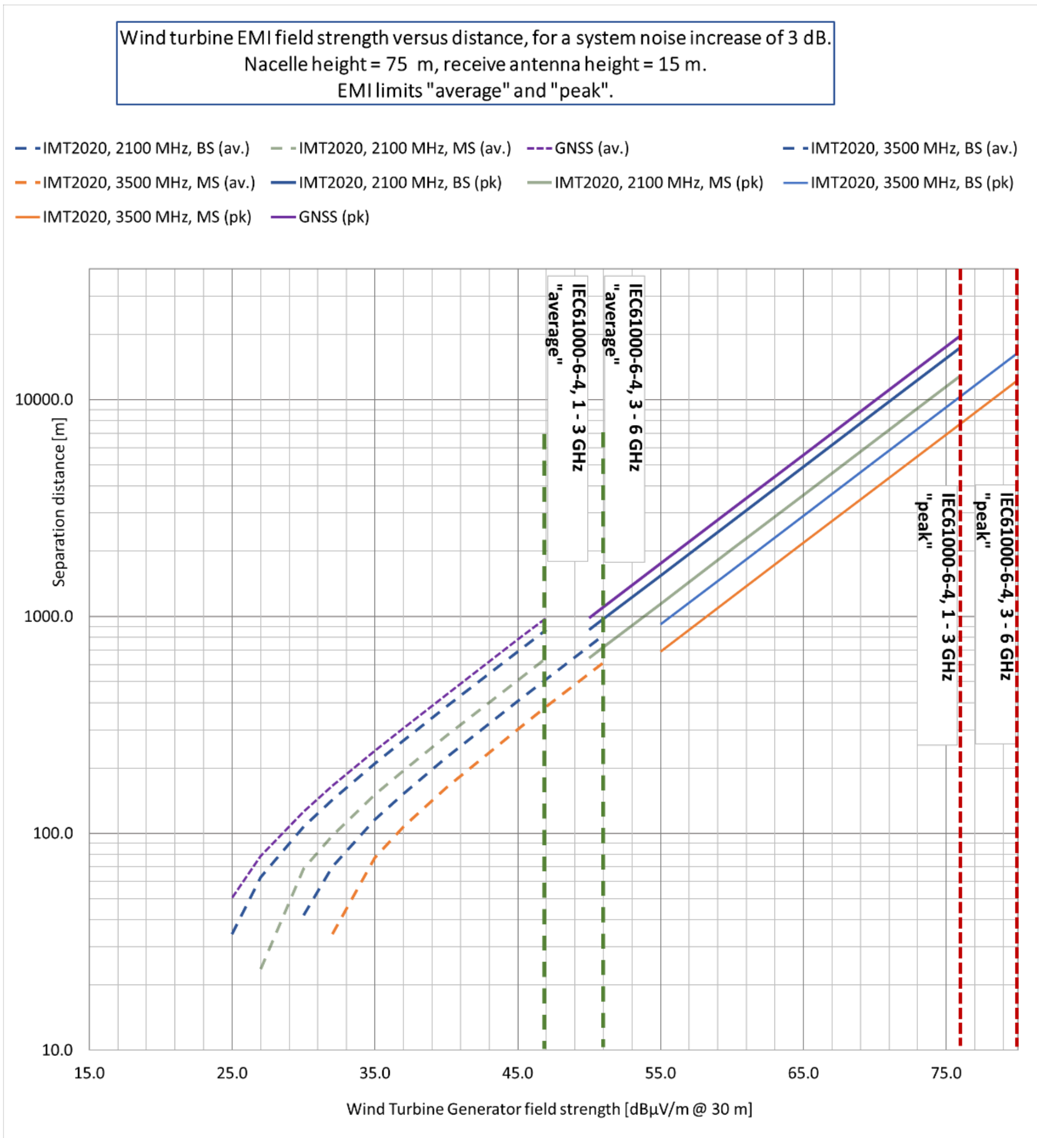


Figure 3.7 Minimum separation distances versus “average” (dashed lines) and “peak” (solid lines) field strength levels, for frequencies between 1 - 3 and 3 - 6 GHz.

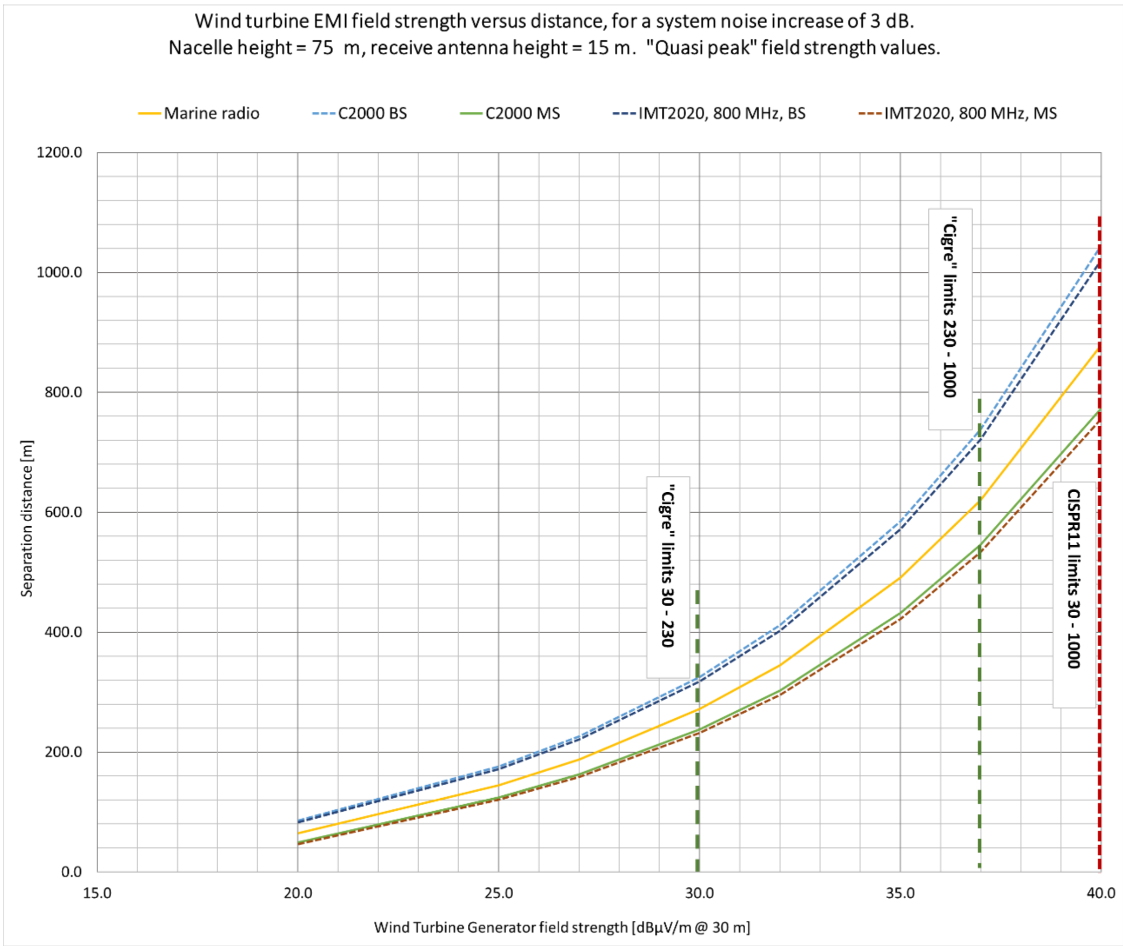


Figure 3.8 Separation distance versus emitted field strength The field strength emission levels are shown for a *single* turbine.

For very low emission levels (< 20 dBµV/m), which would result in very short separation distances (≈100 metres), the height effects of the receive antenna and the interfering nacelle become significant, and have consequences for the separation distances by roughly +/- 10%.

Marine radio and AIS require a minimum separation distance of 275 metres, based on the self-imposed EMI-level limits of 30 dBµV/m.

C2000 and IMT2020, 800 MHz base stations are the most vulnerable to RF-noise increases, followed at short distance by marine radio. For a *single EMI-source*, providing a field strength level of 37 dBµV/m (frequency > 230 MHz), a safe separation distance of 720 metres is required in order to safeguarding all communication systems.

Providing the actual measured EMI-levels of wind turbine generators by manufacturers may offer a great advantage for wind park owners. For example, if it can be guaranteed that the EMI field strength level also for frequencies > 230 MHz is equal or less than 30 dBµV/m instead of 37 dBµV/m, the minimum separation distance to a receive location may be reduced to 320 metres.

As the minimum separation distances depend on:

- Type of communication system,
- frequency,
- EMI-level produced by the wind turbines,

the obvious way to minimize separation limitations to be impose is to decrease the EMI-level of the wind turbine generators or to provide actual measurement data. Otherwise default EMI-levels for wind turbine generators should be enforced to calculate the separation distances.

3.2.3 Multiple wind turbines as EMI-sources

A windfarm is composed of tens or even hundreds of wind turbines. The contributing RF-noise effect of an individual turbine quickly fades with increasing distance, but in case of a windfarm the cumulative effects can become significant.
There is no generic rule, as there are several topologies, depending on local circumstances. However, there are certain grid lay-outs which are often followed, these have been used to provide estimates of the cumulation of the field strength of wind farms consisting of 1, 3 and 19 WTGs.

There are many articles to be found on the internet regarding the optimum grid point between wind turbines. They focus on optimum energy production, but also on the effects of wind turbulences and the associated audible noise. The present rulings often suggest implementations which use a distance of 7 times the rotor diameter for the prevailing wind direction, and 5 times the rotor diameter abreast. Larger grid point distances[31] will increase the individual yield of turbines, but diminish the yield per square kilometre.

Calculations have been performed based on the following conditions:

1. A wind turbine grid based on widths of 7 by 5 rotor diameters;
2. Based on new research which advocates 15 by 8 rotor diameter grid point distances;
3. Simulation frequencies of 160 and 390 MHz;
4. Receive antenna height: 15 metres;
5. Wind turbine nacelle (spindle) height: 75 metres;
6. Number of wind turbines: 1, 3 and 19.

Result: an increase of the EMI, due to cumulative effects, which is translated to a new separation distance compared to the single wind turbine situation. Three different scenarios, as denoted in the list under point 6, are shown in the subsequent pictures.
Note: other layouts may provide higher or lower cumulative effects.

[31] Mitchell-Wind-Turbine-Separation-Distances.pdf (na-paw.org)

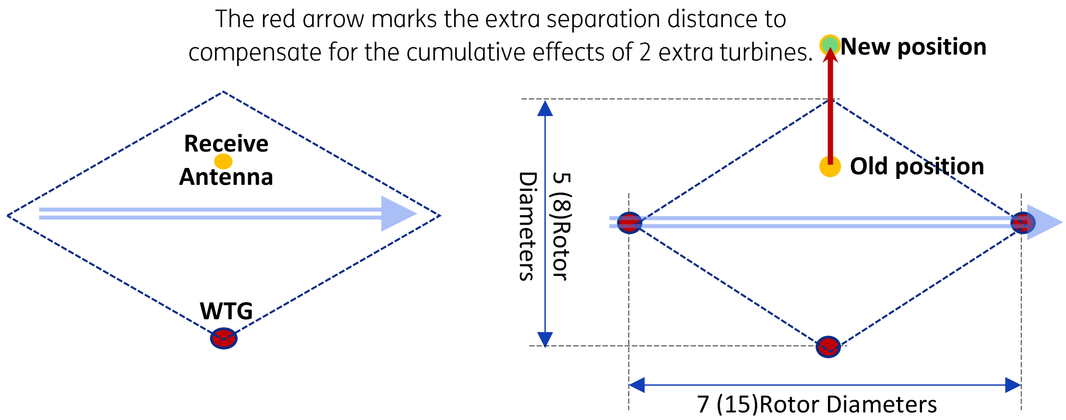


Figure 3.9 Left: Single reference WTG at 2.5 or 4 rotor diameter distance. Right: a configuration with 3 turbines and showing the 7 by 5 or 15 by 8 rotor diameter ratios. The yellow dots envisions the receive antenna, the red dots the sources of EMI (WTGs). The light blue arrow shows the trending wind direction.

The scenario with 3 turbines is a worst-case compared to 1 EMI source, in terms of relative noise increase. The noise of each turbine adds up nearly equally, given the small differences in separation distances between the three WTGs and the receive antenna.

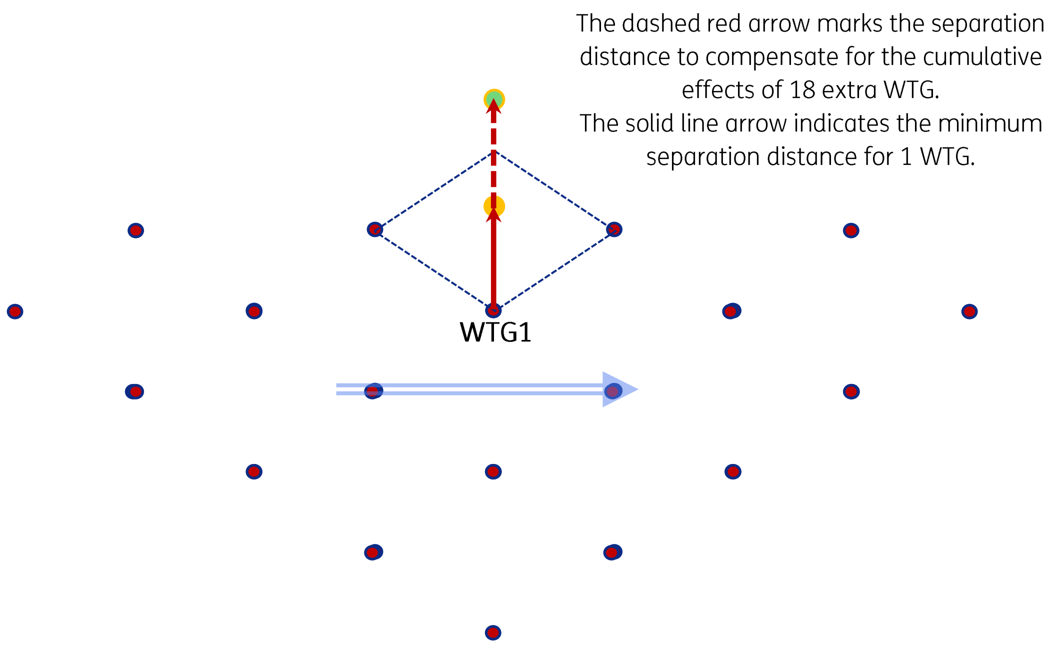


Figure 3.10 Nineteen wind turbine generators in a hexagon layout, measuring 5 x 7 or 8 x 15 rotor diameters. The yellow dot envisions the target receive antenna, the red dots the 19 potential EMI sources. The light blue arrow shows the trending wind direction.

The layout examples in the previous figures, are “worst case”, i.e. the base line separations between the wind turbines has been set to either 5 or 8 rotor diameters, instead of 7 or 15.

The cumulative EMI-effects have been calculated and are shown for two specific EMI situations. In Table 3.2 the separation distances have been calculated assuming that the self-imposed limits are applicable, and no (lower) actual values can be provided by the manufacturers. This is likely a “worst case” scenario. In such situation a wind farm with 19 wind turbines or more, should obey a minimum distance towards a base station with C2000 of more than 2.5 km! This is due to the lower sensitivity levels to EMI for the C2000 receive system and the higher emission levels which are applicable between 230 and 1000 MHz. But even when only marine radio systems will be employed, a separation distance of 910 metres may be required. This situation changes considerably when the EMI-levels of the wind turbines are deceased to 25 dBµV/ (@ 30 metres), as is shown in Table 3.3.

Table 3.2 Simulation scenario results for wind farms consisting of 3 and 19 turbines, compared to a single turbine marked as WTG 1 in Figure 3.10. The nacelle height is 75 metres, receive antenna is situated at 15 metres height. The “required distance” is for all circumstances with respect to WTG 1.

EMI field strength of each WTG is compliant to self-imposed limits 30-230 MHz: 30 dBµV/m, 230-1000 MHz: 37 dBµV/m (field strengths referenced to 30 m)			
Number of WTGs	WTG separation ratio (w.r.t. rotor blade diameter)	Marine applications at 160 MHz Distance to WTG1 [m]	C2000 BS applications at 390 MHz Distance to WTG1 [m]
1		275	700
3	7 x 5	530	1340
19	7 x 5	910	2860
3	15 x 8	326	1026
19	15 x 8	556	2566

An EMI-level of 25 dBµV/m @ 30 metres is not an unrealistic value, as much lower levels of EMI have been accomplished in “*Drentse Monden en Oostermoer*” (see paragraph 4.3.1).

Table 3.3 Simulation results denoting the required separation distance between wind farms and a base station, for an individual EMI-level of the WTGs of 25 dBµV/m. The scenarios are similar to what is used in Table 3.2.

EMI field strength of each WTG is compliant to self-imposed limits 30-1000 MHz: 25 dBµV/m (field strengths referenced to 30 m)			
Number of WTGs	WTG separation ratio (w.r.t. rotor blade diameter)	Marine applications at 160 MHz Distance to WTG1 [m]	C2000 BS applications at 390 MHz Distance to WTG1 [m]
1		137	166
3	7 x 5	205	290
19	7 x 5	370	500
3	15 x 8	146	181
19	15 x 8	176	226

3.2.4 Coverage area and interference regions along waterways

Every wireless network has a certain coverage range. Some networks are limited by interference and capacity, like for example 4/5G, others by the system and ambient noise levels

at their receive locations. Interference limited networks may still be compromised by high ambient noise levels, especially in remote and desolate areas where few or no competitive (interfering) networks are operating.
For marine communications the main restrictions are system sensitivity and ambient noise, i.e.: they are Noise Limited. Especially at the fringes and centre of a designated coverage range, the susceptibility to noise increases. A radio link will be compromised as the ambient noise increases at the base station, while in contact with a communication partner at the far end of the coverage area. The same is true for the partnering vessel at the fringes of the coverage area which will receive a low signal level from the base station due to the distance. This makes it vulnerable to SNR decreases if the ambient RF-noise would rise. Figure 3.11 shows the relative separation distances which have to be maintained along a simulated waterway in order to prevent harmful degradation of the reception..
The middle part of the coverage range is *less* susceptible to interference from RF-noise sources as the signal levels from the base station will still be high. Based on earlier recommendations[32] regarding radar, a minimum distance between a wind turbine and waterway of approximately 100 metres is advised.

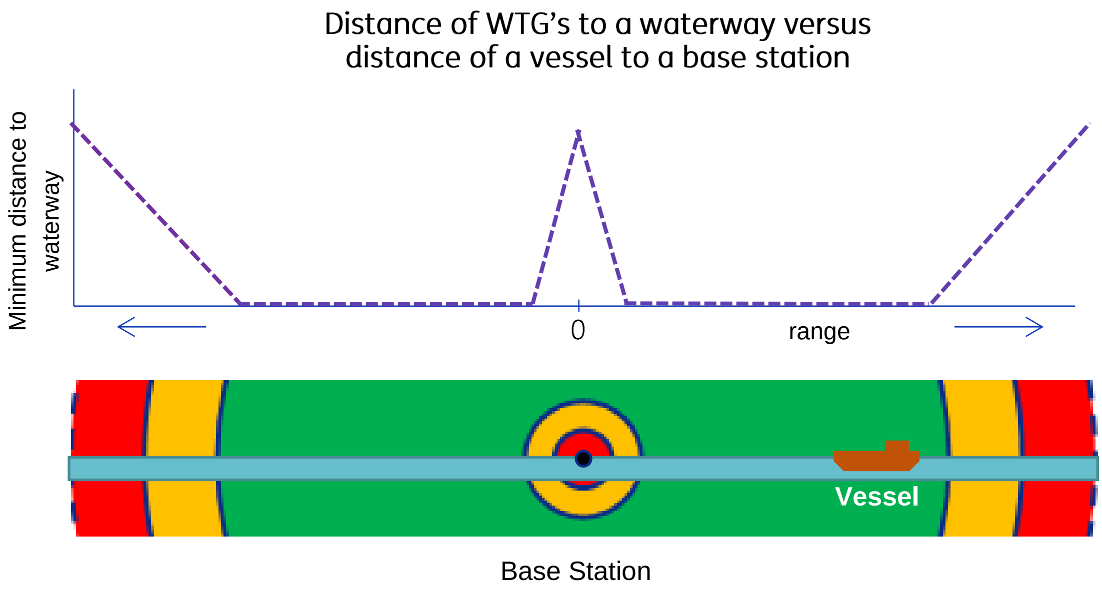


Figure 3.11 Simplified coverage range (not to scale!) along a waterway with a base station located in the middle. The yellow and red coloured regions indicate areas were potentially low SNRs may occur. The dashed purple line resembles the distance from potential RF-noise sources to a “victim” (base station and waterway).

In paragraph 0 and 3.2.2, graphs with separation distances are presented which provide an interference protection distance against EMI for the base station location. A similar scenario can be postulated for the final stretch of the coverage area. Contrary to the base station situation, this involves a certain *percentage* of the coverage range. For example, for a 30 dBµV/m emission level (@ 30 metres) of a single turbine with a nacelle height of 75 metres while employing marine radios, approximately the last 35% of the coverage range requires an increase in separation distance between the waterway and wind turbines in order to provide

[32] Effecten van windturbines op binnenvaartscheepsradars.
Een voorstel tot een nieuwe nationale regelgeving, TNO 2016 R10617 | 2.0, 16 september 2016

sufficient protection against interference. The maximum required separation distance is the same as for the base station situation.

3.3 EMC directive 2014/30/EU and its implications

The EU EMC Directive[33] (EMCD) refers to EMC-standards like CISPR11, which ordain the maximum RF-emission levels of electronic equipment. The maximum permissible emission levels depend on frequency and power ratings and apply to domestic as well as industrial devices and systems. For many years these field strength levels have been interpreted as the "ruling limits" when interference with radio reception arose. However, the same EMCD provides an "Essential requirements" (annex I), which states that:

"1. General requirements Equipment shall be so designed and manufactured, having regard to the state of the art, as to ensure that:
(a) the electromagnetic disturbance generated does not exceed the level above which radio and telecommunications equipment or other equipment cannot operate as intended;"

Strictly speaking, this statement provides a safeguard against negative EMI-effects from electronic equipment which might effect a wireless system beyond a certain quality level ("operating as intended"). It does not state that the maximum EMI-level of electronic devices is *always* to be permitted under *all* circumstances.

On March 28th 2022 a Dutch court decision[34] ruled in favour of the "Essential requirements". This court decision ruled that the manufacturer of the devices was responsible to solve the interference issue in order to make the affected communication system operate again "as intended".

Despite the court ruling, it is advised to initially ordain separation distances between a receive location and WTGs based on the applicable EMI-limits for WTGs set by the standard ("Cigre EMI-levels"). In order to give consent for a shorter separation distance a WTG manufacturer should clearly prove, prior to the installation, that the radiated EMI-levels are less than set by the applicable standard.

Based on specific EMI-levels (as might be provided by manufacturers) and non-specified EMI-levels (i.e.: EMI-levels as provided by CISPR11 and Cigre EMC limits) separation distances have been calculated in this report.

[33] Directive 2014/30/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to electromagnetic compatibility (recast)Text with EEA relevance (europa.eu).
[34] ECLI:NL:RBROT:2022:2205, Rechtbank Rotterdam, ROT 22/725 (rechtspraak.nl)

4 Literature research and interview based observations on the EMI aspects of wind turbines

This chapter contains the findings from literature and interviews with organisations which are either operators in the wind turbine market, supervisors or research institutes. The interviews reflect personal observations. Where applicable, field strength values have been changed to a base measurement distance of 30 metres for better comparison.

4.1 Interview with Ørsted

Ørsted is a renewable energy company with wind farms all across the north sea.
Participants:

- Ørsted: Mr. K. Torp Hansen (Consultant radio communication)
- TNO: O. J. van Gent, P. C. Hoefsloot

Question:
"Do you have observations were EMI was noticed due to (operating) wind turbine generators, which had a negative influence on marine or Tetra communication in the marine environment?"

Answer:
"I am not aware of any issues regarding reception of marine radio and TETRA which could be linked to EMI emanating from wind turbines in the marine environment."

Observation by Mr. K. Torp Hansen:
All new generation generators employ AC-DC-AC inverters which are installed in the nacelles. Often direct drive generators, i.e. without gear boxes are employed, which are becoming the new trend as it reduces maintenance and failure.
The converters incorporate high power IGBT's, which are switching devices. Off shore transformers will up-convert the low voltage AC either to 33 or 66 kV, on-shore slightly different voltages are used: between 10 and 36 kV. The transformers are often installed in the nacelle, also sometimes at the base of the mast. Due to the weight of the turbine and transformer in the offshore environment, the nacelle enclosure is often made of carbon fibre material to limit the overall weight.

4.2 Interview with the VERON amateur radio EMC-commission

The "Vereniging Experimenteel Radio Onderzoek Nederland" is the largest of three radio amateur organizations in the Netherlands. The EMC-committee advices to radio hams regarding EMC-issues.

Participants:
- VERON EMC-committee: A. Canrinus, J. Kamer
- TNO: O. J. van Gent, P. C. Hoefsloot

Question:
“Does the EMC-commission have (negative) EMI experiences regarding WTG’s in relation to amateur radio operations?”

Answer:
“Large WTG are erected at distances of at least 300 metres from residential buildings, which includes amateur radio installations. There have been no known cases at the EMC-commission about radio operators complaining about the EMI emissions of WTG’s on HF or VHF.
From his professional experience (*Canrinus Consultancy*) André Canrinus stated that much of the EMI originates from the power converters, which reside in the nacelle of a WTG. Most of these RF-emissions is concentrated between 30 and 80 MHz (and is compliant with maximum field strength levels). “

Question:
“Is there any known data regarding the “default” WTG emission levels on VHF?”

Answer:
André Canrinus : “The EMI field strength levels of small wind turbines seem to be 10 dB less than the limits set by the standard (CISPR11 was assumed). No info with respect to high power wind turbines.”

Comment by TNO: based on the information obtained from the other parties, it seems that the observed EMI-levels for small wind turbines is in the same order of magnitude as large wind turbines: ≈25 dBμV/m @ 30 metres reference distance.

4.3 ASTRON

ASTRON, the Netherlands institute for radio astronomy, is sited near the city of Dwingeloo in the north eastern part of the Netherlands. It is responsible for the operation of the Westerbork Synthesis Radio Telescope (WSRT) and the LOw Frequency ARray (LOFAR) which is deployed in the Netherlands and other European countries.

4.3.1 ASTRON covenant and the development of the wind turbine park “De Drentse Monden en Oostermoer”

This area historically has a low population density and human activities are mainly agricultural. Hence, a low man made noise area and an ideal environment to install the Low Frequency ARray (LOFAR) which became first operational in 2010. The LOFAR radio telescope operates between 10 and 240 MHz, together with antenna arrays in 8 other European countries. The total array encompasses more than 70000 dipole antennas.

The low population density attracted the interest of government, wind farm and solar park investors as well in 2010[35]. In spite of heavy protest several possible wind farm locations were allocated in 2012. In 2016 Astron and wind farm[36] as well as solar park investors[37] agreed on a covenant which depicted limits to the RF-emissions of these sustainable energy installations.

In short, the covenant restricts the emissions of the wind turbine installations by 35 dB compared to the EMC limits as set by CISPR11. This EMC-standard is also referred to by the European directive 2014/30/EU. Given the values of Table 2.1, that translates to a maximum emission level of **5 dBµV/m** at 30 m distance (30 – 1000 MHz). Measurements which were conducted in 2019 confirmed that a test wind turbine produced by Nordex complied to these levels. It should be noted that the manufacturer paid special attention in order to comply with the strict limits[38]. This involved more than a year of R&D work by Nordex.

The wind park[39] consists out of 45 wind turbines and has become fully operational in 2022.

4.3.2 Interview with ASTRON

Participants:
- ASTRON: M. Brentjens (radio astronomer and project scientist)
- TNO: R. Kruize, P. C. Hoefsloot

Question: "What is the impression about the standard EMI-levels as generated by generic wind turbine generators?"

Answer: "Measurements have been conducted by us in northern Germany and near Eemshaven. In northern Germany the distance to the objects was about 3 km's, at Eemshaven around 6 km's. In northern Germany emissions emanating from the wind turbines could be detected, and were at a level of approximately 23 dBµV/m (for an equivalent distance of 30 metres), which is substantially less than set by the standard (CISPR11, > 20 kVA equipment, 40 dBµV/m at 30 metres distance).
In Eemshaven it was not possible to clearly detect emissions from the wind turbines. Although the twice as long distance added 6 to 10 dB extra to the path loss, emission levels in the order of 30 dBµV/m (at 30 metres) would have been detected. Hence the actual emissions must have been substantially less than 40 dBµV/m (at 30 metres) as well." [Author: Which is equal to the industrial high power (> 20 kVA) emission level].

Observations regarding sources of EMI by Mr. M. Brentjens:
"The industrial grade inverters employed in wind turbine generators are actually very good when it comes to efficiency and EMI."
During the campaign to modify the Nordex wind turbines for the wind parks *De Drentse Monden en Oostermoer*, Mr. Brentjens observed that often peripheral equipment proved to be a stronger source of EMI than the Mega Watt power converters. For example switching power supplies feeding aeronautical warning lights equipped with LEDs, (cheap) temperature and humidity sensors and blade pitch actuators caused more EMI. These subsystems reside on the outside of the mast or the nacelle, or have wiring which carry RF-noise from the inside to the outside world."

[35] RapportDEF-09122014.pdf (platformstorm.nl)
[36] Convenant tussen Astron Lofar en initiatiefnemers windpark - De Drentse Monden en Oostermoer (drentsemondenoostermoer.nl)
[37] Convenant met Astron zet zonneparken in stroomversnelling - Dagblad van het Noorden (dvhn.nl)
[38] WindTech: How Nordex adapted N131 technology to lower radiomagnetic interference | Windpower Monthly
[39] Windpark De Drentse Monden en Oostermoer - Home (drentsemondenoostermoer.nl)

4.4 Observations by Enercon

Enercon is a manufacturer of wind turbine generators and located in Germany[40].

TNO got this written response regarding EMI from Enercon:
"I am not aware of any interferences between ENERCON wind turbines and radio services in the VHF and UHF frequency range, such as marine radio, C2000 (TETRA) or 4G/5G communication systems. Regarding the emission of electromagnetic fields from wind turbines, typical emissions can be detected in the frequency range below 30 MHz in most cases, caused mainly by power electronic devices inside the wind turbine. Measurements of high frequent field emissions are being conducted on every ENERCON wind turbine type according to FGW TR9, which follows the requirements given in CISPR11 for radio disturbance limits. In the frequency range > 30 MHz, the wind turbine emissions (if any) are typically at least 20 dB below the CISPR11 limits. The wind turbine and the turbine components are developed with respect to EMC (electromagnetic compatibility) development aspects. If there are still any electronic components inside the wind turbine which cause unwanted emission of electromagnetic waves outside the turbine we are able to identify this disturbance sources and take actions to reduce the emissions. "

The CISPR11 reflect the same values as referred to in the EU EMC directive[41], except that the frequency range is 30 to 1000 MHz. The observation of an EMI-level which is more than 20 dB below the limits for > 20 kVA equipment, is a very important one.

4.5 Observation by Vestas

Vestas[42] is a wind turbine manufacturer, located in Denmark.
Contact: Mr M. Heitkamp, who is a sales manager operating for Vestas in the Netherlands.

Mr. M. Heitkamp provided specifications regarding the limits of the radiated electric fields between 30 and 6000 MHz by WTGs. These levels do not reflect the actual emissions, but the EMI-limits similar to the levels provided by Cigre (equal to the industrial standard for *low power* industrial equipment; ≤ 20 kVA).
For frequencies between 1 and 6 GHz Vestas complies with the EMI-levels as provided by IEC 61000-6-4.

4.6 Consultation with Nordex

Nordex[43] is a wind turbine manufacturer and located in Germany.
Contact: Mr. J. Kremer is a Senior Expert Engineer Lightning Protection & EMC.

Mr J. Kremer provided insight in the measurement methods and the fact that the measurement distance to evaluate EMI from (large) wind turbines, is always 30 metres. Field

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[40] Performance portfolio (enercon.de)
[41] Directive 2014/30/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to electromagnetic compatibility (recast)Text with EEA relevance (europa.eu)
[42] Global Leader in Sustainable Energy | Vestas
[43] Home - Nordex SE (nordex-online.com)

strength limits of 30 and 37 dBµV/m are applicable (which is in line with the brochure from Cigre W.G. C4.30).

4.7 Consultation with Frauenhofer

The Frauenhofer research organization is sited in Germany and consists of 76 institutes.
Contact: Mr. S. Hawlitschka is a scientist with specific expertise on HF communications.

Mr. Hawlitschka could not provide information from the perspective of Frauenhofer, but pointed at the brochure of the Cigre C4.30 working group: EMC IN WIND ENERGY SYSTEMS. This document proved to be very valuable as it provided more insight regarding the various aspects of EMC in these kind of installations. Moreover, the EMI-limits for all wind turbine installations are set more strict then was assumed based on their power ratings and standard (CISPR11).

4.8 Consultation with the Authority for Digital Infrastructure (RDI)

The Authority for Digital Infrastructure is (among others) responsible for all wireless communication registrations in the Netherlands. On January 1st 2023 its designation changed from "Telecom Agency (AT)" to the present one.
Contacts: Mr. R de Vries, mr. L. Colussi.

The RDI informed us that there is to date no product standard for wind turbine generators, but compliance with CISPR11 is mandatory. The product standard "to be" will likely be more strict than CISPR11. IEC88[44] is presently working on this standardization. Given the exposure in society of wind turbines, there is a strong incentive by this industry not to cause disturbances to wireless communication systems, hence to self-impose more strict EMI-limits.
RDI pointed also at the "essential requirements" as set in the EU EMC directive (see also paragraph 3.3) which declares that no harmful interference may occur to wireless systems (broadcast, communication, etc). Hence, it is in the wind turbine industry's interest to prevent this.
The large metal structures (mast and nacelle) and rotor blades with integrated lightning rods at heights of 100 metres or more over the ground surface, may reflect radio signals from remote locations and bounce them off to the local receive location. Although not designated as EMI, in case of co-channel situations this may cause some (intermittent) interference.

4.9 Paper: The Electromagnetic Impact of Wind Turbines[45]

This paper was published in 2013, and looked into the impact of a moderate power turbine (1 MW). The investigated wind turbines used synchronous engines, hence no switch mode circuitry in the nacelle. Conclusions:

Little to no EMI increase could be determined at an observing shed at 172 m distance from the wind turbine (rotor span of 59 metres and a 70 metre tall mast, equalling the nacelle

[44] TC 88 - Wind energy generation systems (iteh.ai)
[45] The Electromagnetic Impact of Wind Turbines (dtic.mil)

position). It should be noted that the noise level of the employed equipment between 30 and 500 MHz was relatively high (≈22 dB KT0), which limited the ability to measure modest levels of EMI from the wind turbines.

No other papers regarding EMI effects of wind turbine generators could be found on the internet.

4.10 Siemens Gamesa

In spite of multiple attempts it proved impossible to get into contact with Siemens Gamesa.

5 Non-EMI related effects due to the presence of wind turbines

Large structures may block radio signals, but can also act as reflectors. Wind turbines are such large structures, though will rarely completely block a signal path. For separation distances of a few hundred metres between a receive location and a wind turbines, signal blockage is rarely an issue as the width of the mast is fairly small. The height and large reflection area of the rotor blades may act as reflectors for radio sources located many tens of kilometres away. Signals bouncing off the moving rotor blades may end up at a nearby located receiver and could cause some interference in the event of co-located frequencies.

Possible interference due to reflections will decrease by 6 dB for every doubling of the separation distance.

Fixed radar installations and also radar navigation on vessels may suffer serious consequences. Hence TNO[46] has provided guidelines in the past regarding minimum distances along waterways to limit these effects.

Another effect which is mainly prevalent at frequencies below 30 MHz, is described in literature[47] are “signal absorbing antenna” (1.4 – 6000 MHz) and “rotor blade reflection” effects. For receive locations very close to a large metal structure, it acts like a grounded antenna which terminates all nearby RF energy into the ground. Although these effects are reduced at VHF and UHF frequencies, it is still present within a radius of approximately 150 metres. Outside this area the absorbing effects are insignificant and can be ignored.

Main non-EMI effects due to the presence of WTGs:
- For frequencies between 90 and 3000 MHz 3 dB peak to peak signal variations due to the movement of the rotor blades may occur for distances less than 200 metres.;
- A decrease of signal strength for distances less than approximately 150 metres from the base of the mast (1.4 to 6000 MHz);
- Below 100 MHz and at very close proximity to the wind turbine, losses up to 10 dB have been reported;
- The metal of the mast and integrated wire in the rotor blades may reflect radio signals from distant locations and cause interference.

[46] Effecten van windturbines op binnenvaartscheepsradars.
Een voorstel tot een nieuwe nationale regelgeving, TNO 2016 R10617 | 2.0, 16 september 2016
[47] [The Electromagnetic Impact of Wind Turbines (dtic.mil)]

6 Conclusions and recommendations

Very little data is available on the internet regarding EMI emitted by Wind Turbine Generators. Only one paper[48] describes effects on VHF due to wind turbine generators.

A brochure[49] issued by working group C4.30 provided much insight in the origins of EMI originating from wind turbine generators. Moreover, the brochure revealed EMI-levels which are set to a more strict level than was anticipated based on the industry EMI-levels for high power equipment (i.e. CISPR11, ≥ 20 kVA).

Interviews with several parties strongly suggest that the actual emission levels of wind turbine generators is in the order of *25 dBμV/m*[50] (referenced to a measurement distance of 30 metres), which is 15 dB less than the maximum level ordained by CISPR11 for ≥ 20 kVA equipment and 5 to 12 dB less compared to the levels listed in the Cigre brochure of W.G. C4.30.

ASTRON has gained much knowledge regarding EMI caused by wind turbine generators. In order to facilitate wind farms near the receive location of ASTRON's LOFAR antenna arrays near Dwingeloo (*Drentse Monden* and *Oostermoer*), an agreement was made with the entrepreneurs and the wind turbine manufacturer (Nordex). It was agreed that the maximum emission limits should be 35 dB *less* than set by the CISPR11 EMC-standard for equipment rated ≥ 20 kVA. Nordex was able to fulfil these requirements, although this involved a year of R&D work. Such low emission levels are not strictly necessary in order to protect marine or emergency communications situated near wind turbine generator plants, but it proves that it is possible to produce wind turbines which comply with very low EMI-levels and still be able to be exploited commercially.

Actual emission data from manufacturers was very hard to obtain, some did not respond at all on requests for information. Three manufacturers provided data, most of which was in line with the forementioned (relatively low) EMI-levels.

The influence of peripheral equipment (aeronautic warning lights, temperature sensors, etc) should not be ruled out and should be *incorporated in the EMI footprint of the wind turbine*. A few poor quality switch mode power supplies which may power lighting LEDs, can produce more EMI than the Mega Watt turbine power inverters. Hence, it is strongly recommended to apply (additional) common mode filtering of power and data lines which connect to the outside of the mast and nacelle.

Based on the forementioned feedback and observations, it is assumed that most wind turbines generate EMI-levels in the order of 25 dBμV/m (@ 30 metres) or less. This would require a separation distance between a single large wind turbine and a receive location of 140 metres for marine radio systems and 180 metres for C2000 (based on a system SNR

[48] The Electromagnetic Impact of Wind Turbines (dtic.mil)
[49] EMC IN WIND ENERGY SYSTEMS, WORKING GROUP C4.30
[50] Based on observations from Enercon, par. 4.4, Astron, par. 4.3

decrease of 3 dB). This minimum distance is more than government policy requires[51]. When more than one turbine are anticipated to be erected in the same area, the separation distances to the nearest wind turbine needs to be increased to compensate for the cumulative EMI effects. Table 6.1 provides a few examples for different EMI-levels.

Table 6.1 Minimum separation distances for 30/37 dBµV/m ("self-imposed" limits) and 25 dBµV/m EMI-levels generated by WTGs.

EMI of each WTG [dBµV/m @ 30 m]	Remarks	Separation distance [m]	
Self-imposed limits	Based on 7 x 5 rotor diameter WTG grid	Single WTG	19 WTGs
30	Applicable to marine radio and AIS, based on the self-imposed standard.	275	910
37	Applicable to C2000 base station, based on the self-imposed standard.	700	2860
37	Applicable to IMT2020, 800 MHz base station, based on the self-imposed standard.	685*)	2800*)
Example based on 25 dBµV/m (@ 30m).	Based on 7 x 5 rotor diameter WTG grid	Single WTG	19 WTGs
25	Applicable to marine radio and AIS	137	370
25	Applicable to C2000 base station	166	500
25	Applicable to IMT2020, 800 MHz base station	162*)	480*)

*) Based on noise limited network coverage. As most IMT2020 networks are interference limited, the actual required separation distances for 4/5G networks may likely be substantially smaller.

Non EMI effects
Large metal structures, like wind turbines, may have a negative effect on the received signal strength as it acts as a kind of "signal absorbing antenna". This effect is frequency dependant and disappears virtually completely for distances more than 150 metres of a wind turbine.

At VHF and UHF the large metal structures (mast and nacelle) and rotor blades of wind turbines, with heights of 100 metres or more over the ground surface, may reflect radio signals from remote locations and bounce them off to the local receive location. Although this is not designated as EMI, in case of co-channel situations this may cause some (intermittent) interference. Increasing the separation distance between the receive location and wind turbines will decrease the severity of such interference.

Summarizing the EMI and non-EMI effects, shows that for a single wind turbine which complies to the self-imposed (Cigre) limit levels, regarding only marine radio, a minimum separation distance of 275 metres is required. If C2000 is allocated at the same base station, the minimum distance needs to be increased to 740 metres.
Wind parks with multiple wind turbines installed require larger separation distances.

Recommendations

- Perform baseline field strength measurements at the base station location, prior to the deployment of a wind turbine park. Specific frequency bands should be measured which are likely to be used or already presently operational at that specific location.

[51] https://wetten.overheid.nl/BWBR0013685/2015-11-21

- It is in the interest of wind turbine manufacturers to give insight in the EMI of their products. In the absence of verifiable data, the maximum limit levels should be applied as specified in the applicable EMC-certificates provided by the certifying body, which will result in higher separation distances.

- It is strongly advised not to seek the limit values for 3 dB system SNR decrease at a base station, and to leave room to provide a safeguard for marine emergency (rescue) situations. Radio radiocommunication is crucial for vessels in jeopardy and lower than normal signal levels could be expected in such situations.

7 Links to references

PIANC rapport WG 161: Pianc

CISPR22 (= EN55022), Information Technology Equipment, Radio disturbance characteristics, Limits and methods of measurement: EN 55022 CISPR 22 - Compatible Electronics (celectronics.com)

[1] CISPR11 (= EN55011), Industrial, scientific and medical equipment - Radio-frequency disturbance characteristics - Limits and methods of measurement: CISPR 11:2015+A1:2016 en (nen.nl)

[2] Cigre: EMC in Wind Energy Systems, Working Group C4.30, Nov. 2017: e-cigre > Publication > EMC in wind energy systems

[5] Monitor Wind op Land 2018 (overheid.nl)

[7] European EMC Directive: Directive 2014/30/EU of the European Parliament and of the Council of 26 February 2014 on the harmonisation of the laws of the Member States relating to electromagnetic compatibility (recast)Text with EEA relevance (europa.eu)

[12] EMC compliance for renewable energy sources: EMC Compliance for Renewable Resource Power Systems - White Paper (intertek.com)

[13] Radio- en visuele hinder door zonneparken langs vaarwegen: https://open.rws.nl/open-overheid/onderzoeksrapporten/@55500/radio-visuele-hinder-zonneparken-naast/

[14] Electromagnetic compatibility (EMC) - Part 6-4: Generic standards, Emission standard for industrial environments, EN61000-6-4/A1: NEN-EN-IEC 61000-6-4:2007/A1:2011 en

[18] Radio Noise, ITU recommendations: P.372 : Radio noise (itu.int)

[20] Wideband man-made radio noise: Wideband Man-Made Radio Noise Measurements in the VHF and Low UHF Bands (NTIA Technical Report) - ITS

[23] ETSI TS 100 392-2 V3.9.2 (2020-06), Terrestrial Trunked Radio (TETRA); Voice plus Data (V+D); Part 2: Air Interface (AI): https://www.etsi.org/deliver/etsi_ts/100300_100399/10039202/03.09.02_60/ts_10039202v030902p.pdf

[25] ETSI 3GPP TS 36.101 V16.5.0 (2020-03), 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (Release 16): https://www.etsi.org/deliver/etsi_ts/136100_136199/136101/14.03.00_60/ts_136101v140300p.pdf

[26] ETSI TS 136 104 V15.3.0 (2018-07), LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception (3GPP TS 36.104 version 15.3.0 Release 15): https://www.etsi.org/deliver/etsi_ts/136100_136199/136104/15.03.00_60/ts_136104v150300p.pdf

[28] Minimale afstanden tussen windturbines en woningen?: Minimumafstand tussen windturbine(s) en woningen? - NWEA

[29] Verdict preliminary relief judge: ECLI:NL:RBROT:2022:2205, Rechtbank Rotterdam, ROT 22/725 (rechtspraak.nl)

[31] Support research (Drentse Monden en Oostermoer): RapportDEF-09122014.pdf (platformstorm.nl)

[32] Covenant between Astron and entrepreneurs: Convenant tussen Astron Lofar en initiatiefnemers windpark - De Drentse Monden en Oostermoer (drentsemondenoostermoer.nl)

[33] How Nordex lowered EMI: https://www.windpowermonthly.com/article/1674973/windtech-nordex-adapted-n131-technology-lower-radiomagnetic-interference

[37] The Electromagnetic Impact of Wind Turbines: https://apps.dtic.mil/sti/pdfs/ADA580765.pdf

Appendix A
Background noise

A.1 Determination of the RF ambient background noise for the wireless communication and navigation systems of **Rijkswaterstaat**

Table 7.1 shows an overview of wireless communication and navigation systems which are in use by RWS.

Table 7.1 Overview of prevailing marine communication and navigation systems.

System	Freq. band [MHz]
GNDSS	0.3
GMDSS	0.49 / 0.518 / 2.1875 / 4.2095
VDES (= VDE, AIS, ASM)[52]	156 – 162
Marine radio	156 - 162
C2000	380 – 400
IMT2020	700, 800, 900, 1500, 1800, 2100, 2600, 3500
GNSS[53]	Several frequencies between 1164 and 1616
RADAR	3000 & 10000

The ambient noise levels are determined by natural sources like the Galaxy, and Earth's atmosphere. Man-made noise sources like electronic equipment and machines have become a major additional source of RF noise over the past century.

The intensity of RF noise, including man-made noise, can be divided in 5 categories, as used by the ITU[54]:
a. City;
b. Residential;
c. Rural;
d. Quiet rural;
e. Galactic.

Galactic noise is mainly applicable for applications which direct their antennas towards space, although in very quiet regions this noise may be the ruling noise even for terrestrial communication.
The most modest levels of RF noise ("Quiet rural") can be found in remote areas with very little human activities. Such regions have become scarce in the Netherlands, or for that

[52] Technical characteristics for a VHF data exchange system in the VHF maritime mobile band (itu.int)
[53] Global positioning system - Wikipedia
[54] RECOMMENDATION ITU-R P.372-16 - Radio noise*

matter in many parts of the world. Even at (remote) farms many electronic appliances can be found, not to mention solar panels and (noisy) inverters.
Ships have their share of electronics, apart-of communication, which contribute to the rise of their own ambient noise beyond “quiet rural”. Think of switch mode power supplies which power LED lights and cooling installations.

To determine a reference bottom line sensitivity, it seems prudent to use the “rural” curves. Base stations located a few kilometres from industrial and domestic areas, will likely have ambient noise levels equal to this. It is evident that lighting and other installed equipment at such a base station should be suited not to increase the ambient noise to such a level that reception is compromised.

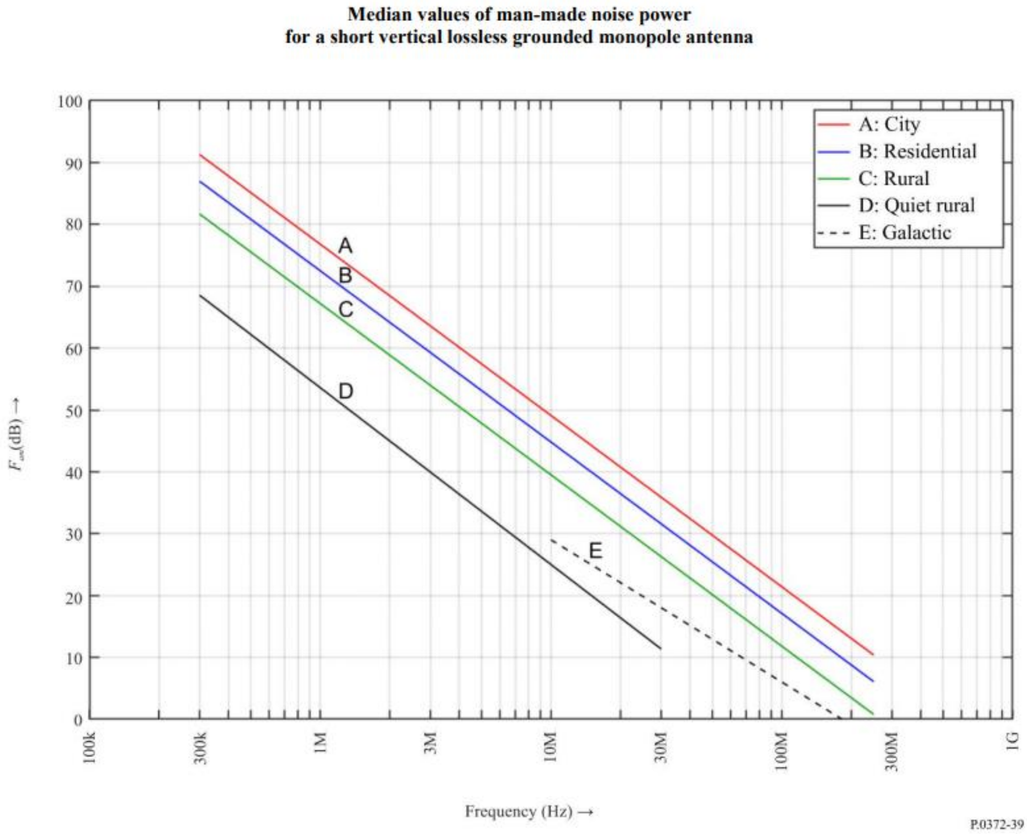

Figure 7.1 Man-made ambient noise levels between 200 kHz and 230 MHz[55].

An extrapolation of the ITU curves of Figure 7.1 has been made in order to be able to set ambient noise level limits between 230 and 1000 MHz, see Figure 7.2. At present no man made noise measurements have been published for frequencies over 1000 MHz. In general the generated RF noise tends to decrease with frequency, but the advent of very high speed switching technologies may counter this.

[55] page 100, RECOMMENDATION ITU-R P.372-16 - Radio noise*

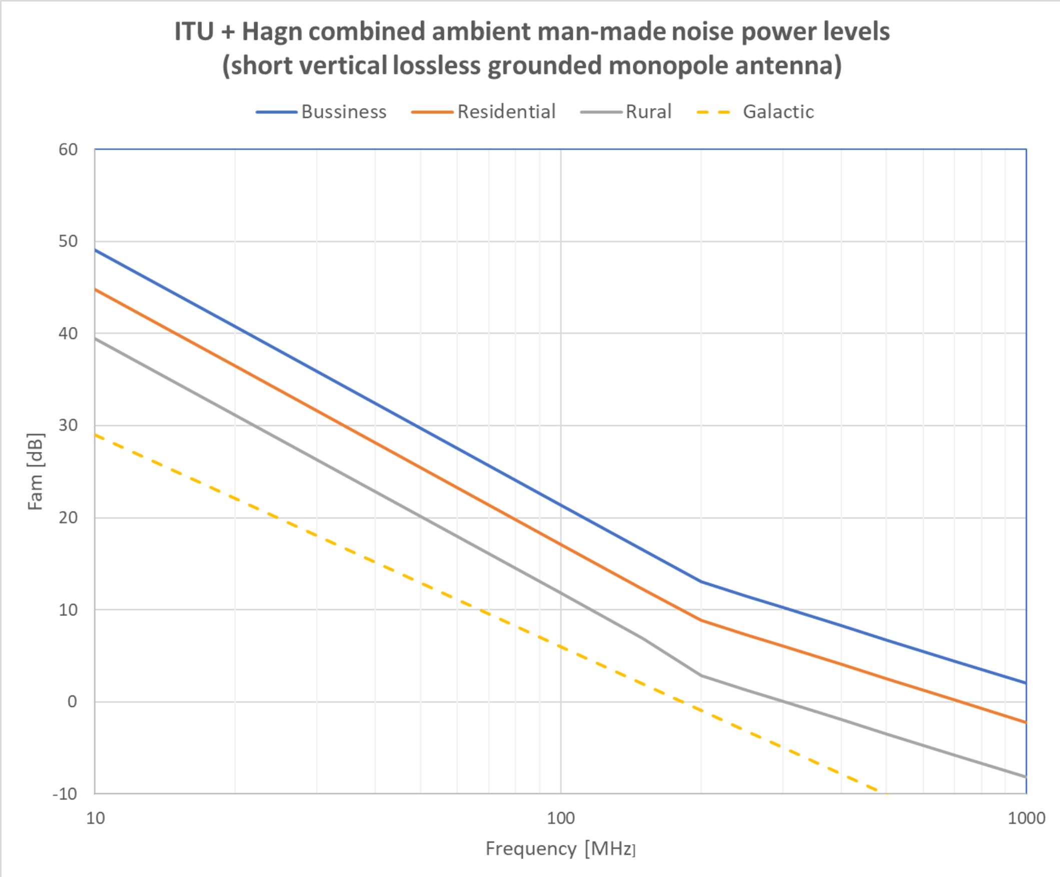

Figure 7.2 Ambient noise extrapolated to 1000 MHz.

Based on present literature, a “quiet rural” estimate of the ambient noise for frequencies over 1 GHz can be made. The actual temperature of the ground starts playing an increasingly important role, as well as properties of gasses (oxygen and nitrogen) and moisture in the air.

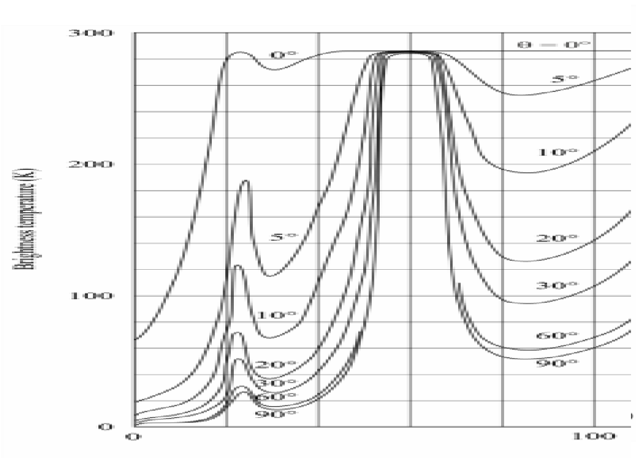

FIGURE 4

Brightness temperature (clear air) for 7.5 g/m³ water vapour concentration (surface temperature and pressure equal to 15°C and 1 023 mb); θ is the elevation angle

Figure 7.3 Influences of the ground versus antenna elevation[56].

The blue curve “no man-made noise, equals “quiet rural”. As can be seen, the rural curve resembles a noise situation 4 to 10 dB higher than “quiet rural”. The rural curve is used in this report as one of the parameters to determine the maximum interfering field strengths at receive locations for a 3 dB decrease in system SNR.

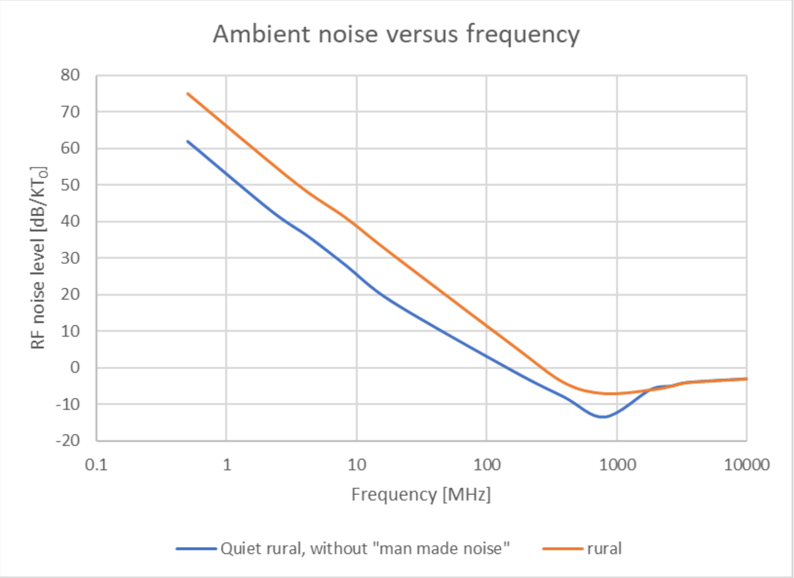

Figure 7.4 Ambient noise curves for rural and quiet rural (= “man-made” noise).

Appendix B
Transport of electricity: AC or DC?

B.1 Transport of electricity from Wind Turbines to off shore substations and main land

Electric energy needs to be transported from a production site to domestic and industrial locations. Losses during transport are for 99% due to resistive losses in the cables, hence the lower the current, the smaller the resistive losses. To accomplish this the produced electricity from a wind turbine is up transformed from 650 V to 33 or 66 kV (off shore) to minimise the losses between a wind turbine and off shore substation (OSS) as the distances are small, no more than 15 to 20 km.

B.2 AC-AC transport

At an OSS the power of all wind turbines is combined and may encompass as much as 1 Giga Watt. Special cables have been developed which can carry 380 kV voltages (3 phases) and transport about 600 MW over a hundred km long stretch or more without very high losses (about 1 %)[57]. Skin effects and reactive power start to play a more prominent role when distance increases, hence DC comes into play.

B.3 DC-DC transport & AC<>DC conversion

With increasing size and distance from the coast line of future wind parks, the losses and power handling of cables become substantial. Employing DC instead of AC has a major advantage that the whole copper core is used, instead of a thin skin layer for AC. Even including the additional losses of conversions between AC and DC, the total losses are less than using a similar size AC-cable. For distances roughly larger than 100 km this becomes a factor to consider.
On either side of the trajectory a very powerful rectifier and DC to AC converter will have to be installed, which is a serious investment (hence the 100 km distance where the trade-off becomes positive).

[57] Blz. 18, Technische ruimtelijke en organisatorische aspecten enz 2014 blg-348049.pdf

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