EXPERT GROUP STUDY
ON

RECOMMENDED PRACTICES FOR WIND TURBINE TESTING AND EVALUATION

5. ELECTROMAGNETIC INTERFERENCE

PREPARATORY INFORMATION

Submitted to the Executive Committee
of the International Energy Agency Programme
for
Research and Development
on Wind Energy Conversion Systems

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FOR WIND TURBINE TESTING

5. ELECTROMAGNETIC INTERFERENCE

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FOREWORD

The evaluation of wind turbines must encompass all aspects of a Wind Energy Conversion System (WECS) ranging from: energy production, quality of power, reliability, durability and safety, through to cost effectiveness or economics, noise characteristics, impact on the environment and electromagnetic interference. The development of international agreed upon evaluation procedures for each of these areas is needed now to aid in the development of the industry while strengthening confidence and preventing chaos in the market.

It is the purpose of the proposed recommendations for wind turbine testing to address the development of internationally agreed upon test procedures which deal with each of the above noted aspects for characterizing wind turbines. The IEA expert committee will pursue this effort by periodically holding meetings of experts, to define and refine consensus evaluation procedures in each of the areas:

1) Power Performance
2) Cost of Energy from WECS
3) Fatigue Evaluation
4) Acoustics
5) Electromagnetic Interference
6) Safety and Reliability
7) Quality of Power

For items, 1, 2, 3, 4 and 7 documents have been issued during the years 1982–1984. However items 5 and 6 have turned out to be difficult to treat within the same framework as items 1–4 and 7. The present paper which addresses item 5 therefore is presented as *preparatory information* on the subject of Electromagnetic Interference.

In spite of this limited scope it is felt that the information contained in this paper can be of great value to planning authorities and to manufacturers and users of wind turbines and therefore justifies the presentation of the document in this series of Recommended Practices.

Contents

1. INTRODUCTION

The procedures necessary for evaluating the electromagnetic interference effects of wind turbines on radio services involve many parameters. These include the frequency of the susceptible radio system, its antenna characteristics, their spatial position relative to the wind energy system and the modulation scheme. The relevant parameters of the wind energy system include the type of machine, vertical or horizontal axis, the diameter and number of its blades, their shape and electromagnetic properties of their materials, and the height of the support tower.[1] Also relevant for machines with blades made of dielectric materials are the shape and location of any metal parts, such as lightning conductors, or spars.[2] The performance is also dependent upon the local terrain around the sites of both the wind energy and radio systems.[3]

An Expert Group of the International Energy Agency has investigated the problem and found that a large number of radio systems are potentially at risk from interference generated by wind turbines. A number of different effects have been identified concerning a variety of services, but in general the group has concentrated on services involving the safety of life and terrestrial communications. Interference to TV broadcasting has been considered and the mechanisms involved identified.[4]

In view of the many radio services that may be susceptible to interference from wind turbines, and the limited amount of data currently available, the Group is unable to produce a recommended code of practice for wind turbine testing and evaluation, without making it excessively restrictive. The electromagnetic spectrum is one of man's most limited and precious resources and the successful operation of so many radio services without mutual interference has only been achieved by its careful management over many years. However, it is recognised that the wind energy community requires guidance on means of successfully introducing their potentially interfering structures into an existing congested electromagnetic environment and achieving compatibility. The problem may be compounded because some hill top sites are attractive for the siting of both wind energy systems and radio installations.

The objective of this document is to present an indication of the mechanisms that have so far been identified as contributing to the interference, to report some of the undesirable effects that have been noted and to recommend appropriate remedial action, if any. It is intended that in the absence of an all embracing code of practice this will indicate the type of studies that should be undertaken on each wind turbine. At present this must be done on a case by case basis but operators are encouraged to publish their findings and thereby contribute to the wider experience necessary to establish a code of practice.

The expert group considered the desirability of producing a Code of Practice on ways of measuring the interfering signals generated by wind turbines. However, it was concluded that this was not appropriate at this time and this Preparatory Information has therefore been compiled. All measurements reported to the group involved the use of well defined measurement sets operated in accordance with the maker's recommendations, typically by PTT (Posts and Telecommunications) organisations. Under these circumstances it has been found possible to readily compare results which might have been recorded by equipments differing in cost by almost two orders of magnitude. Measurement techniques are currently being rapidly developed and improved and in view of the wide range of problems that may be encountered it is not timely to formulate a fixed measurement procedure.

In subsequent sections the mechanisms potentially contributing to the generation of interference from wind turbines will be investigated, some of the interference problems noted and where available the specific remedial actions undertaken will be reported. Operators of wind turbines should note the criteria adopted in these cases but should realise that as further experience is gained more restrictive criteria may emerge to provide the margins of protection for radio services demanded by international agreements.

2. THE MECHANISM BY WHICH WIND TURBINES MAY GENERATE INTERFERENCE

The essential mechanism by which a wind turbine generates electromagnetic interference is shown in Figure 1, which indicates a transmitter and receiver adjacent to a scattering object, the wind turbine. The figure indicates that there are now two transmission paths, the direct path (d) and the unwanted secondary path ($d_t + d_r$). These two signals will combine at the receiver either in or out of phase or at any intermediate value, leading to an observed carrier to interference ratio (C/I). Although some radio services may be able to accommodate multi-path signals, for others some special precautions may be required even for static structures; the difference in the effect caused by a wind turbine is that the unwanted interfering signal varies periodically.[5]

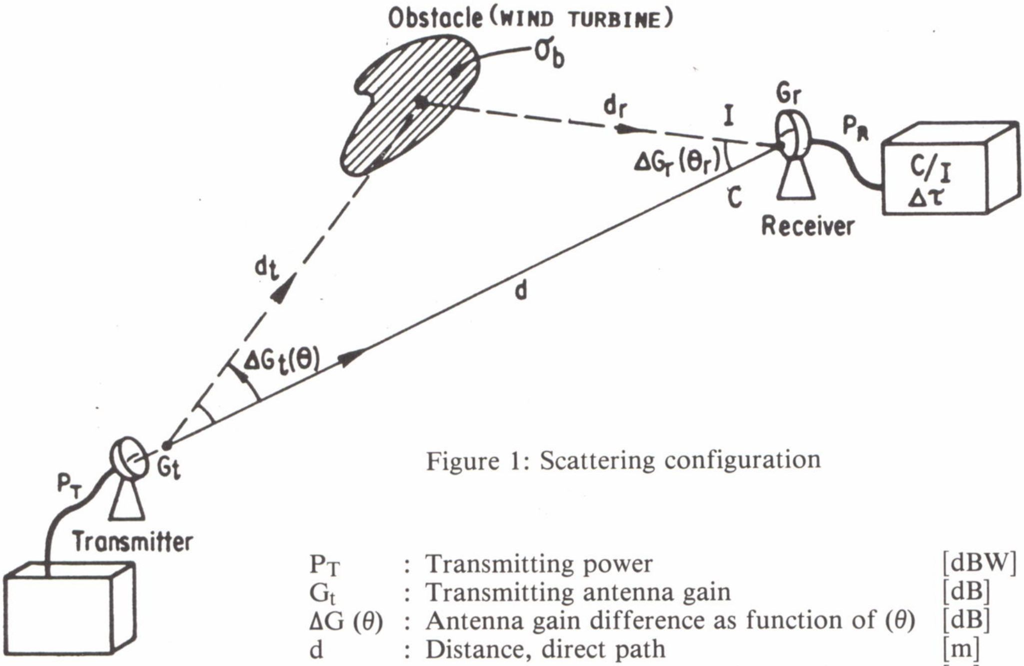

Figure 1: Scattering configuration

P_T	:	Transmitting power	[dBW]
G_t	:	Transmitting antenna gain	[dB]
$\Delta G\ (\theta)$	:	Antenna gain difference as function of (θ)	[dB]
d	:	Distance, direct path	[m]
$d_t + d_r$	:	Distance, unwanted secondary path	[m]
$\Delta G_r(\theta)$	:	Receiving antenna gain	[dB]
σ_b	:	Bistatic radar cross-section	[dBm^2]
P_R	:	Receiving power	[dBW]
C/I	:	Carrier-to-interference ratio observed at receiver	[dB]
$\Delta\tau$	:	Time delay difference between direct and secondary paths	[sec]

The predominant additional interference effects caused by the rotating blade of a wind turbine is to produce an amplitude modulated interfering signal, but there are also time delay effects which may appear as a doppler shift. For amplitude modulated (AM) radio systems the variation in level may be the most serious effect while for frequency modulated (FM) systems the doppler shift may be the most destructive. In some cases, depending on the signal wavelength (λ) and the dimensions of the wind turbine, the amplitude modulation is of an impulsive nature and appears to be like a radar signal,[6] but no information has yet been published indicating its harmful effects if any upon radar installations. In assessing the impact of a particular wind turbine on potentially vulnerable radio services, it is necessary to first determine the variation of the electromagnetic fields caused by scattering from the turbine as well as the time delay to be expected, and then establish the impact of this variation on the particular radio system. Both these procedures involve describing processes that are dependent upon a large number of variables, the relative importance of which vary widely from installation to installation in a manner that with the present state of knowledge can not be readily assessed. This is the reason the Group is not inclined to issue all-embracing guidelines because they would have to be written as if the worst case situations applied to all parameters simultaneously; this is a most unrealistic situation which is unlikely to occur and would make any guidelines unacceptably restrictive. However, it is known that the performance of specific types of radio system can rapidly degrade if certain critical parameters are exceeded. Given the large numbers of different radio services, their modulation formats and signal frequencies, and the small number of systems for which reliable measurement data is available, present collective international experience does not span the problem, particularly with regard to large wind turbines (more than 15 m in diameter) and wind turbine parks.[7]

The scattering properties of an obstacle are expressed by its radar cross-section and, is defined as 4π times the ratio of the power per unit solid angle scattered in a specified direction to the power per unit area in a plane wave incident on the scatterer from a specified direction. Three cases are distinguished:

1) Microstatic or backscattering RCS when the incident and scattering directions are coincident and of opposite sense.
2) Forward scattering RCS when the two directions and senses are the same.
3) Bistatic RCS when the two directions are different.

3. THE ELECTROMAGNETIC SCATTERING PROPERTIES OF WIND TURBINES

The electromagnetic scattering properties of wind turbines, like those of other scatterers, are not simple to describe. It involves three dimensional vector fields incident upon a time varying structure and requires many parameters for its description. This is not an unusual situation in the wider context of electromagnetic scattering. Although it is not necessary, or possibly desirable, to use electromagnetic analysis techniques to investigate all wind turbines installations, they do allow the many different situations to be categorised in three classes dependent upon their dimensions in terms of a wavelength. The three regions are the low frequency region where the scatterer is small in terms of a wavelength, the high frequency or optical region where the scatterer is many wavelengths in extent and the intermediate or resonant region where the scatterer's dimensions are comparable to the wavelength. The predominant physical mechanisms present in each region are different and if described mathematically would be completely separate.[8] A particular wind turbine may produce effects corresponding to each region because of the wide range of frequencies possibly incident upon it. Some of the typical ways in which a wind turbine may scatter electromagnetic energy in each region are[9]:

(a) For the low and resonant frequency regions, major effects are likely to be predominantly specified by the gross parameters of the wind turbine structures. The height of the tower, and the length and number of blades would be expected to be of major interest. A simple example of this type of behaviour can be indicated by considering a horozontal axis single bladed machine. When the blade is pointing skywards, the structure of blade and tower may be considered to be a large monopole antenna supporting a quarter wave resonance. Rotating the blade so that it points towards the earth effectively removes the quarter wave antenna from the environment. The alternate insertion and removal of a resonant scattering object from an electromagnetic field causes major disturbance. When this is repeated cyclicly as the blade rotates an interfering signal can readily be generated. All wind turbines will support a number of electromagnetic resonances most of which are not so easily described as the lowest order resonance of a single bladed machine referred to above.

(b) The high frequency or optical region. In this region the scattering properties of the wind turbine are best described by drawing rays in an optical fashion. The size of the wind turbine is many wavelengths in extent and the incident electromagnetic field is able to resolve many of the fine details of the structure. In this region the number of parameters that have to be included in any investigation is therefore large.

Due to the complicated structure of the wind turbine, a detailed description of the individual contributions to the total scattering signal is rarely warranted. The bistatic radar cross-section is an important parameter in estimating the interference to the radio system. *For the initial estimation of this paramter the Group recommends that the projected geometrical area of the complete wind turbine is employed.* More precise estimates may be possible but these require a more detailed investigation.

4. RELEVANT WIND TURBINE PARAMETERS

Some of the relevant machine parameters for establishing the possible electromagnetic interference generated by wind turbines are[9]:

(a) **The type of machine.** Different types of interfering waveform have been observed from horizontal and vertical axis machines, with distinct modulation types and frequences.

(b) **The number of blades.** It has been observed with both types of machines that the number of blades is significant. With a single blade horizontal axis machine a large amplitude variation in scattered signal may be observed, the main spectral components of which may be related directly to the machine's speed. With more blades the amplitude variation of the scattered signal may be smaller but the main energy may be present at much higher modulation frequencies.

(c) **The rotor diameter.** The diameter of the wind turbine rotor is important in establishing the frequency bands where resonant scattering may occur. For some of the smaller machines this will lie in the VHF band while for the large machines (up to approximately 100 m in diameter) it will occur in the HF or lower parts of the electromagnetic spectrum.

(d) **The rotation speed.** The rotation speed of the wind turbine is relevant because the frequencies of the potential interfering signals are related to it.

(e) **The blade cross-section, material and construction.** The blade cross-section, material and method of construction are all significant. In general, less severe scattering is observed from blades made from a dielectric material, such as fibreglass, because blade scattering occurs from both the external and internal surfaces and the two effects are unlikely to add constructively to give a radar cross-section equivalent to that of a metallic structure. It should be noted however, that adding any metallic components, such as lighting conductors to a dielectric blade may significantly increase the radar cross-section.

(f) **The yaw, twist and pitch of the blades.** The yaw, twist and pitch of the blades is also of importance. The scattering produced by each blade has its own three dimensional radiation pattern. Comparatively small changes in the angular position of the blades can cause major lobes in the pattern to be shifted either towards or away from the potentially susceptible radio system.

(g) **The tilt, cone and teeter angles of the wind turbine.** For similar reasons to (f) small variations in the tilt, cone and teeter angles of the complete wind turbine may cause wide variation in the interference observed.

(h) **The type of support tower, its height and construction.** The support tower itself may act as a resonant scatterer or, in conjunction with the blades, support resonances. It will have its own scattering radiation pattern which is then modulated by the blades of the wind turbine chopping this signal.

(i) If the wind turbine is part of a wind farm then the interaction effects within the wind farm require consideration. The interference observed from wind farms with many individual machines operating in random phase may be added on a root mean square basis. If the machines are synchronised greater interference levels than this may be observed.

5. RELEVANT PARAMETERS OF THE POTENTIAL VULNERABLE RADIO SERVICES

The major parameters of relevance to the vulnerability of radio services to interference include[10]:

(a) The spatial positions of the transmitter and receiver with respect to the proposed wind energy system. (Re-siting a wind energy system away from the direct path of a micro-wave link would be anticipated to reduce interference).

(b) The carrier frequency. The scattering mechanisms present will depend upon frequency as described in section 3 of this document.

(c) Polarization. The polarization of the signal will affect its propagation characteristics and the effective scattering cross-section of the wind turbine. Polarization effects are less dominant when the wind turbine is large in terms of the wavelength of the radio signal.

(d) The modulation type. Amplitude modulated signals are likely to be susceptible to amplitude modulated interference. It should be noted that some of the more recently introduced highly efficient digital modulation schemes allow little degradation in system performance before information is lost.

(e) The modulation frequency. If the modulation frequency of the signal coincides with a high harmonic of the rotor speed then degradation of RF performance is likely.

(f) The time constants of the automatic gain or other controls. This is important in con-trolling interference to TV broadcasting.

(g) The symbol rate of digital systems.

6. SPECIFIC RADIO SERVICES

Although there is little existing experience of the effects of wind turbines on all types of radio services, particularly of the effects of large machines in the HF and VHF bands, some comments on effects so far observed are relevant.

(a) **VOR** (VHF Omnidirectional Ranging).

This is one of the most important services for aircraft navigation and is known to be susceptible to interfering amplitude modulated signals. Interference from a wind turbine is likely to lead to the pilot being supplied with false information about his position.

The performance of VOR stations may be degraded by large static scatterers. American experience strongly suggests that the rotating blades of a wind turbine do not cause further degradation. Existing internationally agreed and FAA (Federal Aviation Agency) regulations do not allow any structure of the size of a wind turbine to be erected within 1 km of a VOR station. (Longer distances apply for large structures). At present there is no evidence to suggest that more severe regulations are required for wind turbines. Operators should note that VOR stations are not always sited adjacent to airfields, as some VOR stations provide en route information.

(b) **ILS** (Instrument Landing System)

This service operates in a similar frequency range to VOR and is critical to aircraft approaching runways. Although the specific effects of wind turbines on this service are likely to be less than on the VOR, concern has been expressed that at many major cities, because of the extension of the FM broadcast band to 108 MHz, there is no margin for further degradation of performance. Where wind turbines are to be sited adjacent ($\simeq$ 5 km dependent upon direction relative to the runways) to airfields it is essential to assess the impact on this service.

(c) **LORAN**

LORAN is a long range position finding system that is similar to VOR. It operates on such a low frequency however that the interaction of its signals with a wind turbine are not at present considered to be significant.

(d) **Conventional TV broadcasting**

Investigations on interference to TV service by wind turbine generators has been widely reported[5, 6, 7, 8, 10] because the services aim to provide universal coverage. The impact of this interference can be limited by siting the wind turbine in a favourable position relative to the TV transmitter and the local population. The level of signal at which the interference becomes unacceptable is subjective. However, if the signal is to be re-broadcast little degradation will be acceptable to the broadcasting authority. It should be noted that Teletext services are now being combined with conventional TV broadcast signals. Dutch experience indicates that these signals are vulnerable to interference at lower levels than those required to degrade the TV picture.

(e) **Cellular radio**

Cellular radio is a new service which like TV broadcasting aims to provide universal coverage. However, it is designed to operate in an urban environment where severe amplitude fading occurs. The effects of the wind turbine are likely to be similar so that this service will be robust to this form of interference.

(f) **Microwave links**

The Danish PTT has reported severe interference problems on 7.4 GHz 8 Mbit/sec data-rate microwave links operating with Frequency Shift Keying modulation. Error rates exceed the thresholds contained in the international Comité Consultatif de Recherche en Informatique rules above which it is required that the link is shut down.

The Danish and Dutch PTT have applied some compatibility guidelines to the siting of wind turbines adjacent to microwave links and these are presented in Section 7.

(g) **Satellite service**

In general, apart from in extreme northerly or southerly latitudes, the elevation angle of geostationary satellites and the gain of the ground station antennae are considered to ensure adequate isolation from any effects generated by a wind turbine. If present, interference is expected to be most noticeable on the 1.5 GHz mobile service where low gain earth station antennae are allowed.

(h) **Radars**

No experience could be made available to the Group concerning the effects of wind turbines on radars. However, many radars are fitted with a Moving Target Indication (MTI) which is designed to remove the effects of scattering from adjacent static objects, and indicate targets that are moving. The blades of a wind turbine, particularly the tips, are likely to be moving at a speed exceeding the MTI thresholds and may thus generate interference. A radar with a low MTI threshold, such as required to track the migration of birds or insects, could be more severely affected than a radar designed to track only high speed aircraft.

(i) **SOLAS (Safety of Life at Sea)** (0.5 MHz)

The Safety of Life at Sea transmission could be adversely affected by offshore installations. These are emergency bands used only by ships in difficulty and the performance could be degraded if a ship was close to a wind turbine installation.

The above list is not exhaustive but includes some of the services considered in meetings of the Expert Group.

7. INTERIM ASSESSMENT

Procedures

The range of possible radio services which may be affected by a wind turbine, and the number of its parameters that should be investigated, makes the preparation of a general code of practice impractical, particularly given the lack of previous experience in many areas. Nevertheless, it is recognised that those responsible for the design, installation and operation of wind turbines require as much guidance as reasonably possible to ensure that electromagnetic interference problems either do not occur, or that their effects are limited.

The interim recommended procedure involves an initial assessment of the present or planned radio services likely to be affected by the proposed installation of a wind turbine. An investigation of the topology of the local terrain with respect to transmitter locations and required service areas is then essential. Based upon this assessment the particular radio services potentially at risk may be identified. A detailed investigation of the robustness of these services with respect to the anticipated interference must then be pursued, to establish if a problem exists or to propose remedial action.

The steps required to complete this are:

(1) **To establish the present or proposed radio services radiating through the volume of the proposed wind energy installation**

Initially this may be undertaken by referring to the appropriate Radio Regulatory Authority and requesting information on existing and proposed transmissions. However, records are rarely complete so it is essential to undertake a site survey of transmissions actually present. This must be conducted over a suitable period to ensure variations with time are recorded. HF transmissions change frequency according to a regular pattern dependent upon the time of day. TV transmitters are not always switched on and some services serve work day activities while others are associated with leisure. The survey should note the requirements of mobile users in the area such as the emergency services, shipping, aircraft and the public utilities.

The information to be recorded includes the frequency, signal strength and direction of arrival of radio transmissions. It is assumed that a modern spectrum analyser or equivalent in sensitivity will be employed for these measurements.

(2) **Establishment of radio services potentially at risk from interference generated by a wind turbine**

Based upon the information generated in (1) it is then necessary to study maps and the topology of the area around the wind turbine site. The objective of the relevant radio transmissions with respect to the requirements of the local population must be estimated. It may be that within the area possibly affected by the wind turbine there are no requirements for fixed radio services. The requirements of mobile users only must then be considered. The objective is to establish the radio services potentially at risk of suffering from interference generated by a wind turbine installation by determining in which service areas and adjacent to which radio paths it is sited.

(3) **The determination of the effects of the proposed wind turbine on the radio services potentially at risk**

The third step is to determine if the effects of the proposed wind turbine will in practice degrade the radio service. This is the most difficult step and the area where at present little experience exists. The problem is two-fold in that the time variation of the field strength caused by the wind turbine must be assessed and then its effects on the radio system determined. In both areas little evidence is available other than in relation to television broadcasting. For that service the interference is likely to be only a nuisance, and remedial action may be offered by cable television if re-siting to avoid unfavourable paths is not possible at the planning stage. Particular attention must be paid to vital services; these are ones on which the safety of life may depend. At present if such a transmitter is sited in the vicinity of a proposed wind turbine installation the particular parameters of the situation should be investigated, with possibly the effects of interference modelled in the laboratory on a similar radio system. Operators are encouraged to publish the findings of similar investigations to provide the basis for more comprehensive recommended practices.

A simple conservative method of assessing the potential interference to a radio system has been applied to the protection of microwave links. The method involves using the estimate of the wind turbine's radar cross-section based upon its geometrical areas to indicate the peak magnitude of the scattered signal. The interfering signal is then considered to vary cyclically between this maximum value and zero. Based upon this estimate of the interfering signal level, and the geometry around the wind turbine, contours of constant carrier to interference level are constructed.

For the protection of different radio systems a range of carrier to interference levels will be appropriate. For example, on microwave links, the Dutch PTT[13] require a minimum carrier to interference ratio of 65 dB. Allowing for propagation conditions a margin of 20 dB is made for fading and the 85 dB carrier to interference contour around the wind turbine is the dividing line between acceptable and unacceptable interference situations.

8. CONCLUSIONS

For members of the wind energy community unfamiliar with the procedures adopted by radio engineers in planning new services, the steps described in this report with regard to the planning of new wind turbine systems may seem demanding. However, they are in principle no different from the procedures in common use for ensuring compatibility between diverse radio services. In this sense, a new wind turbine, as a potential source of interference to existing radio services, is similar to any new transmission and it must be carefully planned if it is not to cause disruption.

The electromagnetic spectrum is one of man's most limited and yet widely used resources which has effectively been rationed by international agreement throughout the twentieth century. Most of the developments in radio technology have been aimed at making better use of this limited resource. New services have only been technically feasible when new advances have been made. Against the background of this congested environment, this report is aimed at developing techniques for introducing new wind turbines in a compatible manner. Much work is yet required and this document is envisaged as the first step in that process.

9. ACKNOWLEDGEMENTS

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