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Wind Farm Gapfiller Concept Solution

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Abstract— **This paper describes a Gapfiller concept solution to mitigate the potential negative effect from a wind farm upon a military surveillance radar system. The problem is described as well as the technical solution to mitigate the problem. This paper does not describe signal processing techniques that can be applied to the main surveillance radar, but it describes some important technical requirements and a Gapfiller solution that can be used to complement a surveillance radar system. The application of a Gapfiller deployed within an offshore wind farm is described and other relevant applications are suggested.**

I. Introduction

The Gapfiller project came about as a result of plans for constructing an offshore wind farm. The two Norwegian renewable energy companies Statoil ASA and Statkraft ASA have formed the company Scira Offshore Energy building the Sheringham Shoal Offshore Wind Farm consisting of 88 turbines located 25 km off the coast in North Norfolk UK (see Fig 1). An air defence radar system covering the area, operated by UK Ministry of Defence (MoD), is located in the seaside town of Trimingham. Due to some signal processing and hardware limitations in the radar system, a shadowing zone is created behind the wind farm that may reduce the performance of the radar system.

For full wind farm operation a condition has been imposed upon the wind farm operator that the negative effects on the military radar shall be mitigated.

In general, three alternative mitigation solutions exist; either to modify the existing surveillance radar, or to replace the existing radar with a wind farm hardened surveillance radar, or to use a gap infill radar (Gapfiller) that provides radar surveillance coverage of the affected area. This paper describes the Gapfiller concept and its proposed implementation.

Fig 1. Sheringham Shoal Offshore Wind Farm in United Kingdom

II. The Problem

Preliminary impact analysis carried out in 2008 [1] indicated that, for turbines with a predicted peak RCS of 35 000 m^2 [2] in line of sight to the air defence radar, there could be a number of potential radar impacts:

- **Clutter**: Increased number of unwanted returns reported in the area of the wind farm due to the detection of wind turbine echoes, both stationary towers and the rotating blades that have a considerable Doppler frequency spectrum.
- **Desensitisation**: Potentially reduced probability of detection for wanted air targets in a region extending above and around the wind farm in both range and azimuth. Due mainly to potentially large turbine range processing sidelobes extending behind the wind farm for a distance comparable to the length of the transmitted signal pulse; i.e. up to 10-20 km beyond the wind farm
- Consequent loss of wanted target plotting and tracking performance in the affected areas

In the case of the Trimingham radar, the affected area was predicted to extend to about 10-20 km behind the wind farm (see Fig 2). Hence, any reduced radar performance within the affected area must be mitigated.

During 2008-2009 BAE Systems conducted a feasibility study [3] on contract with Statoil that has formed the basis for pursuing alternative means of mitigating negative effects on the regional military air surveillance radar.

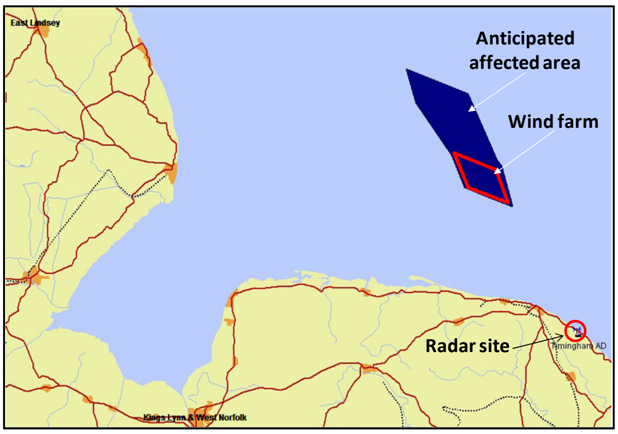

Fig 2. Overview of the scene with MoD radar site at Trimingham, the wind farm located 25 km offshore and the anticipated affected area

III. Electromagnetic Considerations

Wind farm impact on radar and potential mitigation options were considered in papers published in 2007 [4], [5], the following sub-sections provide an overview of more recent analyses.

A. Electromagnetic Interactions

During the past few years, several international studies of electromagnetic interaction with radars, communication systems and wind turbines have been conducted. The following studies [6]-[12] illustrate relevant relationships of wind turbine tower radar cross section (RCS), signal shadowing and radar signal blockage.

With reference to the above studies, representative measured electromagnetic values for wind turbine considerations are as follows:

- If the tower side slant angle is 0.8º, the tower RCS becomes about 100 m^2, and it is reduced as a function of increasing slant angle (i.e. 10 m^2 at 2.7º slant angle). This is consistent with typical RCS values for large transport aircraft such as the Boeing 747.
- The turbine blades constitute a much weaker radar signal return than that of the tower (in the order of 30 dB weaker)
- Blockage and shadowing from a wind turbine is very small. The shadow from a wind turbine tower extends only a few hundred meters directly behind the tower with a width comparable to the tower diameter.

Hence, it can be safely concluded that radar system receivers and digitisation circuitry have sufficient dynamic range to handle the types of signal levels reflected from wind turbines.

B. Radar Detection

There is no uncertainty about the fact that radars can detect wind turbines. The only way to be absolutely sure that radars will not be affected by a wind farm is to avoid direct electromagnetic line of sight between the radar and the wind farm. However, radars are made to detect different types of targets. Hence, detection of a wind farm is in general not considered to be limiting for radar detection capability.

A wind turbine is composed of three main parts that can be detected with varying signal strength. These are the tower, the nacelle mounted on top of the tower and the turbine blades.

UK Coast Guard has carried out experiments using land based marine radar systems. The results show clearly that vessels can easily be detected even when operating inside or behind a wind farm [7].

The immediate advantage of a wind turbine tower is that it does not move; it is located at the same position for years on end, and the tower reflected radar signals are located exactly to where the turbine is positioned. This means that the detected object – that is the wind turbine – is very well known to the radar operator. A wind farm in close proximity to the sea is often equipped with AIS so that it is identified in the radar picture independent of radar detection.

C. Signal Strength

When radars illuminate a wind turbine, the strongest reflections originate from the turbine tower. The signal can become very strong if the tower is at right angle to the radar line of sight (mirror reflection) and the distance between the radar and the tower is short. The strong reflected signal will mask reflected signals from other targets in close proximity to the tower.

However, the turbine tower mirror reflection condition is a very rare incident, because the tower slant angle of typically 0.6º - 0.8º gives rise to a much weaker reflected signal. Using the worst case calculated RCS is therefore considered to be too conservative when modelling expected reflected signal strengths from a wind turbine, which in turn would impose too stringent radar system requirements.

D. Range Accuracy

As a rule of thumb, radar range accuracy is proportional to the inverse of the radar bandwidth, while the antenna beam width regulates the azimuth accuracy. Typical modern radar systems utilise Frequency Modulated (FM) long pulses with a relatively high bandwidth that provide high range accuracy across the radar instrumented range. A wind farm does not influence the radar range accuracy.

E. Range-Azimuth Gating (RAG)

One method to stop a signal from entering the radar receiver is to close the receiver for a certain range interval when the radar is looking at a known strong reflectivity target; such as a mountain range, a large industrial building, a busy road bridge, or a wind turbine. Many modern radar systems are equipped with such a functionality called *"range-azimuth gating"* or *"RAG mapping"*. The effect of using a RAG is that the radar will not receive or process signals from certain directions and range intervals.

Based on the radar type, signals up to a few hundred meters in front of and behind a range-gated interval will also be removed. However, the radar will operate as usual outside the range gate interval [6]. In modern radar systems, the range gate can be implemented in software to remove a strong signal reflection from a known target.

F. Shadowing

During the years 2007-2009, several experiments [11] were conducted to measure the radar shadow behind a wind turbine. The radar shadow is measured to be up to 2 dB reduced signal level a few hundred meters behind the wind turbine tower at a width comparable to the tower diameter. The radar shadowing is hardly measurable for longer distances.

Shadowing is considered to be much less of a problem than previously anticipated. In most reported cases, shadowing is a radar hardware and/or software induced effect; not an electromagnetic problem.

IV. Performance Requirements

The mitigation performance requirements are the result of a negotiated compromise between what can be achieved (mitigation measures) and what can be accepted by MoD. The performance requirements - denoted the "*Aviation Specification*" - are illustrated in Fig 3 and described as follows:

- Full radar performance outside a volume defined as 2 km around the wind farm area - between sea level and 2500 feet altitude,
- The performance requirement within the surveillance area is a probability of detection PD ≥ 80 % of 1 m^2 Swerling case 1 target,
- Within the wind farm volume, a probability of detection PD > 0 % is not required.

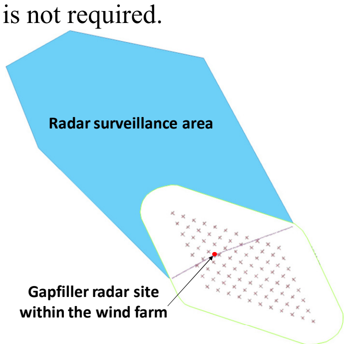

Fig 3. Required Gapfiller radar surveillance area

Due to the existence of agreed performance requirements, it will be possible to verify that the Gapfiller meets the requirements through the use of flight tests when all wind farm turbines are installed and in operation.

It is important to note that MoD has agreed to a limited performance degradation of their surveillance system. From experience, it is considered quite unusual that the military accept any degradation. The fact that no surveillance data is needed within a 2 km distance of the wind farm - from sea level up to 2500 feet – makes it much easier to find technical solutions. An agreement between the parties is critical to the existence of the wind farm, and without it, wind farm operation would not be possible.

It is strongly emphasised that representatives from the military and utilities seek to reach similar agreements in future projects.

V. The Site

There are two options for the siting of a Gapfiller radar; onshore or offshore. Each has its own benefits and limitations.

To operate an onshore radar in the case of Sheringham Shoal Offshore Wind Farm would require an operational range of at least 50 km. One of the main reasons for not choosing land, was that no site could be identified that provided sufficiently low level cover in the gap filler region to satisfy MoD without building a prohibitively tall tower. Thus offshore was the preferred option.

The traditional approach to deploying a radar system is to locate it away from any source of interference. However, in the case of the Sheringham Shoal Offshore Wind Farm, it will be both difficult and expensive to position the radar on a dedicated platform away from the wind farm area. At some point it was considered to position the radar 20 m above sea level on a cantilever mounted on the north-western wind turbine tower giving unobstructed view of the radar surveillance area. However, maintenance access up a turbine tower in varying weather conditions was considered difficult, and subjecting maintenance personnel to such high risk prevented that solution. Hence, an alternative location had to be found.

It is possible to tolerate high RCS returns from objects such as wind turbines if special care is taken in the radar design and through the use of software controlled digital radar systems. That opens up the possibility of locating the Gapfiller 25 m above sea level on the offshore monopole substation (see Fig 4) within the wind farm with about 20 turbines in direct line of sight in the direction of the radar surveillance area; the nearest less than 1000 meters away.

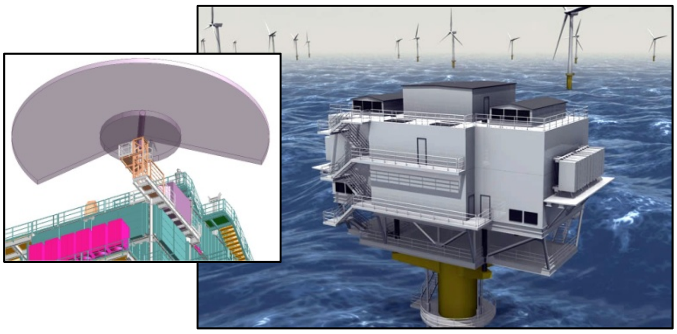

Fig 4. The Gapfiller location is a cantilever on the monopole substation 25 m above sea level within the wind farm area

VI. The Solution

The fact that the Gapfiller can be located on a monopole substation within the offshore wind farm solves many problems and reduces the Gapfiller range requirements considerably as compared with alternative solutions positioning the Gapfiller on land.

The immediate positive effect of a relatively short operational range opens up the possibility for using low power solid state radar systems as a Gapfiller. Typical transmitter peak power of a solid state radar is today around 200 W with system weights of about 100 kg and electrical power needs of 2 kW. An extra bonus would be the lack of special radhaz measures due to the low transmitter power.

The negotiated 2 km exclusion zone around the wind farm area gives rise to two in particular useful effects. The first one means that the radar signal can propagate through the wind farm area while the radar receiver is switched off, only to be turned on once the radar signal has reached beyond the 2 km wind farm boundary. Hence, any signals reflected off the wind turbines will never be allowed to enter the radar receiver.

Alternatively, if the radar receiver is left open, it will have ample time to recover from any high wind turbine RCS returns due to the 2 km boundary zone. Typical receiver recovery time of a modern radar system is in the order of 100 ns or less corresponding to a distance of 15 m.

The second useful effect is that any radar signal shadowing due to the wind farm towers will be virtually nonexistent by the time the radar signal reaches the 2 km boundary, due to the fact that electromagnetic signals tend to creep around vertical cylindrical structures such as wind farm towers. Any shadowing will last only a few hundred meters behind a tower, and only across a width comparable to the tower diameter. Shadowing of a radar system [12] is considered to be a much smaller problem than only a few years ago.

The main features of the Gapfiller solution [13] are:

- PD ≥ 80 % of 1 m^2 Swerling case 1 target
- X-band (or S-band pending on application)
- Solid state
- Software controlled
- Coherent pulse Doppler system
- Short pulses (0.1-100 μsec)
- High range accuracy (15 m)
- Narrow antenna beam width (~0.6°)
- High availability (≥ 99 %)
- Integrated plot extractor
- ASTERIX data feed

The Gapfiller is remote controlled through a local area network. In the case of the Sheringham Shoal implementation, the plot extracted Gapfiller data would have been transferred ashore through an optical fibre cable and connected to the UK Air Defence Ground Environment Command and Control System (UCCS) that will use the Gapfiller plot extracted data feed to complement their recognized air picture.

VII. Applications

At time of writing, two manufactures of solid state digital radar systems capable of meeting the requirements listed above have been identified.

The instrumented range becomes significantly longer and even more attractive if less stringent RCS and detection requirements are needed as compared to the 1 m^2 Swerling case 1 target. This opens up for several other applications.

In addition to the offshore wind farm Gapfiller application, which has been detailed to some extent in this paper, the Gapfiller can easily be deployed in similar or less demanding applications, such as surveillance radar for small airports or for coastal surveillance. And there is in fact no need to be located near a wind farm to use such a Gapfiller. If there is a need for a radar system, the Gapfiller concept solution meets most demands for cheap and reliable surveillance.

VIII. Conclusions

The identified Gapfiller concept solution has high performance, solid state, no radhaz, low weight and volume, low power consumption, short lead times, high availability and low price. The concept solution exceeds military air surveillance performance requirements and with good margin.

In the case that a wind farm license is subject to a provisional clause, for example that an agreement between a radar owner and the wind farm developer must be reached prior to wind farm operation, the Gapfiller will easily solve that problem and to a very small cost as compared to conventional radar systems.

It is interesting to observe that there is a strong correlation between the cost and the weight of radar systems. Conventional radar systems' weight is about ten times that of a solid state radar system, and the cost is about ten times as high. This means that the price per kilo is about the same for solid state radar systems as for conventional radar systems.

In the case of a Gapfiller solid state radar application, cheap may be just as good as a conventional high performance radar system, and it is much easier to deploy.

IX. Epilogue

Since submitting the abstract for this paper, MoD and Scira Offshore Energy have reached an agreement to replace the existing regional air surveillance radar system at Trimingham with a new TPS-77 from Lockheed Martin. Hence, the Gapfiller will not be implemented at Sheringham Shoal Offshore Wind Farm. Even so, the Gapfiller concept solution has reached such maturity and had been accepted by the UK MoD as an acceptable mitigation for Sheringham Shoal. Such a system may be used almost anywhere there is a need to complement an existing surveillance radar system or even to replace older 2D radars with a modern digital radar. Neither the cost nor the complexity would limit a wide use of the presented concept solution.

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