ELECTROMAGNETIC INTERFERENCE EFFECTS OF WIND TURBINES

Dipak L. Sengupta
Radiation Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Arbor, Michigan 48109

ABSTRACT

The University of Michigan Radiation Laboratory's investigation of the electromagnetic interference (EMI) effects of a variety of wind turbines on the performance of a selected number of electromagnetic systems are summarized. Such work has made it possible to assess the impact of a proposed wind turbine or windfarm on its electromagnetic environment.

Prepared for presentation at the meeting of:

The Working Committee on EMI
International Energy Association (IEA)

to be held on August 21, 1984, Copenhagen, Denmark.

ELECTROMAGNETIC INTERFERENCE EFFECTS OF WIND TURBINES

Dipak L. Sengupta
Radiation Laboratory
Department of Electrical Engineering and Computer Science
The University of Michigan
Ann Abor, Michigan 48109 U.S.A.

1. Introduction

Any static or time-varying multipath source in the vicinity of a receiver (or transmitter) of signals from a given electromagnetic system may act as a potential source of interference to the performance of that system. When the installation of large wind turbines (WTs) was proposed in the 1970s it was therefore speculated that the rotating blades of a WT could produce interference to television (TV) reception in its neighborhood. Our studies carried out in 1976, and subsequently, confirmed the fact that such television interference (TVI) does occur. To some extent, all electromagnetic systems are affected, and by analysis, simulation and where practicable, experiments, the effects on a variety of systems have been quantified.

During 1976-1983 the University of Michigan Radiation Laboratory, under the sponsorship of U.S. Department of Energy, studied the electromagnetic interference (EMI) effects of a variety of wind turbines on the performance of a number of electromagnetic systems. We have performed wide-ranging theoretical and experimental investigations of the EMI effects of horizontal and vertical axis wind turbines (HAWTs and VAWTs) on the performance of the following systems: (i) FM Broadcast,

(ii) Television Reception, (iii) Very High Frequency Omni Range or VOR and Long Range Navigation or LORAN-C, (iv) Microwave Link, (v) Earth Station communicating with satellite. The present paper gives an overview of our studies, highlighting some of the most recent results.

II. General Considerations

To a receiver of signals in the vicinity of a WT, the rotating blades act as a time varying multipath source. As a result of the scattering from the blades, the total signal received is generally amplitude and phase (or frequency) modulated, the former being dominant. This extraneous modulation of the desired signal, if sufficiently strong, can adversely affect the performance of an electromagnetic system. The nature and degree of the resulting interference effects will depend on the signal transmission and reception methods used by the system, and on the electromagnetic scattering characteristics of the blades. The basic parameter that is used to judge such EMI effects on a given system is the interference to the desired signal ratio at the receiver, and is defined as

$$\Gamma = \frac{E^S}{E^R} , \qquad (1)$$

where E^S is the amplitude of the scattered or secondary signal received,

E^R is the amplitude of the desired ambient or primary signal received.

Depending on the system under consideration, the severity of interference effects are judged on the basis of certain largest values of Γ that the system can tolerate without suffering unacceptable degradation of its performance.

For simplicity let us assume that the environment is free space and the receiving antenna is omnidirectional. Under these assumptions it can be shown [1] that the maximum value of Γ at a receiving point it

$$\Gamma_{max} = \frac{E^B}{E^R} \frac{A \cos \phi/2}{\lambda r} \qquad (2)$$

where E^B is the amplitude of the ambient signal of the WT-blade phase center B,

A is the equivalent scattering area of the blade,

ϕ is the angle between the WT-transmitter and WT-receiver directions,

λ is the operating wavelength of the system under consideration and

r is the distance between the receiver and the phase center of the WT blades.

In an actual situation, Eq. (2) requires to be modified by the ground reflection characteristics, the blade scattering pattern and the receiving pattern of the antenna used [2]. In the case of flat or smooth spherical earth approximation, the quantities E^B and E^R in Eq. (2) may be obtained by using the radio wave propagation theory. However, no such acceptable theoretical model is available for rough terrain. Quite often these quantities are best obtained by measurements.

The equivalent scattering area A plays a dominant role in the EMI effects produced by a WT. For HAWTs it is related to the projected physical area of the blade by

$$A = \eta A_p \qquad (3)$$

where η is defined as the scattering efficiency of the blade. On the basis of laboratory scale model [3] and full scale field measurements [2] it has been found that for commonly used metallic HAWT blades $\eta \simeq 0.65$. For the 200 kW MOD-0A machines with baldes 38 m tip-to-tip $A = 12\ m^2$, whereas for the 2 MW MOD-1 machines (blades 61 m tip-to-tip), $A = 40\ m^2$; for the 2.5 MW MOD-2 machines having a single tip-controlled blade 91 m in length, $A = 140\ m^2$. If the blades are made of composite material or wood, the effective A can be as much as a factor 2.5 smaller depending on the amount of metal remaining. It is necessary to provide lightning protection in the form of metallic strips along a non-metallic blade; this may increase its A almost to that of the corresponding metallic configuration [3].

For a metallic VAWT like the Darrius, A may be determined from the following high frequency approximate expression, confirmed by full-scale measurements [4]

$$A = W\sqrt{D\lambda} \quad , \tag{4}$$

where W is the width of the blade and D is the average equatorial diameter of the loop formed by the Darrieus blades.

Because of their fundamental importance, the electromagnetic scattering parameters for presently operational large horizontal axis wind turbine blades have been determined from scale model and full scale measurements. The former were performed at microwave frequencies using scale model blades in an anechoic chamber, and the latter were carried out in the vicinity of the wind turbines using the available television signals as the RF sources. A theory has been developed to determine the desired scattering parameters from the full scale measurements, and the results are in good agreement with those obtained from the laboratory scale model measurements. Some of the results are already quoted. Details of the measurements and data analysis are described in [2].

III. The TVI Effects

Our studies of the TVI effects have been most extensive both theoretically [1,3,5,6] and experimentally. The experimental work included simulation experiments [3,5], laboratory studies with scale model WTs [3,6] and full scale studies with operating WTs [3,4,7,8,9]. We shall describe the TVI effects of a large HAWT in some detail.

As shown in Fig. 1, in a neighborhood of a WT the signal scattered by the blades combines with the primary signal, thereby amplitude modulating the total signal received. The modulation waveform generally consists of sinc-like pulses whose width is inversely proportional to the electrical length of the blade with amplitude directly proportional to the equivalent scattering area, repeating at twice the rotation frequency of the blades. If sufficiently strong, these extraneous pulses can distort the received picture, whereas the audio information, being transmitted by frequency modulation, generally remains unaffected. Generally, at a given distance from the WT, the interference increases with (i) the increase of A or larger WT and (ii) increasing frequency, and is therefore worse for the upper UHF TV Channels than on the lower ones. It also decreases with increasing distance from the machine, but in the worst case can still produce objectionable effects up to a few kms. For ambient signals well above the noise level of the TV receiver, there is in general no significant dependence on the ambient signal strength, and no audio distortion has been observed.

When the blades are stationary the scattered signal may appear on the TV screen as a "ghost" whose position (i.e., separation from the direct picture) depends on the time difference between the time delays suffered by the direct and scattered signals. A rotation of the blades then causes the ghost to fluctuate, and if the ghost is sufficiently strong, the resulting interference can be objectionable. In such cases, the received picture displays a horizontal jitter or pulsation of the video reproduction. With a machine having coned blades, each blade contributes separately, and the interference occurs at twice the blades rotating frequency. As the interference increases, the entire (fuzzy) picture also shows a pulsed brightening, and still larger interference can disrupt the TV receiver's vertical sync, causing the picture to 'roll' (flip) or even break up. This type of interference occurs when the interfering signal reaches the receiver as a result of scattering, primarily specular (or mirrorlike), off the broad face of a blade, and is called the backward region interference. As the angle ϕ (see Fig. 1) between the WT-transmitter and the WT-receiver directions increases, the separation of the ghost decreases, and a somewhat greater interference is now required to produce the same amount of distortion. In the scattering region where the WT is almost in line between the transmitter and the receiver ($\phi \simeq \pi$ in Fig. 1), there is virtually no difference in the times of arrival of the primary and secondary signals.

The ghost is then superimposed on the undistorted (direct) picture, and the video distortion due to interference appears as an intensity (brightness) fluctuation of the picture in synchronism with the blade rotation. This type of interference is called the forward region interference. In all cases, the amount of interference depends on the strength of the scattered signal relative to that of the primary signal at the receiver and this decreases with increasing distance from the WT.

The observed video distortion also depends critically on this ratio, i.e., on the modulation index m ($\simeq \Gamma$ defined earlier) of the total received signal, and the modulation threshold m_0 is defined to be the largest value of m for which the distribution is still judged to be acceptable. The threshold is obviously subjective, but as a result of laboratory simulation studies, scale model measurements, and field testing using operational WTs, it has been established as $m_0 = 0.15$ for ϕ = zero degrees (where the time delay difference is maximum) increasing uniformly to $m_0 = 0.35$ for $\phi = 180$ degrees (where the time delay difference is zero). In other words, if $m = E^S/E^R > m_0$, the interference is too severe to be acceptable, and thus defines a region of possibly unacceptable interference about the WT.

For a given TV transmission and given WT, the interference zone can be computed by taking into account the propagation conditions [10]. If local terrain effects are ignored, the zone is typically a cardioid (Fig. 2) with a forward 'spike' directed away from the transmitter. The spike often represents the largest distance out from the WT where the interference can reamin objectionable, and in the case of the MOD-1 WT at Boone, NC, such interference has been measured out to 5 km from the

WT. The maximum distance from the WT where unacceptable interference may occur is defined as the interference distance of the WT. For a HAWT above a perfectly conducting flat earth the interference distance (r_H) under free space conditions is approximately given by

$$r_H = \frac{2A}{\lambda m_0} E^B/E^R \tag{5}$$

where it is assumed that the receiving antenna is omnidirectional.

The larger the WT, the larger the blade size (and, hence, A) and it is now clear that the larger the interference zone. An increase in size of a machine also increase its height above the ground, and this will in general expose the blade to a stronger ambient field. In practice, the height differential between the blade and the receiving antenna has a major effect on the size of the interference zone. In addition, the zone increases with frequency (or TV Channel number), and all other things being equal , the interference is worst on the upper UHF Channels. A small WT of a few kW capacity such as an individual homeowner might have produces the same type of interference, with the zones extending out at most a few tens of meters [11].

An interference zone is merely a region where unacceptable interference could occur with a poor quality (omnidirectional) receiving antenna, and there are many factors that affect the actual interference observed. In the first place, the maximum scattered signal is received only when the blade is so positioned to direct this signal to the receiver. As the wind veers and the machine rotates in azimuth, the interfering signal will shift to a different sector of the zone. Thus, at any given instant, only a small portion of the zone will suffer interference, and the probability of interference at any particular location in the zone depends on the prevailing wind direction and speed [6]. Moreover, since the zones differ from one TV Channel to another, it is unlikely that any one location will simultaneously experience interference on two different Channels. The antenna used can also be important. In the cardioid (but not in the forward scattering) portion of the interference zone, a high performance directional antenna can be deployed to discriminate against a secondary signal from the WT. Lastly, there are the local site and terrain effects. A hill, building, or even trees that shield the antenna from the WT can markedly reduce the interference, but if these attenuate the primary signal instead, the interference will be increased.

Most of the above comments also apply to the interference caused by a VAWT such as the Darrieus [4] but there are differences in detail. In particular, the modulation waveform introduced by a Darrieus contains broad pulses and narrow spikes, with repeating at twice the blade rotation frequency. The pulses produce video distortion with a threshold $m_0 \simeq 0.28$, but the spikes do not produce any observable distortion. From the considerations of scattering and interference zone, it can be shown that the interference distances of r_V, r_H for a VAWT and HAWT, respectively, are related by

$$\frac{r_V}{r_H} = \frac{W\sqrt{D\lambda}}{A} , \qquad (6)$$

where D,W pertains to the Darrieus and A is the equivalent scattering area of a HAWT.

Assuming 50 kW rating for both machines, $D = 17$ m, $W = 0.61$ m, and $A \simeq 6$ m^2,

$$\frac{r_V}{r_H} = 0.42\sqrt{\lambda}\ . \tag{7}$$

The interference distance is therefore identical ($r_V = r_H$) when $\lambda = 5.8$ m i.e., on Channel 2, but as the frequency (or Channel number) increases, the Darrieus produces progressively less interference than a HAWT e.g., by a factor of two on Channel 13, and by a factor of four on Channel 74.

Although the TVI effects of large HAWTs are fairly well understood at the present time, theoretical predictions [10] assume an idealized scattering model of the WT located above a smooth and homogeneous spherical earth. Unfortunately, WTs are often installed in rough terrain for which there is presently no acceptable electromagnetic model to compute the required field quantities. In such cases, and also to obtain the detailed information regarding the interference effect of an operating WT in an actual environment required for a site assessment, it is often necessary to rely on measurements. These are carried out by receiving commercially available TV signals at test sites selected in the neighborhood of the operational WT. Detailed discussion of results obtained from full scale measurements of TVI effects of various WTs may be found in the references cited earlier. Such measurements have been standardized as described in [12].

IV. Interference to FM Broadcast Reception [3]

Laboratory simulation techniques were used to study the interference to FM broadcast radio reception by artificially modulating the received signal with a pulse similar to that produced by a HAWT. The interference was assessed by listening to the quality of audio reproduction as a function of the ambient level of the signal and applied modulation index. The test receiver was a typical stereo receiver used in automobiles. When the ambient level of the input signal was high (signal-to-noise ratio $S/N \gtrsim 15$ dB), no distortion was found until the modulation index (m or Γ) reached about 0.73; even with a weaker signal ($S/N \lesssim 15$ dB) there was no significant distortion for $m \lesssim 0.38$ but as m was increased beyond this level, there was an increasing amount of audio distortion in the form of a pulsed high frequency hiss superimposed on the desired sound. The results imply that the effects of WT-interference to FM radio reception will be negligible except possibly within a few tens of meters of the WT; and even then the audio distortion will be perceptible only if the WT and the receiver are located in a region of low signal-to-noise ratio for that particular FM station.

V. Interference to Microwave Communication Link Systems [3]

Microwave communication links are widely used for transmission and reception of a variety of information and there are few locations throughout the USA that do not have a microwave link in their vicinity. To quantify the effect of WT interference on the performance of typical communication link for telephone and television signals, a deterministic analysis was carried out on a free space basis, i.e., neglecting the presence of the earth. Any degradation in performance depends on the sensitivity of a repeater receiver to modulation that a WT introduces, and this in turn is a function of the receiver characteristics. From a knowledge of the type of signals, modulation and modulation schemes used for the links, it was possible to specify a minimum level of interference which would adversely affect the link's performance. Using the pattern of the receiving antenna and the equivalent scattering area of a WT blade, the minimum level defines a "forbidden" zone around a repeater station where the siting of a WT could cause unacceptable interference.

However, it is often not necessary to determine the complete forbidden zone for the purpose of a WT site assessment. The satisfactory performance of a microwave link system requires that there be adequate clearance between the link path, i.e., the optical line-of-sight transmission path between the two link antennas, and any nearby scattering objects. It is often sufficient that all scattering objects lie outside the first few Fresnel zones appropriate for the two antennas. For the siting of a WT in the vicinity of a microwave link we use the following criterion:

$$H \geq 3H_1 \quad , \tag{8}$$

where H is the clearance of the line-of-sight path from the top of the WT, and H_1 is the distance from the line-of-sight path to the boundary of the first Fresnel zone. In some cases it is also necessary to evaluate the maximum secondary field at one of the receivers produced by the WT blade scattering, i.e., calculate Γ and make sure that its value is less than the threshold value appropriate for the system.

Similar analysis can be carried out to evaluate the impact of a WT on the performance of an earth station receiving signals from a geostationary satellite.

VI. Navigational Systems [3]

Navigational systems of varying types are widely deployed throughout the United States, and because of their vital role in ensuring safe and effective transportation, it is important to assess the potential impact of WTs on these systems. To date we have considered following systems.

VOR. The VOR and DVOR (Doppler VOR) systems are extensively used for (commercial) aircraft navigation over the continental United States, and in fact over the world. Due to this and their apparent vulnerability, we chose to analyze the impact of a rotating WT on the performance of those two systems. The analysis was carried out by comparing the direct and WT-scattered VOR (DVOR) signals at an aircraft and then using the detection characteristics of the receivers to estimate the resulting error in the predicted aircraft locations. The analytical procedures employed are logical extensions of those the FAA (Federal Aviation Administration) found acceptable in the case of static scatterers [13], and showed that the interference when the WT blades are rotating is less troublesome than when the blades are stationary. It therefore follows that the siting of a WT can be carried out according to the standard guidelines established by the FAA.

LORAN-C [6]. The performance of a Loran-C system in the presence of a MOD-1 WT ($A = 40\ m^2$) has been theoretically investigated. Since the physical dimensions of the WT are very small compared to the extremely large wavelength ($\lambda = 3 \times 10^3$ m) of Loran-C signals, the scattered signals from the WT are found to be about 100 dB lower than the direct signals at the receiver even when the WT is located as close to 100 m to the transmitter or the receiver. It is unlikely that the Loran-C receiver performance would be degraded by such low level interfering signals. The mutual interaction effects of the WT on the performance of the Loran-C transmitting antenna are found to be insignificant for a WT located as close to $\lambda/12$ (~ 2.50 m) to the transmitter. From the results discussed it appears that a WT located at a distance $\geq \lambda/12$ (~ 250 m) from any transmitter (a receiver will not have any significant effect on the Loran-C performance.

Conclusions

The EMI effects of both HAWTs and VAWTs on a selected number of electromagnetic systems have been investigated. Although much more work remains to be done with these and other systems, our knowledge of the interference that a WT produces is now sufficient to provide guidance in the siting of a WT or windfarm to minimize its impact on the electromagnetic environment.

References

[1] D. L. Sengupta and T.B.A. Senior, "Electromagnetic Interference to Television Reception Caused by Horizontal Axis Windmills," Proc. IEEE, Vol. 67, No. 8, pp. 1133-1142, August 1979.

[2] D. L. Sengupta and T.B.A. Senior, "Electromagnetic Scattering Parameters for Large Horizontal Axis Wind Turbine Blades," submitted to the International Journal of Wind Engineering.

[3] D. L. Sengupta and T.B.A. Senior, "Electromagnetic Interference by Wind Turbine Generators," Final Report No. 2 on Contract EY-76-S-02-2896.AOUT, Wind Systems Branch, Division of Solar Energy, Department of Energy, Washington, D.C., USA, March 1978.

[4] D. L. Sengupta, T.B.A. Senior and J. E. Ferris, "Measurements of Television Interference Caused by a Vertical Axis Wind Machine," SERI/STR-215-1881, UC Category: 60, Subcontract No. XH-0-9263-1, Solar Energy Research Institute, Golden, CO, 80401, USA, January 1983.

[5] T.B.A. Senior, D. L. Sengupta and J. E. Ferris, "TV and FM Interference by Windmills," DOE/TIC-11348, Energy Research and Development Administration, Washington, D.C., USA, February 1977.

[6] D. L. Sengupta and T.B.A. Senior, "Wind Turbine Generator Interference to Electromagnetic Systems," DOE/ET/20234-TI (DE 82019039) U.S. Department of Energy, Division of Solar Technology, Wind Systems Branch, Washington DC 20595, USA, August 1979.

[7] D. L. Sengupta, T.B.A. Senior and J. E. Ferris, "Television Interference Tests on Block Island, RI," Technical Report No. 3, on Contract No. EY-76-S-02-2846.A0004, Wind Systems Branch, Division of Solar Energy, Department of Energy, Washington, D.C., USA, January 1980.

[8] D. L. Sengupta, T.B.A. Senior and J. E. Ferris," Measurements of Interference to Television Reception Caused by the MOD-1 Wind Turbine at Boone, NC," Technical Report No. 1 on Contract No. DE-SERI-XII-0-9263-1, Solar Energy Research Institute, Golden, CO, 80401, USA, January 1981.

[9] D. L. Sengupta, T.B.A. Senior and J. E. Ferris, "Television Interference Measurements Near the MOD-2 WT Array at Goodnoe Hills, WA," SERI/STR-211-2086, DE 84000030, Subcontract No. DE-AC02-76-ET 20234, Solar Energy Research Institute, Golden, CO, 80401, USA, November 1983.

[10] T.B.A. Senior and D. L. Sengupta, "Large Wind Turbine Siting Handbook: Television Interference Assessment," Final Subcontract Report, SERI/STR-215-1879, Subcontract No. EY-76-S-02-2846.A0004, Solar Energy Research Institute, Golden, CO 80401, USA, January 1983.

[11] D. L. Sengupta, T.B.A. Senior and J. E. Ferris, "Study of Television Interference by Small Wind Turbines," Final Subcontract Report, SERI/STR-215-1880, Subcontract XH-9263-1, Solar Energy Research Institute, Golden, CO 80401, USA, January 1983.

[12] D. L. Sengupta, T.B.A. Senior and J. E. Ferris, "Measurements of Interference to Television Reception Near Large Horizontal Axis Wind Turbines," submitted to the International Journal of Wind Engineering.

[13] "Handbook: VOR/VORTAC Siting Criteria," Report 6700.11, Federal Aviation Administration, Department of Transportation, Washington, D.C., USA, August 1968.

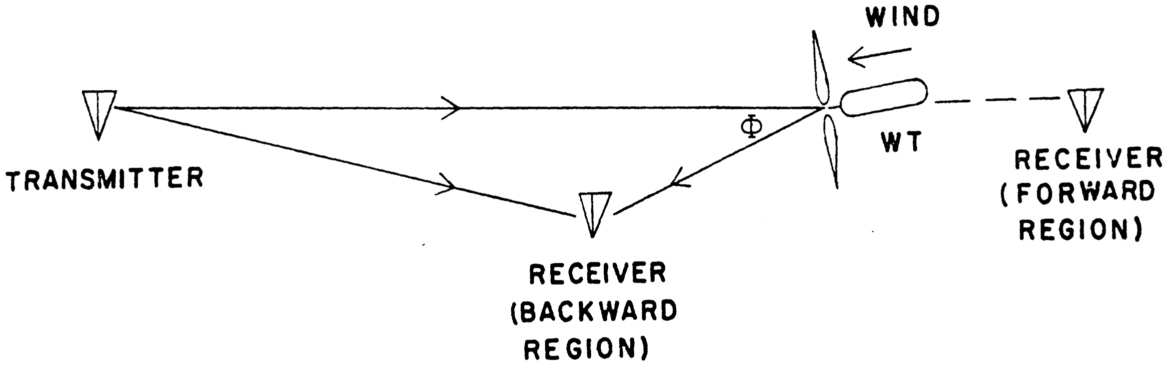

Fig. 1: Geometry of the WT Blade Scattering.

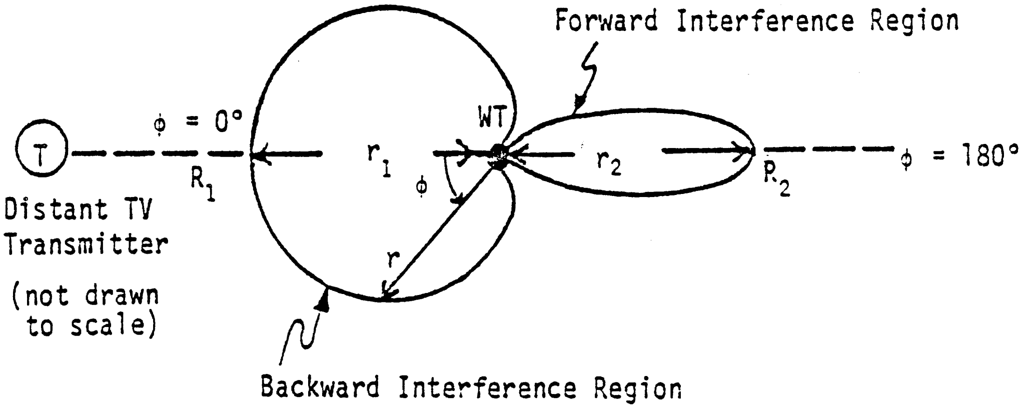

Fig. 2: Sketch of the TV Interference Zone of a WT.