Wind turbine generators with active radar signature control blades

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ABSTRACT

The large radar cross section of wind turbine generator (WTG) blades combined with high tip speeds can produce significant Doppler returns when illuminated by a radar. Normally, an air traffic control radar system will filter out large returns from stationary targets, however the Doppler shifts introduced by the WTG are interpreted as moving aircraft that can confuse radar operators and compromise safety. A possible solution to this problem that we are investigating is to incorporate an active layer into the structure of the WTG blades that can be used to dynamically modulate the RCS of the blade return. The active blade can operate in one of two modes: firstly the blade RCS can be modulated to provide a Doppler return that is outside the detectable range of the radar receiver system so that it is rejected; a second mode of operation is to introduce specific coding on to the Doppler returns so that they may be uniquely identified and rejected. The active layer used in the system consists of a frequency selective surface controlled by semiconductor diodes and is a development of techniques that we have developed for active radar absorbers. Results of experimental work using a 10GHz Doppler radar and scale model WTG with active Doppler imparting blades are presented.

Keywords: Radar, Wind turbine generator, Doppler

1. INTRODUCTION

The problems of global warming and the limited life span of carbon based energy sources are increasingly becoming issues of international concern. In the United Kingdom the British Government is actively pursuing policies to increase the proportion of UK energy generation produced from renewable sources, and to reduce its dependence on fossil fuels. Due to the geographical location of the UK, one of the most suitable forms of future renewable energy is electricity generation from wind turbine generators. Research carried out by UK electricity generation companies has identified that many of the prime locations for wind farms are on the exposed landscapes surrounding the UK’s regional airports. However, planning permission for such installations is often being denied due to objections from the UK’s civil aviation regulators on the grounds of air safety [1]. The problem arises because the moving blades of the wind turbines interfere with the operation of airport radar systems. Airport primary surveillance radars typically operate at frequencies around 1GHz and 3GHz, and track the position and speed of aircraft in their surrounding airspace using pulsed Doppler radar techniques. Such radars are equipped with signal processing software that eliminates the radar returns from spurious targets, such as large buildings, terrain clutter and road traffic. The filtering out of stationary and slow moving targets is relatively straight forward as, although they may produce a large reflected signal, the associated Doppler shift will be zero or below a preset threshold. A problem arises however when an airport radar receives returns from a wind turbine installation as the motion of the blades can impart a significant Doppler shift onto the received radar signal that is comparable with that expected from an aircraft. For example, a modern wind turbine generator may have a hub height of 90m with a blade diameter of 80m rotating at up to 30 revolutions per minute. The blade tip speed of such a turbine can therefore exceed 100m/s.

The Doppler shift imparted to the radar signals that are reflected from the turbine blades will also vary with the rate of rotation of the blades and their aspect as viewed by the radar. Furthermore, the amplitude of the reflected signals is not constant as the blades rotate and reflection “flashes” may cause sudden and unpredictable changes in Doppler frequency thus causing the radar to break track or to predict multiple targets when only one actually exists. This situation becomes unmanageable when there are many turbines present as a farm. Although some of these deleterious effects may be tackled in the radar signal processing software, it may still be necessary to seek additional amelioration measures in the form of modifications to the electromagnetic scattering properties of the wind turbine blades.
2. POSSIBLE SOLUTIONS

Conventional techniques for modifying the radar scattering characteristics of an object involve either shape change or the use of radar absorbent materials (RAM). Clearly the former is unacceptable in the present application since the shape of the turbine blades must be determined by aerodynamic considerations. The design and application of RAM at the frequencies of interest (1 – 3 GHz) is well established and is currently being investigated as a potential solution to the blade scattering problem [2]. For any RAM solution, the fundamental issues to be resolved will centre on absorber bandwidth, material thickness and weight. Clearly any acceptable RAM must be of the structural type (i.e. one whose topology forms a part of the blade load-bearing structure) rather than of the appliqué type (i.e. placed on top of an existing blade skin), since this should result in a minimum weight solution; nevertheless, the trade-off between good absorber performance at 1 GHz and minimum RAM thickness is still a difficult one to achieve. A further complication with the use of passive RAM is that it is difficult to produce a design that is optimum for all aspect angles of illumination and so inevitably some compromise in performance will have to be accepted.

An alternative approach to passive RAM is the use of adaptive, or active, RAM. An adaptive RAM is a structure that is able to sense the radar illumination and modify its electrical characteristics accordingly to minimise detection. Research into generic types of dynamically adaptive RAM (DARAM) has been underway at The University Sheffield since 1990, and the approach we have used is based on arrays of semiconductor devices embedded into a composite structure. The advantage of incorporating adaptive RAM into wind turbine blades is that the electromagnetic scattering properties of the blades can be changed in real time in response to variations in both blade rotation and illumination aspect angle.

A further advantage of the adaptive RAM approach is that it can be deliberately used to impart ‘false’ Doppler modulation onto the reflected signals. Hence it is possible to code the reflected signals from individual wind turbines thus enabling the radar processing software to uniquely identify and reject such returns. This approach also has the added advantage of providing high quality calibration signals needed for the correct operation of primary surveillance radars.

3. THE PHASE-SWITCHED SCREEN

The Phase-Switched Screen (PSS) is one technique for achieving a DARAM [3-6]. The simplest form of PSS consists of a single active layer placed in front of, and at a distance d, from a conducting back plane, as shown in Figure 1. The active layer takes the form of a thin sheet that can be switched rapidly between very high and very low resistance states. Consider first the case of an ideal screen in which the active layer can be switched between totally transparent (OFF, $R_{OFF} = \infty \Omega$) and totally reflecting (ON, $R_{ON} = 0 \Omega$) states. If the screen is illuminated at normal incidence by a unit amplitude plane wave of frequency $f_0$, the reflected field may be described by \( \cos(\beta_{0} \pi t) \) when the screen is ON, and by \( \cos(2\pi f_0 t + 2\beta_d) \) when the screen is OFF. Here \( \beta = \frac{2\pi}{\lambda} \). When \( d = \frac{\lambda}{4} \), the reflected signals produced by the ON and OFF states are 180° out of phase and the resultant signal is phase modulated. If the active layer is switched between these two states by a periodic square wave with an equal mark-space ratio and period $T$, the normalised power spectrum of the reflected field is given by
\[ P(f) = \sum_{n=\pm\infty}^{\infty} \left[ \frac{\sin(n\pi/2)}{n\pi/2} \right]^2 \delta(f + f_c - n/2T) \]  

(1)

The spectrum consists of discrete sidebands whose amplitudes follow a \( \frac{\sin(x)}{x} \) envelope centred on the illuminating frequency. Crucially however, the spectrum has no component at \( f_c \) and so the time-averaged reflected energy at the illuminating frequency is zero. To exploit this property in a practical application, for example that of radar signature reduction, the frequency at which the screen is modulated, \( f_S \), must be sufficiently high to move all the sidebands in the reflected spectrum outside the bandwidth of the receiving system.

The active layer in a practical PSS will not exhibit ideal switching characteristics but instead may be characterised by an ON resistance, \( R_{ON} > 0 \), and an OFF resistance, \( R_{OFF} < \infty \). The non-ideal screen is conveniently analysed in terms of a switched reflection coefficient which may be derived using a transmission line analogue. Assuming a planar structure of infinite transverse dimensions and normal plane wave incidence, the reflection coefficients of the ON and OFF states are given by

\[ \rho_{ON}(f) = \frac{Z'_{ON} - Z_0}{Z'_{ON} + Z} \quad \text{and} \quad \rho_{OFF}(f) = \frac{Z'_{OFF} - Z_0}{Z'_{OFF} + Z} \]  

(2)

Where \( Z'_{ON} \) and \( Z'_{OFF} \) represent the input impedances at the front face of the structure and are given by

\[ Z'_{ON} = \frac{R_{ON}Z_0\tan(\beta d)}{R_{ON} + jZ_0\tan(\beta d)} \quad \text{and} \quad Z'_{OFF} = \frac{R_{OFF}Z_0\tan(\beta d)}{R_{OFF} + jZ_0\tan(\beta d)} \]  

(3)

The time-averaged reflection coefficient of the screen, assuming a symmetrical square-wave switching function, is given by

\[ \rho_{ave}(f) = \frac{\rho_{ON}(f) + \rho_{OFF}(f)}{2} \]  

(4)

Solving (5) for zero reflectivity when \( d = \frac{\lambda}{4} \) leads to the result

\[ R_{ON}R_{OFF} = Z_0^2 \]  

(5)

Obviously this condition may be difficult to achieve in practice, but zero reflectivity may still be obtained by adjusting the mark-space ratio of the switching waveform. This case may be analysed by letting the active layer be switched on for a time \( \tau \), and off for \( T - \tau \), where \( T \) represents the period of the modulating waveform. The time-averaged reflection coefficient is now given by

\[ \rho_{ave}(f) = \frac{\tau\rho_{ON}(f) + (T - \tau)\rho_{OFF}(f)}{T} \]  

(6)
Solving (7) for $\rho_{\text{ave}}(f) = 0$ and considering only valid solutions for $\tau$ (i.e. $0 \leq \tau \leq T$) leads to the conditions

$$R_{\text{ON}} \leq Z_0 \text{ and } R_{\text{OFF}} \geq Z_0$$

(7)

Hence, provided that the resistance of the active layer can be switched between values that are above and below the impedance of free space, the zero reflectivity condition can be obtained by adjusting the mark-space ratio of the modulating signal. Note that when $R_{\text{ON}} = R_{\text{OFF}} = Z_0$ the PSS defaults to a conventional Salisbury screen.

4. PRACTICAL IMPLEMENTATION OF A PSS

To realise a practical PSS we need a surface that can be switched rapidly between two impedance states. Potentially this could be achieved using some type of functional material such as an active conducting polymer; however, our present active layers consist of a two-dimensional grid of half-wavelength bow-tie dipoles that are loaded at their centres with pin diodes, as shown in Figure 2. Under no-bias conditions the pin diodes present high microwave impedance and the dipoles may be considered open circuit. Hence the grid of dipoles is non-resonant and represents a high impedance equivalent surface. When the diodes are biased ‘on’, however, their high frequency impedance becomes low and the dipoles are resonant at the half-wavelength frequency. Hence the grid of shorted dipoles becomes a strong scatter and represents a low impedance surface. In practice the active surface is constructed on a standard, low-cost PCB substrate (FR4) using photo-etching techniques, and the pin diodes are in surface mount packages to aid the manufacturing process and to produce a low-profile surface. A photograph of a section of a prototype active surface designed for operation at 11GHz is shown in Figure 3. To complete the PSS structure, shown schematically in Figure 1, the active surface is spaced from a conducting back-plane by a low-loss dielectric spacer, and the back-plane may be carbon-fibre or copper mesh to reduce weight.

4.1 Performance of a PSS against pulsed radar signals

For the PSS approach to be useful for reducing the scattering from wind turbine blades it must be effective against the type of pulsed illumination used by airport primary surveillance radars. To test this concept we synthesised a pulsed radar signal using a microwave signal generator and a spectrum analyser. The measurements were carried out on a 300mm by 300mm planar PSS in an anechoic NRL arch facility configured to measure monostatic back-scattering. An Agilent E8257C signal generator was used as a source in conjunction with an Agilent E4407B spectrum analyser to record the spectrum of the signal scattered from the PSS. The source was programmed to provide an 11GHz pulsed signal of 1uS duration with a pulse repetition rate of 100uS. The frequency spectrum of the signal reflected by the PSS was recorded over a frequency span of 100MHz for the screen in its ‘off-state’, i.e. with no applied modulation, and also with a 20MHz square-wave signal applied to the PSS and these data are shown in Figure 4. The scattered signal from the unmodulated PSS shows a classic $\sin x/x$ response centred on the 11GHz carrier. The results for the modulated PSS show that the pulsed radar energy has been redistributed into sidebands at 20MHz separation resulting in a suppression of the power spectrum of the original signal of over 30dB and confirming the operation of the PSS.

4.2 Application to rotating wind turbine blades

To investigate the concept of using a PSS to modify the radar returns from wind turbine blades we have taken an experimental approach based on a scaled-model windmill designed for operation at 10GHz. The model has a hub-height of 45cm and three, 36cm long, 4cm wide blades that are driven by a dc electric motor; a photograph of the model is shown in Figure 5. One side of each blade was covered with a rigid foam spacer and a specifically designed active surface to form a PSS structure. A standard laboratory signal generator was used to drive the PSS with a square wave at a frequency of 100kHz. A diagram illustrating the experimental set-up used for the measurements is given in Figure 6. The radar consists of a 30cm diameter centre fed parabolic antenna, driven by a 10.8GHz continuous-wave transmit/receive Doppler module. The time-domain base-band Doppler output was recorded by digital sampling oscilloscope. In this initial experiment, only one side of each blade was configured to act as a PSS, and therefore conventional RAM was used to shield the radar from returns from the untreated side of the blades. Figure 7 compares the time domain Doppler returns obtained from radar measurements on the model with the PSS blades switched off (top) and switched on (bottom). Large reflection ‘flashes’ are clearly seen in the data recorded.
when the PSS was turned off, and occur when the blades are perpendicular to the illuminating radar beam. The time interval between the flashes is approximately 0.23s and corresponds to the rotation frequency of 64rpm. For the case when the PSS was active, the reflection flashes are also present but their magnitude has been significantly reduced.

To investigate the Doppler content of the radar returns from the windmill, the time-domain data of Figure 7 was processed using Fourier transform techniques to provide a frequency spectrum. These results are presented in Figure 8 and show that the Doppler spectrum obtained from the model with the PSS blades switched off contains a range of frequencies from 0Hz to approximately 175Hz. The sharp cut-off at 175Hz corresponds to the maximum Doppler shift that occurs from the tip of the windmill blade rotating at 64rpm. The spectrum obtained when the blades are active shows a significant reduction in the reflected energy contained in the frequency range that corresponds to the region of the blades that covered with the PSS.

To test the concept of imparting a false Doppler code onto the radar reflections from the windmill, a second experiment was carried out in which the windmill hub was covered with a small PSS panel. Time-domain radar data was recorded from the windmill with the PSS switched off and with the PSS modulated by a 400Hz square-wave signal. In both cases the windmill blades were rotating at approximately 75rpm, which gives a maximum Doppler shift due to the blade tips of approximately 200Hz. The Doppler spectra obtained from both these sets of data are shown in Figure 9. As expected, the Doppler shift produced by the rotating blades of the windmill is the same independent of whether the hub PSS is active or not. However, when the hub PSS is active, a clearly identifiable frequency component is visible at 400Hz (the screen modulating frequency). This ‘false’ Doppler component can be programmed to occur at any desired frequency and can be so chosen to uniquely identify a specific windmill.

**CONCLUSIONS**

The PSS is one possible technique for managing the effects of tracking errors in radar systems caused by unwanted reflections from wind-farm installations. Unlike conventional (i.e. passive) RAM, which relies on narrowband phase cancellation or broadband energy absorption, the effectiveness of the PSS is due to its ability to redistribute reflected energy so that it falls outside the pass-band of the receiving system and hence is not detected. Furthermore, the PSS is capable of synthesising or modifying the apparent Doppler shift of the reflected signal, which can thereby be labelled with an appropriate code. In this paper we have reported experimental results obtained from a scaled model windmill with PSS blades operating in conjunction with a 10GHz Doppler radar system. These initial results confirm the basic theoretical concepts of the PSS approach. Future work will investigate the design of PSS for operation at the primary surveillance radar bands at frequencies of 1GHz and 3GHz, and include full-scale field trials.

**REFERENCES**

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Figure 1. Details of the active absorber construction. $d =$ spacer thickness

Figure 2. Layout of PSS active layer showing pin diode-loaded bow-tie elements
Figure 3. Prototype active surface with pin diodes

Figure 4. Measured frequency spectrum of the reflected signal from the PSS with pulsed illumination (grey trace – unmodulated PSS; black trace – PSS modulated with a 20MHz square-wave)
Figure 5. 10GHz Scale model WTG with active PSS blades

Figure 6. Details of the experimental set-up used to measure the radar returns form the model windmill
Figure 7. Time domain returns from the wind turbine model (top: blade off, bottom blade on)
Figure 8. Doppler spectrum obtained from the WTG model with DRAM blades.

Figure 9. Doppler spectrum obtained from the WTG model with DRAM blades.