MITIGATION OF WIND TURBINE GENERATOR INTERFERENCE WITH MILITARY RADARS

A thesis submitted to the

University of Petroleum and Energy Studies

For the Award of

Doctor of Philosophy

in

Electronics Engineering

BY

Ashish Sharma

September 2022

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DECLARATION

I do hereby declare that this thesis submission titled 'MITIGATION OF WIND TURBINE GENERATOR INTERFERENCE WITH MILITARY RADARS' is my own bonafide work. Also, I do hereby declare that, it contains no material previously written or published by any other person nor any work which has been accepted for the award of any other diploma or degree of University of Petroleum and Energy Studies or other institute of higher learning, except where due acknowledgment has been made in the text**.**

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This is to certify that the thesis titled 'MITIGATION OF WIND TURBINE GENERATOR INTERFERENCE WITH MILITARY RADARS'' is a bonafide record of the work done by Ashish Sharma (SAP ID 500063532) in partial fulfilment of the requirement for the award of the Degree of Doctor of Philosophy in Engineering, and is based on an original work carried out by him under our joint supervision and guidance. It is also certified that no part of the thesis in full or parts have been included anywhere previously for the award of any degree or diploma, either in this university or any other institute.

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ABSTRACT

Employment of renewable energy in large military stations present ample opportunities due to the large area available with military stations. There is however, a technical glitch which can restrict the use of wind energy near Air Force establishments. Employment of wind turbines near military stations which use radars can lead to interference between them. Although the vast areas in military establishments are apt for using renewable energy technologies, however employment of wind turbines near radars both (military and civil aviation radars) throws a technical glitch due to the reflections of radar waves from rotating wind turbine blades.

The work undertaken tries to mitigate the current interference issues between radars and Wind Turbine Generators (WTGs).In order to resolve this issue a two pronged approach has been undertaken. Firstly the work provides a signal processing based radar mitigation plan which is verified by simulation studies for military radars and the second approach undertakes formulating a Standard Operating Procedure (SOP) for siting military radars with minimal interference issues. These approaches have been supported by extensive simulation studies.

The study suggests a novel signal processing based methodology for removing the windfarm clutter. The study covers a step by step procedure which utilizes the mathematical processing capabilities of radars. The mitigation process suggests the separation of affected areas due to clutter. Since the wind turbine

clutter will constitute clutter from the static areas of turbine and rotating turbine blades, the reflections from rotating blades will create the problem of Doppler ambiguity. Once the radar has been sited due to some operational constraints inside the interference zone between radar and turbines, the employment of Moving Target Indicators (MTI) is employed for clearing the static clutter of turbine tower. Signal processing techniques are employed for removing Doppler ambiguity.

Use of various filter models is compared based on simulation studies. The selection of filter models is governed by the expected target behaviours. In the final stages towards the mitigation of radar interferences, the employment of micro Doppler techniques is undertaken for removing the WTG returns. The time domain flashes of turbine blades are recorded for each case with different radar and turbine parameters. These return flashes are captured for the specific site and stored inside the radar computer. The radar signal processor identifies these flashes as the returns of turbine blades and separates it from the aircraft target returns.

Further the study also suggests a co-location methodology for siting wind farms near the radars in consonance to interference constraints. The first step towards the formulation of the radar and wind turbine siting is to undertake the line of sight (LOS) distance and terrain analysis for the selected site. In case the radar and the turbines are placed outside the beam formation zone of the radar or the main beams are shadowed by ground contours between the turbines and radars, then only the interference can be avoided.

The study with the help of simulations analyses the effect of various radar parameters which may affect the siting of windmill and radars. The simulation results are carried out for determining the effect of Azimuth on the Radar Cross-section which is directly related to radar clutter. The analysis is also undertaken with the help of simulations on the effect of frequency on wind turbine clutter. Finally the study evolves a mitigation process flow which explains the step wise procedure for co-locating windfarms and radars without interference.

ACKNOWLEDGEMENT

I take this opportunity to express my sincere thanks to my supervisors Dr. Ajay Kumar and Dr. Sushbhan Chaudhury for their guidance and support. I would also like to express my sincere gratitude towards my early stage co-supervisor Dr. V Chintala who along with Dr. Suresh Kumar helped me in topic selection as well as in setting the research objectives. It was a privilege and a great experience working under the guidance of all the above supervisors.

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NOMENCLATURE

Acronyms

ATC	Air Traffic Control
CFAR	Constant False Alarm Rate
IMM	Interacting Multiple Model
LOS	Line of Sight
MNRE	Ministry of New & Renewable Energy
MoD	Ministry Of Defence
MTI	Moving Target Indicator
PRF	Pulse Repetition Frequency
PRI	Pulse Repetition Interval
PV	Photovoltaic
RAG	Range Azimuth Gating
RCS	Radar Cross-section
STC	Sensitivity Time Control
TWT	Travelling Wave Tube
WTG	Wind Turbine Generators

Notations

A_e	Effective area of radar antenna (m^2)
C	Velocity of radio waves (m/s)
E	Expected value and the measurement (No Units)
G	Antenna Gain (No Units)
f_c	Carrier frequency (Hz)
f_d	Doppler frequency(Hz)
h_m	Height of WTG tower (m)
h_r	Height of radar (m)
L	Length of the WTG blade (m)
P_{avg}	Avg power transmitted by radar (W)
P_r	Power received by radar receiver (W)
$\hat{P}_i$ (k/k)	Covariance matrix of model i at instant k (No Units)
r	Distance between radar and target (m)
R_o	Radius of Earth (Km)
s(t)	Time Domain Signature (No Units)
T	Sampling Time (sec)

V	Relative Velocity of Target, m/s
$v(k)$	Process noise (No Unit)
Q_{k-1}	System Noise Co-variance (No Unit)
X_k	Target State Vector (No Unit)
$\hat{X}_{K\text{IK}}$	Posteriori Estimate (No Unit)
$\hat{X}_{K\text{IK}-1}$	Priori Estimate (No Unit)
Z_k	Measurement Vector (No Unit)

Greek Symbols

λ	Wavelength(m)
ξ	Target Coordinates (No Unit)
η	Target Coordinates(No Unit)
Ω	Rotation rate of WTG Blade(Rev/Min)
β	Elevation angle of rotor (Deg)
θo	Angle of scatter of WTG blade (Deg)
τ	Pulse Width (Sec)
σ	Radar Cross-section (m^2)

CHAPTER 1

INTRODUCTION

1.1 BRIEF BACKGROUND

The revolution in military affairs is changing the way military operations are performed. The security and sustainability of energy is one of key elements behind the success of military operations [1]. Energy security traditionally has been about securing itself from disruptions of vital energy generating systems [2].The essence of energy security has been the same since the ancient times; however, the means of achieving the objective have altered. With cumulative increase of renewable energy options and depletion of conventional energy sources, fossil fuels and other conventional sources of energy do not hold the symbiotic relationship with energy security [3].

Over the years government of India has consistently encouraged the use of alternate energy forms[4]. There has been an increase in the percentage share towards use of alternate energy forms[5]. Moreover, India with its varied demography and large military stations has ample unexploited potential of using renewable energy in defence establishments. The Indian Ministry of New and Renewable Energy (MNRE) is conferred with the charge of augmenting India’s capacity in terms of renewable energy [6]. MNRE has given a large push towards utilisation of renewable sources, which now nearly constitutes about 18% of total installed capacity [7]. MNRE also has undertaken an incentive with Ministry of Defence (MoD) and Para Military Forces under Ministry of Home Affairs in the year 2015 for exploring the feasibility for setting up to 300 MW of Grid-connected and off-grid solar photovoltaic (PV) power projects[8] for the Indian Military establishments. Use of wind energy by defence is another area which can be explored however; there are technical glitches which need to be taken in account. Among the option for renewable sources, wind energy is envisaged to play a key role in achieving renewable energy targets. There has been an increase in global installed capacity consistently in last two decades by nearly a factor of 50 from 7.5 gigawatts (GW) in year 1997 to 563 GW in year 2018 [9]. In-spite of the numerous advantages of using wind energy, there are certain barriers towards use of wind energy. Some studies have suggested the health issues which were attributed to use of wind energy. Studies have suggested the physiological effects due to windmill created noise and sleep related-issues[10], [11].

Utilization of wind energy also pose technology related glitches as the wind turbines reflect the radar radio waves from the static structures and Wind Turbine Generator (WTG) blades which create problems of static clutter on the scopes of different types of military and civil aviation radars. The change in Doppler frequencies due to the rotation of turbine blades is likely to create false targets on the radar scopes confusing the operators [12]. Due to these reasons many wind energy projects were either delayed or stalled. These concerns are now being considered as major constraints towards expansion of energy targets[13].

1.2 SCOPE & FOCUS OF THE STUDY

Although some mitigation theories towards the removal of wind clutter have been put forward, however each of these techniques has its own limitation. The existing techniques have suggested use of signal processing methods or designing the turbines with lesser Radar Cross-section (RCS) by use of materials which absorb radar waves.[12], [14]–[21]. Each of these techniques has their inherent limitation and therefore the nuances of radar interaction with wind farms have to be analysed keeping the terrain and environmental conditions. Considering the terrain peculiarities and the technical characteristics of radar, mitigation techniques in terms of reduction of interference between radars and WTGs need to be considered. There are various parameters which will govern the radar and WTGs interference. Each parameter is required to be analysed with the help of simulations, so that an optimized solution can be worked for co-locating the radars near the wind turbines. Based on these inputs there is a requirement of formulating a Standard Operating Procedure (SOP) for siting radars in the vicinity of WTGs. The standard operating procedure can be the guidelines for military and civil aviation agencies for siting the radars near the wind turbines.

1.3 RELEVANCE OF THE STUDY

The study aims to address a live problem which is being faced by radar operators and is also impacting the growth of windfarms. The interference problem between wind turbines and radars has been depicted as an area of concern towards the flight safety by radar operators of civil and military radars.

1.4 OBJECTIVE OF THE STUDY

To propose mitigation technique(s) of Windfarm effect on Radars used in defence sector. The study tries to provide two different approaches for mitigating these issues. One of the methodologies suggested is based on adopting a standard operating procedure for radar siting. This methodology can be instantaneously tested and optimally utilised while co-locating mobile military radars near wind turbines. The second technique involves signal processing techniques to remove the wind-turbine clutter.

1.5 OVERVIEW OF STRUCTURE

The structure of the thesis progresses from identification of problems and culminates by presenting workable solutions to mitigate the problem. Further, summary of each chapter is described below.

Chapter 1 provides a brief introduction to the shift from conventional energy to renewable energy for defence applications. The increased use of renewable energy across the world and the use of renewable energy in Indian defence establishments are highlighted. The chapter discusses the growth of wind energy and the impediments of developing wind energy due to the reflection from radars. The chapter discusses the Scope, objectives and relevance of this study.

Chapter 2 covers the literature survey covering a comprehensive study on the application of renewable energy in defence sector. The scope of literature survey includes wide range of subjects dealing with application of renewable energy in defence sector. The impediments of implementing renewable energy in defence are covered as technical, qualitative and administrative issues. Use of PV systems have also been discussed as stand-by for military systems in case of outages/military or natural catastrophes. The literature survey also discusses the technical glitch in windmill interference with wind turbines.

Chapter 3 discusses the research design and methodology. Based on deductions drawn from various topics in literature survey it was found that the constraints of wind energy are still not addressed. Based on inferences drawn from the literature survey the research gaps have been identified. The problem statement was formulated considering the nuances of military constraints for implementing the renewable energy in defence.

Chapter 4 explains the technical concept behind radar interference with wind turbine generators. The chapter while explaining the functioning of radar principles explains the Doppler ambiguity in radar scopes due to the reflections coming from wind farms. The current mitigation techniques which already exist to mitigate this problem are discussed with their limitations.

Chapter 5 explains the signal processing based methodology for removing the windfarm clutter. The chapter covers a step by step procedure which utilizes the mathematical processing capabilities of radars and evolves a novel signal processing technique to mitigate the interference problem.

Chapter 6 This chapter explains the co-location methodology for siting wind farms near the radars in consonance to interference constraints. A case study for LOS siting efficacy is shown for the Indian state of Gujarat. This is a specific site, which is likely to experience the interference in large scale due to high wind potential and high employment of military radars. The chapter also studies with the help of simulations the effect of various radar parameters which are helpful in siting windmill and radars in close proximity.

Chapter 7 evolved a mitigation methodology process flow. The study concludes that first step towards mitigating the interference issues is to assess the terrain effects and the placement of radars and turbines at an azimuth and angle which will have the least effect. The study develops a process flow based on the results of simulations and techniques covered in previous chapters.

Chapter 8 summarizes and concludes the findings. The chapter also provides recommendations on future scope of work.

CHAPTER 2

LITERATURE SURVEY & CASE STUDY

2.1 SCOPE OFLITERATURE SURVEY

The literature survey for employing renewables in defence sector has been undertaken to identify and understand the impediments of implementing renewable energy in defence. **The scope of literature survey included wide range of subjects dealing with application of renewable energy in defence. Impediments & opportunities for all types of renewable energy like Solar/Wind were explored before narrowing to wind energy problems.** The following areas were explored in the literature survey:-

- ✓ Harnessing renewable energy in defence sector
- ✓ Impediments and opportunities for renewable energy in defence sector
- ✓ Feasibility of using Photovoltaic system in military station
- ✓ Case study to ascertain the feasibility of PV energy for a military station
- ✓ Wind energy employment in defence and wind turbine interference with defence radars

2.2 HARNESSING RENEWABLE ENERGY FOR DEFENCE SECTOR - A GLOBAL PERSPECTIVE

The first wave for migrating to sustainable energy sources came in 1973 after the oil producing and Exporting Countries (OPEC) had unilaterally increased the oil prices. This was the same period when the world was beginning to get aware about environment pollution climate change and global warming issues [22]. The transformation towards sustainable energy is at a level, where fuel prices may not effect its growth. In-spite of plunge in oil prices since mid-2014, there has been a rapid increase in the use of renewable energy [23].

The realisation for addressing the issue came after it was highlighted in a defence report in 2001 on fuel expenditure incurred by different services in United States [24]. It laid emphasis on cooperation in areas of alternative fuels, improving energy efficiency, renewable energy, smart grid, waste to energy and other related areas [25]. Simultaneously US Army, Air Force and Navy took parallel initiatives for seeking energy solutions through renewable energy. In 2009 US Army published its energy security implementation strategy [26]. In 2009, US Navy formulated energy goals for the Department of Navy (DoN), which stated that by 2020, navy will produce about 50% of its energy from sustainable sources [27]. On the similar lines, US Air Force charted its own plan for utilization of alternative sources of energy [28]. The US Government report to Congressional committee on defence renewable energy projects brings to light some of the important facets of use of renewable energy in defence.[29]. The United Kingdom government adopted a quantitative goal for reducing the greenhouse emissions of military in 2008. In China, there are some reports on the use of renewable energy by military for energy efficiency enhancement [30].

Solar energy has a large potential in the field of aviation technology, however, technological advances are necessary to overcome the low conversion efficiency and high cost of the present systems [31]. Joseph et al. have presented a solution to carry out surveillance using a PV powered un-manned vehicle [32]. Un-manned Vehicles (UAV) are finding increased use in military. Oettershagen et al. have presented the design of a solar-powered hand-launched Unmanned Aerial Vehicle (UAV) [33]. Wang et al have recommended the use of wave energy for under water unmanned vehicles [34]. Utilization of liquid bio fuels for gas turbines is on the rise [35]. Bwapwa et al. have reported work on the conversion of microalgae as aviation fuel. According to authors algae biomass has the advantage of faster growth and does not require excessive land for growth [36]. Kandaramath et al. have carried out a comparison amongst the available renewable resources and have discussed various challenges and opportunities emerging in the field of aviation bio-fuel [37]. Meher et al. have reported the technological update on use of Jathorpa based bio-diesel [38]. Biomass derived fuel is the key for aviation industry for reducing the fuel costs and reducing the environment impact [39]. The general findings of a report prepared by National Defence Research Institute on alternative fuels for Military applications laid emphasis on developing alternate fuel to reduce dependence on conventional fuels [40].

India's Defence budget for year 2018-19,envisaged a total outlay 2,95,511.41 Crore Indian rupees (INR), out of which,1,95,947.55 Crore INR was allocated for revenue expenditure for the defence establishments [41]. India being the seventh largest country has the second largest army in the world. With over a million strong army of 13,62,500 personals, India is only next to China [42]. With numerous resources and land areas under the control of Army, Air Force, Navy and other defence establishments, it is vital for the Government to encourage inter ministry cooperation for implementing the success of renewable energy in India. The first major concrete step taken in this direction is the implementation of schemes for grid-connected and off-grid solar PV power plants up to 300 MW by defence establishments [43]. The Indian Navy started "Green Initiatives" program in 2014, which covers Operations, Infrastructure, Administration, and Maintenance functions to reduce its energy consumption from conventional fuels [44].

2.3 IMPEDIMENTS FOR IMPLEMENTING RENEWABLE ENERGY IN INDIAN DEFENCE SECTOR

There are stringent standards for induction/procurement of products, which are meant to be employed for military use. The qualitative requirements for military technical equipment must be conformal with Military Standard (MIL-STD) [45]. The challenges for implementing renewable energy in defence sector have been classified under three heads as shown in Fig.2.1.

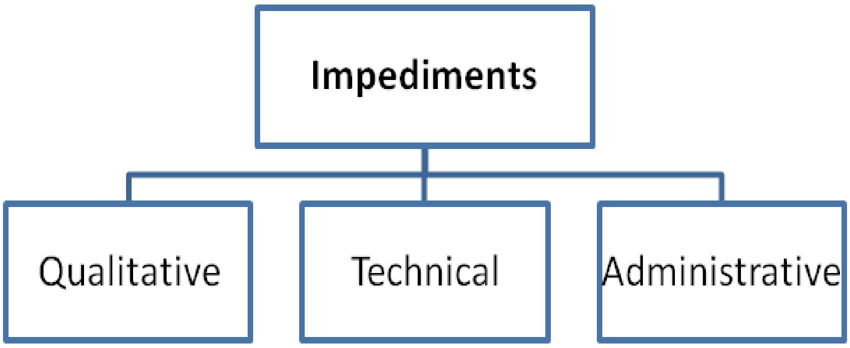

Fig. 2.1 Impediments for renewable energy in defence sector

Qualitative issues

As per the Government of India, Defence Procurement Procedure Manual 2016, the acquisition plan for military is chalked out of the qualitative requirements of the defence services [46]. While military establishments have evolved their own testing procedures, For example, MIL-STD-202 is the standard used for testing electrical component, including environmental tests for military suitability standard [47]. Similarly, MIL-STD-704F lays the testing standards for power systems related to aircrafts [48]. The selection of renewable energy as a source for any military technical equipment will have to undergo the long process of critical design reviews, prototype testing, and various qualification tests like environment testing and field evaluation trials.

Technical Issues

The electrical grid is vulnerable to asymmetric attacks such as cyber-attacks. The technical experts have recommended electric grid by using solar photovoltaic system as distributed micro grids. To address this threat, Prehoda et al. worked on electrical grid fortification [49].While assessing the employability of renewable energy for military, it is to be is understood that the potential threat for a military attack could be a hard kill (physical attack) or a soft kill (cyber-attack). [50]. Moreira et al. have evaluated the security solutions available for electric sub stations and have suggested protocols for protecting substation automatic systems [51]. Arghandeh et al. have focused on the resilience of power systems. The authors have suggested formulating new standards to address cyber-physical interdependency and issues for electric grids [52]. Salmeron et al. have worked on developing analytical techniques on minimizing disruptions caused due to terrorist attacks on electric grids. Techniques to mitigate physical disturbances due to terrorist attack have been modelled [53]. Network security for safeguarding the electric infrastructure is one of the important issue while dealing with power infrastructure for defence establishments [54].

Administrative challenges in Indian scenario

The administrative challenges for implementing renewable energy will depend upon the geo-political factors. No Objection Certificate (NoC) must be sought from MoD for undertaking projects, which in any way directly or directly interfere with defence operations. The MoD notification [55] describes the procedure on seeking clearances from MoD for undertaking power energy projects including renewable energy projects. The timelines and procedures involved are time consuming. As an example, MoD notification [56], National Institute of Wind energy was given Naval clearance for carrying out Met-

Ocean geophysical investigations. These multiple clearances are time consuming and can pose a deterrent towards initiation of new projects[57].

2.4 EMPLOYING SOLAR ENERGY FOR MILITARY STATION

Various initiatives towards addressing the issue of high-energy consumption by defence forces have been initiated, the efforts included emphasis of improving energy efficiency, using alternative fuels, smart grids and other related areas [25], [26, p. 1], [27]–[30]. Solar energy has a large potential in the field of un-manned vehicles and aviation technology. Military companies like Lockheed Martin have built a 120 kilowatt solar array and 300 kilowatt energy storage system at Fort Bliss, Texas connected as a micro-grid [58]. India receives solar energy between 5 to 7 kWh/m^2 for most of the year [59]. By utilizing the available solar resources and technologies, India can fulfil its electricity requirements [60]. Wind, PV, diesel and batteries combination has been a very competitive option for providing energy solutions for remote areas [61].

Utilization of renewables in mountainous terrains and remote islands saves a lot of military logistics effort for military bases [62]. Some people have also proposed Net-zero concept for defence by using renewables [63]. Since the energy balance is the fundamental concept of Net-zero. The energy balance analysis process case evaluates annual energy demand and renewable energy generation [64]. The US Army Net-zero initiative started in 2011 with 17 pilot installations. The focus for the program was to work on reduction, recycling and energy recovery[65]. Various software/modelling tools like Homer are available to evaluate technically and financially viability options for Grid and off grid distributed generation applications [66]. India has military stations spread mostly on its western and eastern borders and naval stations located in south. Fig 2.2 depicts India's solar resource map. The map shows average global solar irradiance over 10 years [67]. The solar map suggests a solar potential of 5-6 kWh/m^2/day in India. MNRE has already taken an initiative for implementation of PV plants on military land.

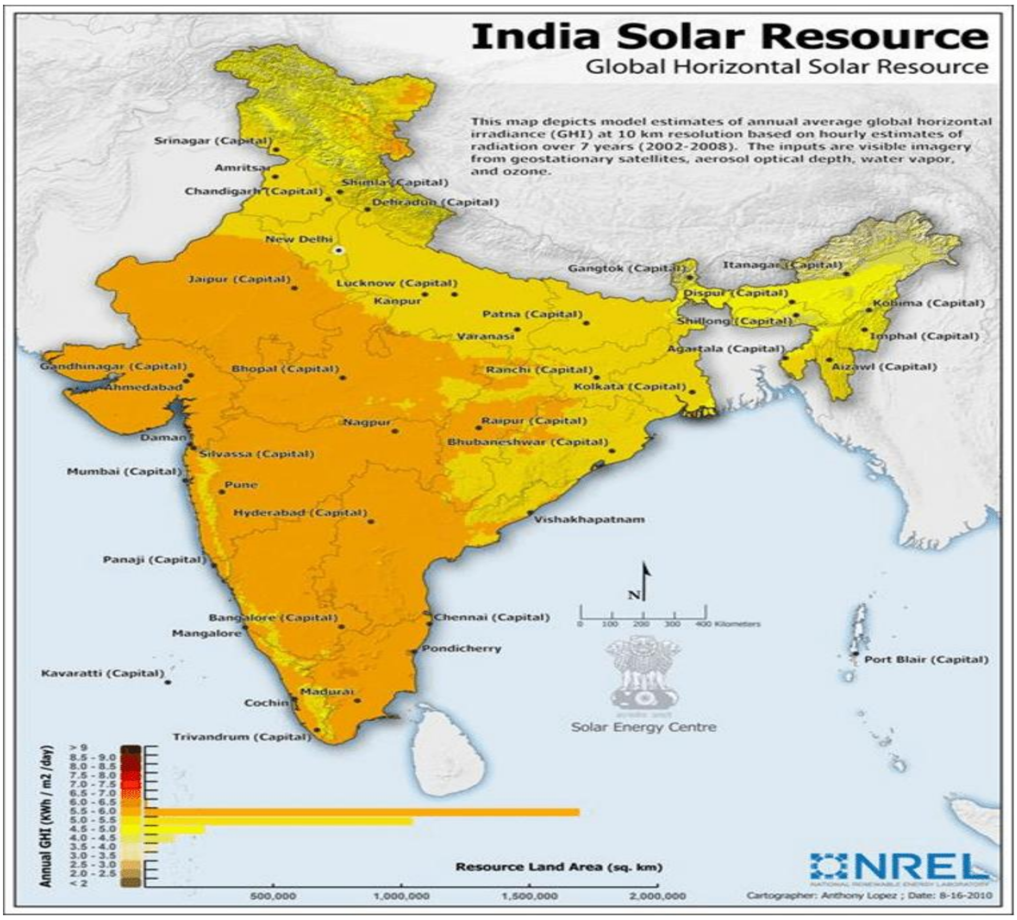

Fig. 2.2Photographic representation of annual average solar irradiance for India [67]

Indian Government has estimated that the solar energy potential in Indian military cantonments is around 5000 MW and in Ordnance Factory Boards (OFB) is approximately 950 MW [68]. India is ranked seventh in terms of land area and has the second largest army in the world [42]. The Indian military establishments, stations, research laboratories of Army, Navy and Air force are spread all over the country. Army Construction Engineering Research laboratory explored the accrued benefits of installing PV Panels on temporary barracks. The task was to examine if PV panels could be economically beneficial even for short duration of time. The study showed that this is cost effective even for short span of two years [69].

2.5 CASE STUDY: FEASIBILITY OF PHOTOVOLTAIC SYSTEM IN A MILITARY ESTABLISHMENT

During the course of literature survey on various kinds of renewable energy sources, a case study was undertaken on PV system applications in military stations. This also provides another unexplored research area, therefore post deliberations the case study has been briefly included in the thesis. Use of PV systems has also been suggested as stand-by for military systems in case of outages/military or natural catastrophes. Military equipment needs highly reliable and secure power infrastructure. This may require extra layer of security and redundancy for critical systems, which will warrant extra financial and logistics support. A military establishment in India is selected for practicality study for installation of PV plant. The first step is estimation of solar potential for the selected site. The estimation of was done with System

Advisor, which is a National Renewable Energy Laboratory (NREL) simulation tool.

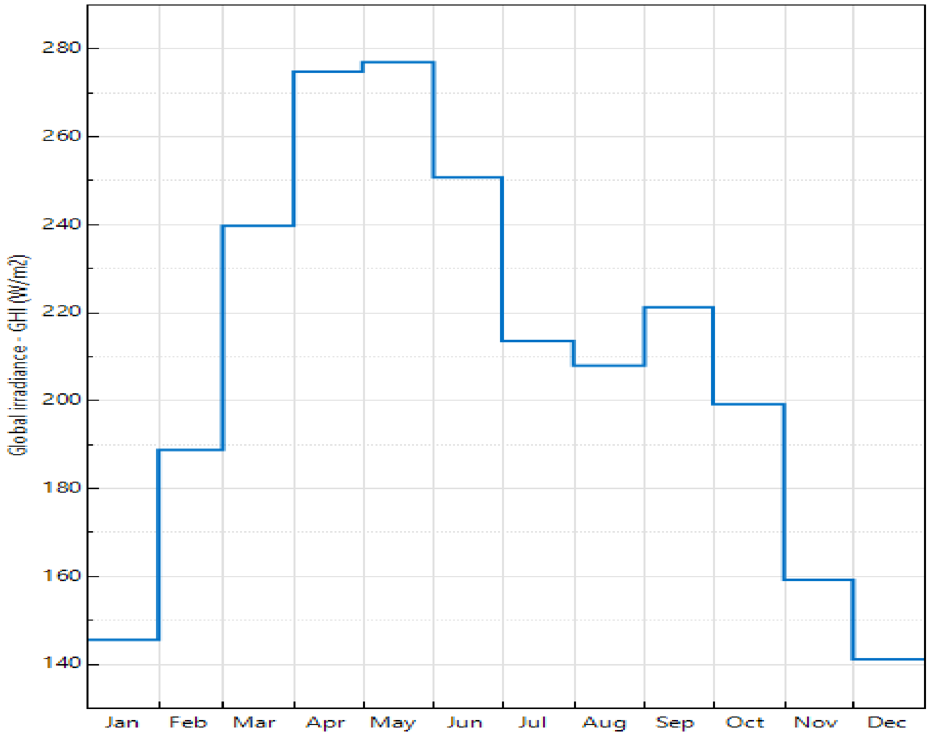

Fig. 2.3 Global irradiance for site

The average daily solar energy which is incident in India is between 4kWh/m^2/d to 7kWh/m^2/d. Solar Irradiance is considered as the most vital factor for determining the suitability of site for installing PV plants. The areas which have a GHI value of more than 4kWh/m^2/d are considered economically viable for setting of PV Plants [70]. The monthly Global Irradiance (W/m$^{2)}$ at the site under study is given in Fig 2.3. The average Global Irradiance for April to June is greater than 6kWh/m^2/d. The annual solar average is 5.06kWh/m^2/d which qualifies the chosen site for setting a Photovoltaic system.

Power generation capacity assessment

The System Advisor modelling tool is used to estimate the solar potential at the chosen military station. The System advisor provides the performance model and data base for commercially available solar modules. The software provides the system performance data under known reference conditions. The military site was surveyed in order to identify usable infrastructure, Area (sqm) which includes workshops, barracks and residential buildings. Out of the total roof area available, the ideal shadow free effective area is identified for carrying out the estimation of potential available with military station. The PV potential is calculated in Table 2.1. After calculating the usable roof top area and by utilizing 250 watts per 2 Sqm solar panels, the military station was estimated to have potential for more than 3 MW generation capacities.

Table 2.1 PV potential of selected military station

Sl No	**Infrastructure/ Building**	**Available area (Sqm) (A)**	**Usable roof area for PV installation (Sqm) (B)**	**Possible installed capacity of Solar Panels (1 panel per 2 Sqm) (C=B/2)**	**Possible Power Generation in (Watts) (250 Watts per panel) (D= C*250)**
1	Hangers (08 Nos)	22728	14206	7103	1775750

2	Training Area (03 Nos)	1170	756	373	93250
3	Storage Area (03 Nos)	4700	2970	1485	371250
4	Station Rest area	209	150	75	18750
5	Crew Area 1	161	100	50	12500
6	Crew Area 2	163	110	55	13750
7	Admin Space	1102	739	369	92375
8	Qtr type 1 (15 Nos)	1200	750	375	93750
9	Qtr type 2(20 Nos)	1890	800	400	100000
10	Qtr type 3 (25 Nos)	1180	750	375	93750
11	Qtr type 3 (40 Nos)	1800	800	400	100000
12	Type 5 Qtr (40 Nos)	1100	600	300	75000
13	Commercial Area 1 &2	5500	3950	1975	493750
14	Airmen Mess 1	402	275	137	34375
15	Staff Canteen	378	225	112	28000
Estimated generation capacity = 3396250 Watt					

PV System Performance Simulations by System Advisor Model

The System Advisor Model (SAM) is a performance evaluation and financial model design software developed by National Renewable Energy Laboratory (NREL) for the U.S Department of Energy (DOE).The system advisor software predicts cost of energy estimates for power projects based on operating costs design parameters as inputs. The software provides an option of using PV Watts where, the user specifies the DC capacity and DC to AC ratios. The SAM also has the option of using detailed photovoltaic module, where the modules and Inverter rating can be specified and the number of modules and the number strings in the array can be defined. Standard crystalline modules are chosen for our study. The DC to AC ratio is defined as the ratio of inverter's AC rated size with array's rated DC size. The array type is simulated as the fixed array roof type. The total losses considered in the simulations include shading, soiling & other miscellaneous losses.

The useful service life of the system is calculated by understanding degradative reactions, establishing expected levels of degradation, and utilizing the experimental methods. Module service life prediction depends on degradation mechanisms that limit the service life of the module [71].The total useful life of the project is calculated based on the shelf life products used and is estimated as 25 years. The system parameters used for simulation are illustrated in Table 2.2.

Table 2.2 PV Plant simulation parameters

PV Module	Multi-c-Si
DC system rating	3300 kW
DC to AC Ratio	1.2
Efficiency of Inverter	96%
Orientation & Tilt	Fixed, 33 degrees
Total losses	14.08%
Selected degradation rate	0.5% per year

Table2.3 Solar Irradiance and Monthly Energy production calculated by SAM

Month	Solar Irradiance ($kWh/m^2/day$)	DC Output	AC Output
Jan	4.83681	378300	362445
Feb	5.76587	397633	381342
Mar	6.56455	474096	455056
Apr	6.67282	461285	442333
May	6.16873	432772	414644
Jun	5.3787	377263	361074
Jul	4.64571	347969	332466
Aug	4.81112	367634	351462
Sep	5.73964	416399	399006

Oct	5.83053	437777	420095
Nov	5.01421	370851	355874
Dec	4.76665	378844	363366

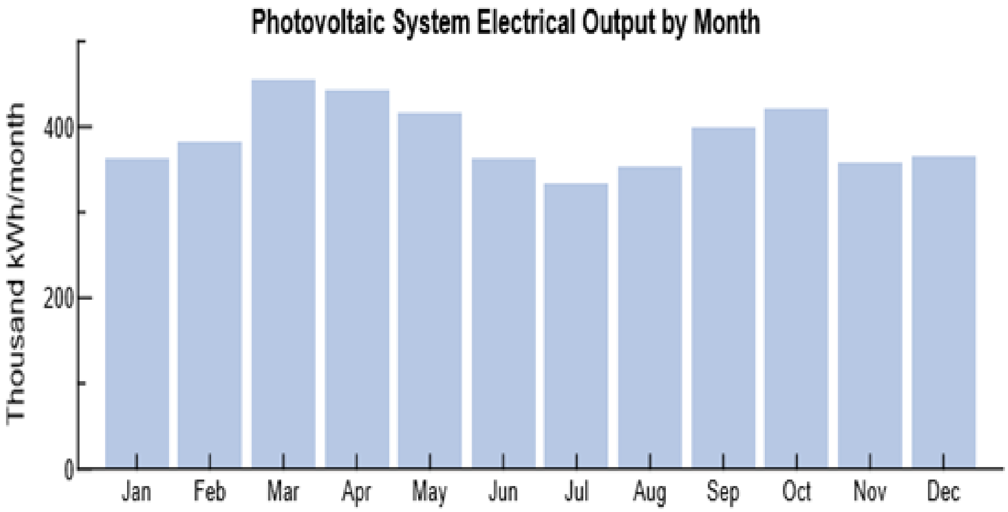

Fig. 2.4 The monthly energy production as calculated by SAM

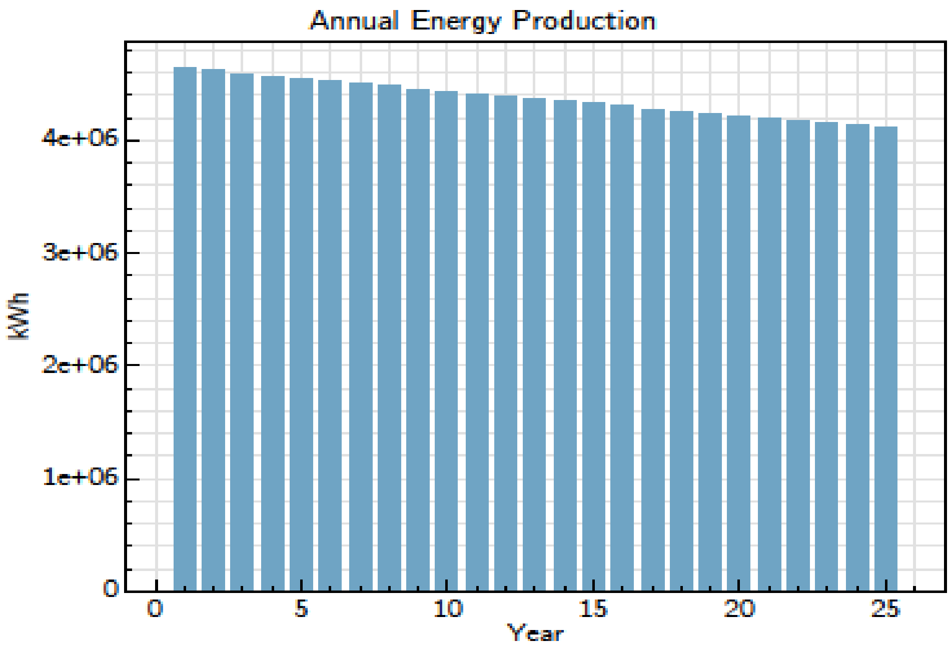

Fig. 2.5 Annual energy production calculated by SAM for the total useful life of Plant

The PV system has been designed with life of 25 years with 1% degradation factor. The simulation results predict the production of annual energy as 4,639,162 kWh in the first year to 4,113,330 kWh in the 25th year.

PV Potential Vs Actual Energy Requirement

The simulation result predicts monthly energy production varying between 3,32,466 kWh (July) to a maximum of 4,55,056 kWh (March). The actual load is divided into the domestic load and the technical area load. The technical area is defined as the area which has military hangers, workshops and other equipment and associated offices. The domestic area includes the residential areas. The location of the site under study has a wide variation of temperature between summers and winter. The actual units consumed for residential area in the month of May 2018 was 2,40,000 kWh and the energy consumption in technical area in May 2018 was 4,21,030 kWh. The total units consumed (Technical + Residential) in the month of May 2018 was 6,61,030 kWh. The total simulated potential for PV production as shown in Fig. 2.4 for the month of May is 4,14,644 kWh.

The Actual total annual unit consumption for residential area and technical area is 1,905,450 kWh and 3,643,400 kWh respectively. The total combined annual energy requirement is 5,548,850 kWh as per current energy consumption pattern. The total annual energy potential for the PV plant is 4,639,162 kWh as depicted in Fig 2.5. The energy produced by PV plant can cater for 75% of energy requirements at the site [72].

2.6 CONSTRAINTS FOR APPLICATION OF WIND ENERGY

Among the renewable energy sources, Wind energy is among the most rapidly growing technology. There has been an increase in the installed capacity by a factor of 50 in the last twenty years with an increase from 7.50 gigawatts (GW) in the year 1997 to 562 GW by the end of year 2018 [9]. Although there are countless benefits of using wind energy, there are some technological constraints towards application of wind energy. Some studies have suggested the health issues due to windmills. Some studies presented the physiological effects due to wind farms and sleep related issues[10], [11]. Deployment of windfarms near military or civilian radars also poses technical glitch as the Wind Turbine Generator (WTG) interfere with surveillance, tracking radars, metrological and other civil aviation radars**.** The large sized wind turbine blade and static tower of turbine result in large reflections thus driving the radar receiver into saturation. Although the receiver saturation may be compensated by using negative gain; however, the more critical issue arises due to the Doppler shift from rotating blades of wind turbines. The Doppler can create false targets on the radar scopes which may create uncertainty for the operators in identifying the correct targets[12]. There have been many occasions where wind energy proposals were stalled or cancelled due to such impediments. These radar and windfarm interference concerns have now been considered as a major impediment for reaching energy targets via wind energy [13]. Although some theories and mitigation techniques have been suggested for reducing interference problems between radars and WTGs, however there are constraints for each of these techniques.

The mitigation techniques have suggested modification of radar parameters, re-designing wind turbine structures with lesser Radar Cross-section (RCS) and theuse of radar absorbing materials for turbine blades to lessen these effects [12], [14]–[21]. Each of these techniques has their own constraints with no unique solution. The problem of interference between radar and WTG needs resolution for the radar static clutter of wind turbine tower which is due to the large Radar Cross-Section (RCS) and second issue is the Doppler returns from rotating blades which can generate false target images on radar. ***This technical issue still remains unresolved and is comparatively an issue***

which has limited research material available due to the exclusiveness of military domain.

2.6.1 The radar and windfarm co-location problem

The Wind Turbine Generators in a windfarm rotate and the radio waves emitted by the radar transmitter are reflected back to the radar from the rotating and static portions of turbine. The military radars are mobile as well as static radars. On number of occasions these radars are sited near windfarms due to military operation requirements.

If an article/object is in constant motion, then the transmitted frequency of radio waves will be different from the frequency of the received signal. By calculating the shift in frequency, which can be positive or negative depending upon the motion of the object, radar can determine the target velocity. These Doppler frequencies are used for estimating the velocity of the object in motion. These frequencies which are generated from target aircraft and outer tips of turbine blades may fall in the same spectrum depending upon the speed of aircraft and turbine blades. Wind farms in or near defence land will pose a major challenge due to the fear of interference with radars. As per MNRE circular dated 18 Oct 2018, MNRE has directed all Wind Turbine Generator operators to place the remote of SCADA system of all Wind farms with Indian Air Force so that they can be stopped in case of any interference with Military Radar Operations [14].

Table 2.4 Overview of literature review deductions

Literature Survey Topic	Deductions
Harnessing renewable energy in defence sector	Due to growing cost of energy, defence forces across world have starting exploring the feasibility of using renewable energy for its energy requirements.
Impediments and opportunities for renewable energy in defence sector	The defence equipment is designed as per Military standards; therefore there are technical constraints for implementing renewable energy in defence sector.
Feasibility of using Photovoltaic system in military station	Govt. of India has planned the use of photovoltaic systems on the roof tops and spaces of land available in the Military stations.
Case study to ascertain the feasibility of PV energy for a military station	A case study was undertaken for an Indian Military station and it was concluded that the military station was capable of producing 75 % of its energy requirements

	by employing Photovoltaic systems
Wind energy employment in defence and wind turbine interference with defence radars	The interference between radars and windmills due to the reflection of radar signals and the Doppler signal from rotating blades of wind turbines is an unsolved problem. Mitigation techniques and Standard Operating Procedures are required to be formulated for employing radars near windfarms.

CHAPTER 3

RESEARCH DESIGN

3.1 RESEARCH GAPS

Based on deductions drawn from various topics in literature survey it was found that there are immense opportunities for implementing renewable energy technologies in defence sector however, the impediments need to be addressed. It was found that wind energy expansion is being withheld due to Wind Turbine and Radar interference issues. Based on inferences drawn from the literature survey the following research gaps have been identified.

- ✓ Employment of wind-mill presents a technical glitch as the windmills cause reflections from the windmill blades which interfere with military surveillance/tracking radars.
- ✓ Resolution of the Wind Mill Clutter must be resolved for encouraging wind mill development in India.
- ✓ The research brought out one of ***the foremost live problem of MNRE*** as per the MNRE circular which mandates all Wind farm operators to provide the SCADA remote with Indian Air Force for switching off the wind mills in case of interference.

- ✓ The Literature Survey also brought out the issue of seeking NOC from MOD & the issue of Wind Mill Clutter which is presently a live unsolved issue for MNRE.

PROBLEM STATEMENT: It is imperative to understand the "***Nuances of Military Constraints"*** for undertaking the feasibility studies of implementing renewable energy in defence sector.

Nuances of Military Constraint Matrix

Type of Constraint	**Effect of Constraints**	**Scope of Work**
Interference between Radars and Wind Turbine Generators.	Wind Farms projects have to seek clearance from Defence and whenever required , the Air force can switch off the wind turbines in case of any interference	Design feasibility studies and providing technical solutions and formulation of Standard Operating Procedure (SOP) for Co-locating radars near WTGs.

3.2 MOTIVATING FACTOR

From the literature survey it emerged that there is a large potential for using renewable energy in defence establishments. The feasibility of using PV at a military station was undertaken for an Indian military station and it was shown that 75% load requirement of military station alone could be met with stations with good solar irradiance. It was however, seen that in terms of development of wind energy there are important unresolved issues as WTGs create interference with radars. The problem has not been addressed and provides a pertinent issue for which research needs to be undertaken. The resolution of this issue will have immense contribution for wind farm growth in India.

3.3 OBJECTIVES

The following are the objectives to address the problem statement: -

To propose mitigation technique(s) of Windfarm effect on Radars used in defence sector.

Sub Objectives incidental to main objective are:-

(i) Overcome the limitations of existing mitigation methods for removing the interference between the Windfarms and Radars

(ii) Compare the Wind farm Clutter reduction methodologies with help of simulations.

(iii) Formulate a Co-Location methodology for Windfarms and Radars.

3.4 METHODOLOGY AND DATA COLLECTION

The study undertakes two pronged approach to address the live problem existing due to co-location of windfarms and radars. In the first approach Signal processing techniques have been employed which have been tested with the help of extensive simulations. The second approach follows a formulation of Standard Operating Procedure (SOP) for siting mobile radars with minimum interference. The results were proven with help of simulations.

The data used for radars in terms of frequency, wavelength, polarisation etc is available on open domains**.** "**No classified military data has been used during the research".**

CHAPTER 4

TECHNICAL CHALLENGES IN REMOVING WIND TURBINE AND RADAR INTERFERNCE

4.1 TECHNICAL CONCEPT BEHIND RADAR INTERFERENCE WITH WIND TURBINE GENERATORS

Radars are devices which are used for detection of targets and weather conditions. The word radar is derived from Radio Detection and Ranging. The radar directs a burst of radio waves towards the target or aircraft which needs to be tracked and the reflected energy from the target which is received back forms an echo. The type and method of radiating these radio waves depends upon the kind of information required. The speed by which the energy is received back by the radar receivers is measured and used for calculating the target distance. Since the radio frequency waves undertake a round trip due to the reflection back from the target, therefore only half the time taken is calculated. Once the distance and Azimuth of the target has been calculated, this information is projected on the radar screen in reference to own coordinates of radar.

The operator receives this information in terms of Target speed, Azimuth, Height and spatial position in space with respect to other targets. The primary surveillance radars are active systems which radiate their own energy in radio waves. The kind of waveforms, modulation, pulse width and other characteristic features of radio waves depend on the type of application for which the radar has been designed. The working principle of radar is explained in Fig.4.1 (a).

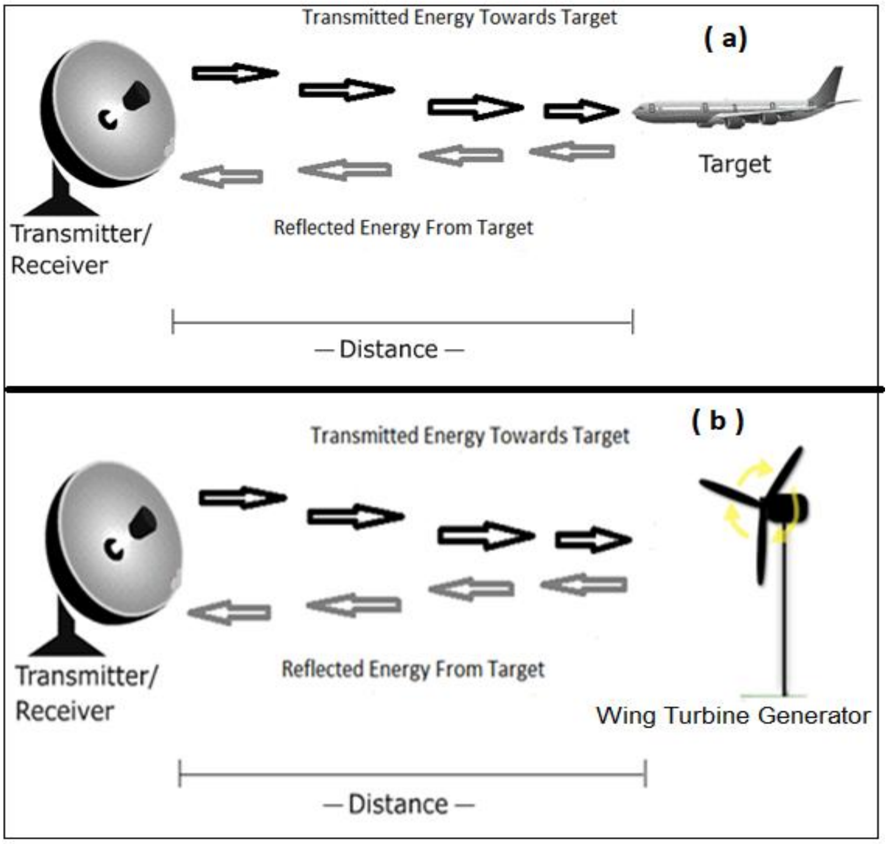

Fig. 4.1 The Radar basic principle (a) Radar Aircraft detection (b) Energy reflected from Wind Turbine

The wind turbine also rotate and the radio waves radiated by radar are reflected from the static and rotating structures of the wind turbines back to the radar as shown in Fig.4.1 (b). The Radar Cross-section (RCS) for the wind turbine is large, the static tower of the turbine reflects the radio waves back without any Doppler effect, thus contributing to saturation and clutter in the radar receivers. The rotating blades of turbine reflect the radio waves towards radar with Doppler frequency thus mimicking as real aircraft targets and confuse the radar operator with false target. The calculation of the Doppler frequency signal is used by radars to calculate the target velocity. The Doppler frequencies from target and windfarm fall in the same region due to the high speeds of the tip of the turbine blades, thus creating false echoes which resemble as the echoes from true aircraft.

The radar operator faces two types of technical challenges. First challenge is the problem of static clutter which is generated from large static turbine tower. The clutter is due to the large stationary parts which reflect the radio waves back to radar and due to their large size; they form a large echo mimicking a large target. The second is the Doppler ambiguity due to the rotation of turbine blades. To solve this issue, some techniques have been suggested by radar designers. However, each of these mitigation techniques have inherent limitations, therefore there is a requirement of technical analysis for the possibility of interference before undertaking any radar siting near vicinity of WTGs.

4.2 EXISITING MITIGATION TECHNIQUES & LIMITATIONS

A summary of the existing mitigation techniques with limitations is summarized in Table 4.1.

Table 4.1 Existing mitigation techniques and their limitations

Sl No	Mitigation Technique	Limitations
1	Use of stealth Techniques	Using Radar Absorbent Material have shown reduction in Radar Cross-Section (RCS) up to 10-15 dBsm. This technique is expensive but reduction of RCS, will reduce the strength of clutter. However unless all radiations are absorbed the Doppler ambiguity cannot be resolved
2	Moving Target Indicator	The technique is helpful for removing the static clutter; however implementation of the technique alone will not help in resolving the target returns from WTG blades. The use of MTI will have to be combined with other techniques.
3	No track in Wind Turbine Generator (WTG) sector	The technique will prevent the WTG clutter; however inhabitation track generation from the WTG sector can lead to loss of track.

4	Sensitivity Time Control (STC)	Minimizing the sensitivity at shorter ranges will prevent the radar receiver from going to saturation; however it is ineffective against the WTG blades generating false targets.
5	Constant False Alarm Rate (CFAR)	The technique is not suitable for resolving Doppler ambiguities due to rotation of turbine blades.
6	Using multiple sensors	The system will apply multiple sensors working in Integrated mode; however the system is not cost effective.
7	Signal Processing Techniques	Radar signal processing can be used to reduce the clutter and resolve the target; however this will require advanced data processing systems to be incorporated in radars. Moreover these techniques alone may not be able to resolve the interference issues completely.

CHAPTER 5

MITIGATION OF RADAR AND WINDFARM INTERFERENCE

5.1 RADAR FUNDAMENTALS

The fundamental principle for radar radio returns and interference was explained in the previous chapter. The radar waveforms are of two types, the continuous wave and the pulsed waveforms. In the pulsed operations the radio waves are transmitted in pulses and the radar receives the echo from the target. The carrier frequency f_c (Hz) is related to wavelength λ (m) as given in equation 5.1

$$\lambda = C/ f_c \tag{5.1}$$

In equation 5.1 C is the velocity of light.

The pulse-width τ (s) determines the amount of power which can be radiated by radar and affects the range resolution of the radar. The Pulse Repetition Interval PRI(s) is the time for the next pulse after completion of one cycle and it is the opposite of Pulse Repetition Frequency PRF (Hz).

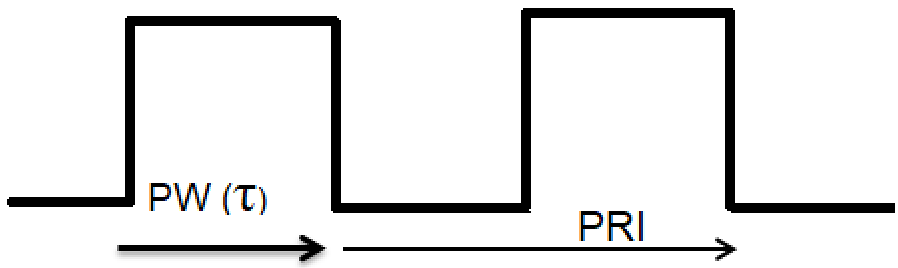

Fig. 5.1 PRI and PW of Pulsed radar

The choice of PRI and Pulse Width (PW) play an important part in the radar characteristics and the performance capabilities of the radar. The PW of the radar will determine the maximum range of the target since wider the pulse width, the more energy can be pumped into the radar waves, however wider the pulse width, the more difficult will it be for the radar to resolve the targets. Longer PW are desired for larger ranges but the increase in PW will limit its range resolution, therefore there is a design compromise between these factors. In the modern radars, however pulse compression techniques are employed for achieving good ranges and resolution at the same time.

These radar characteristics will also affect the capability of the radar to resolve between radar returns from WTGs and targets returns. The choice of PRF will also decide about the Doppler frequencies and range ambiguities. The reason behind this is because each pulse sent by the radar must be returned back before the next pulse can be transmitted as to avoid the range ambiguities which will decide the PRF. This problem can be resolved by using staggered PRF.

Radar Range Equation

The performance parameters of radar are determined by the radar range equation.

P_r= Power received by radar receiver (W)

P_{avg}=Avg power transmitted by radar (W)

G = Antenna Gain (No Units)

A_e = Effective area of radar antenna(m^2)

r = The distance between target and radar (m)

σ = Radar Cross-section (m^2)

$$P_r = P_{avg} G^2 \lambda^2 \sigma / (4\pi)^3 r^4 \quad (5.2)$$

As seen from the range equation the Power received (Radar Echo) will describe the performance of radar and target pickup ranges. One of the most important parameter of interest is the Radar Cross-Section (RCS) as this will directly be responsible for the clutter of the wind turbines.

5.2 A NOVEL SIGNAL PROCESSING METHODOLOGY FOR REMOVING THE WINDFARM CLUTTER

The use of signal processing techniques and the flexibility of modern radars can be effectively employed for mitigating the interference effects of wind turbines. The wind turbine interference zone can be easily earmarked on the radar and the flexibility to employ different processing techniques for the earmarked sector can be used to mitigate the interference effect. The requirement is to implement suitable signal processing and filtering techniques to mitigate the effect of WTGs. In this section a signal processing based procedural method will be described, having the advantage of simple implementation without undertaking major design changes in the existing architecture of the radar. ***The procedural methodology will tweak the existing capabilities of the radar to overcome the problem of interference between radars and WTGs***.

5.2.1 Separating the WTG clutter zone

The first step towards developing a signal processing methodology for removing the clutter will start with the identification and isolation of the WTG clutter area on the radar scope. The process will involve the steps given in following paragraphs:-

The static clutter segregation

The effect of Wind Turbine Generator on radars shall vary and will depend on the radar parameters like wavelength, polarization and processing techniques. Before employing any signal processing technique the segregation of clutter in radar scope has to be undertaken.

Earmarking Wind Turbine Zone on Radar Scope

The modern generation radars are inherently capable of undertaking various functions like tracking, search and track while scan and can even perform the task of supporting missiles for guidance. The Active Phased Array radar have small modules called as Transmit Receive Modules (TRM) which are responsible for transmitting the beam and these have replaced the microwave conventional devices like Klystron, Travelling wave Tubes (TWT) & Magnetrons.

The TRM are controlled electronically by the radar computer and the radar signal processor. The TRMs modules control the radar beams and have the flexibility to rotate the beams by electronic means. The flexibility of modern radars provides the freedom for applying the radar processing techniques and decides as to how the target echoes will be presented on the radar scopes. The scope of radar can be segregated into sectors by radar operator based on operational requirements. These operational requirements like "No emission zones" (Area where radar will not transmit), "Low emission Zones" (Areas where the radar transmission power will be reduced). Sectors which are critical and may require quick target identification and verification, sectors which may require larger radiation on aircraft target for confirmation.

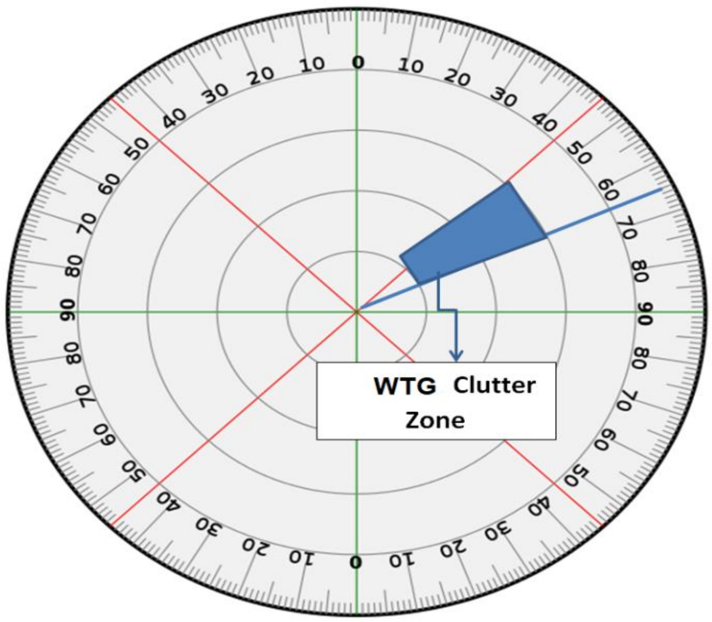

Fig. 5.2 Sector classification for interference zone

Range Azimuth Gating

The radar operator will configure the radar for different signal processing techniques for the selected sectors on radar scopes. The typical example is shown as the area marked as WTG Clutter zone in Fig.5.2. Combination of Range Azimuth Gating (RAG) and inhibition of plot-track conversion should not be used for resolving this issue as this technique will always have the inherent risk of dropping the track on radar scope[20]. Range Azimuth Gating should only be employed for earmarking the wind turbine zone. The sector classification will be used for the Wind Turbine interference sector by applying the Range Azimuth Gating (RAG) for the chosen sector. This sector is marked as the WTG clutter zone in Fig 5.2. In the WTG clutter zone, no tracks are initiated automatically.

Creation of Clutter Maps using Range Azimuth Gates.

Wind Turbine Generator (WTG) has a large area and will therefore present a large Radar Cross-section (RCS). The clutter from the WTG will consist of clutter created from the echoes returning from the reflections from the stationary tower and the radio waves, which are reflected back from the rotating blades of wind turbines thus creating the Doppler ambiguity. A clutter map generation algorithm for primary radar will measure the echo strength of radar reflected returns at various range azimuth gates and generate a clutter map [73]. The process of clutter map generation begins after the radar has been deployed at a designated site. Each radar receiver is optimized for identifying the target returns from the noise based on a pre-set threshold.

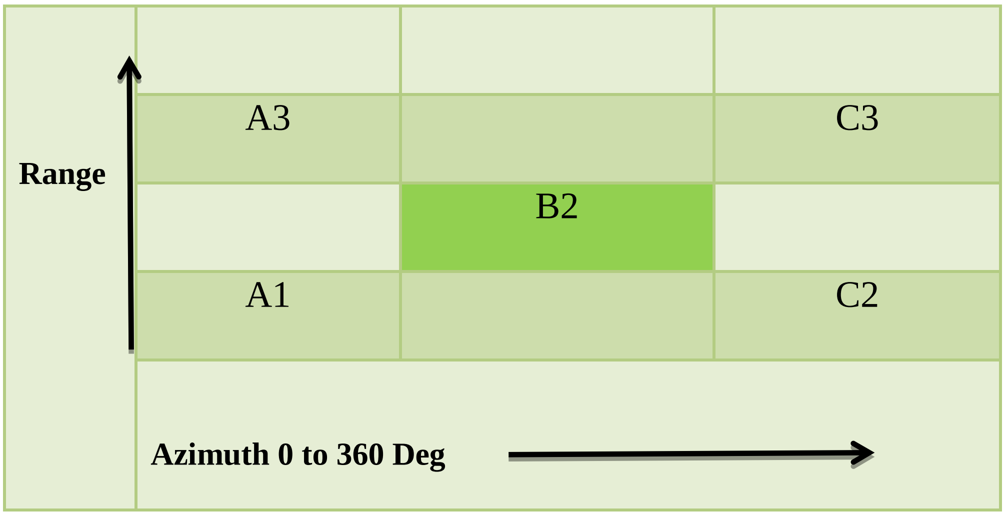

Fig. 5.3 Range Azimuth Gates

The strength of the echo signals received is expected to be in a pre-defined range as set in the radar signal to noise ratio in the radar receiver. The echo received from static structures like buildings, trees, terrain features, urban clutter will remain same and can be marked on the radar scopes and help in generating the permanent clutter areas in the radar.

The clutter maps are generated from the reflections of the ground clutter within each range azimuth gates divided into small cells. The total azimuth on radar scope is segregated into small range azimuth-cells as depicted in Fig.5.3. The area covered by these cells will depend upon the resolution of the radar and is a design parameter. Each range azimuth cell compares the power of the received reflected signals and identifies the returns as permanent ground clutter in case they are above the pre-defined threshold. These returns will classify the reflected returns from static parts of wind-turbines like the static towers of the Wind Turbine Generators. Moving Target Indicator (MTI) can be used to identify and suppress these returns. Identification and Creation of clutter maps will be undertaken as the first step when the radar is switched on at the site.

5.2.2 Static Turbine clutter removal using Moving Target Indicator (MTI)

The first step towards mitigation of clutter removal is the removal of ground clutter which is created by the non-moving parts of WTG. The radio waves which are radiated from the radar are reflected back after striking the WTG.

The radio waves reflected from the turbine blades create Doppler ambiguity and the reflection from static tower produces clutter. Whereas, clutter due to WTG blades requires resolution, however static clutter can lead to target drop as the target might be over masked by the static clutter of WTG.

In a wind turbine, the static tower can result in large clutter which can be even more than the clutter produced by turbine blades. The spectrum of static clutter will be close to f=0 and its periodicity depends on the Pulse Repetition Frequency (PRF) as shown in Fig.5.4.

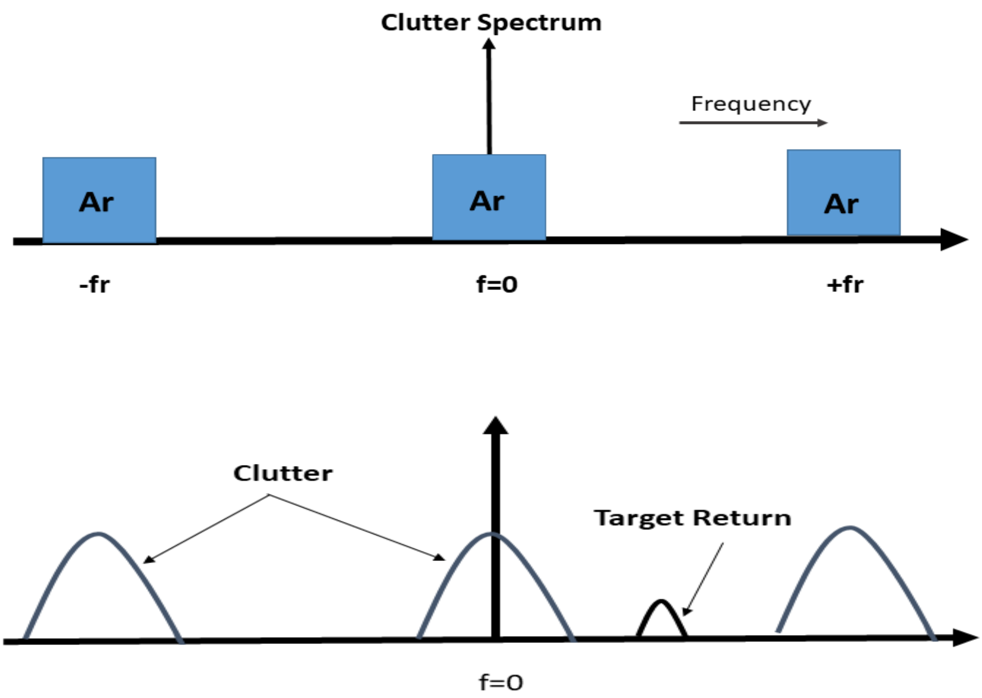

Fig. 5.4 The reflected target and clutter frequency spectrum

The response of the MTI filter is intended to have no output near zero frequency so as to cancel the ground returns and the output from the moving targets is not cancelled.The Doppler frequency f_d is dependent upon the velocity and wavelength

$$f_d = 2\,V/\lambda \tag{5.3}$$

Where V is the target velocity and λ is the radar wavelength

Let us assume a case where the radar is operating with a carrier frequency = 8 Ghz, The wavelength can be calculated by $\lambda = C/f$; where C is the velocity of light. Therefore, for carrier frequency of 8 Ghz the wavelength = 0.037 m. In case the WTGs blade is rotating between velocity (1m/s to 100m/s) the Doppler frequency can be calculated from Eq 5.3.

The Doppler frequencies for the radar operating at 8 Ghz will produce Doppler frequencies between 54 Hz to 5347 Hz for turbine blades rotating between 1m/s to 100m/s. Although WTG blades are not expected to rotate as high as 100 m/s, however the calculations are done for the purpose of explanation. The Moving Target Indictor system already exists in most of the radars. It generates a reference signal using a coherent oscillator. In addition to generating the reference signal the coherent oscillator output is also mixed with the local oscillator frequency. The Transmitted signal is in phase with reference signal. The reference signal and the echo signal are fed into a phase detector. The output of the phase detector is proportional to the phase difference between the input signals. The phase of the signal is sampled and 180 degrees phase rotation is undertaken for the cancellation of echo signals from stationary targets.

The cancellation process is undertaken using a delay line canceller. The delay line canceller delays the output in reference to one Pulse Repetition Frequency. Delay line canceller known as recursive filters have a feedback loop which shapes the frequency response[74]. The tip speed of WTG blades for a 1 MW Wind turbine will be anywhere between 100 to 200mph, these Doppler frequencies cannot be filtered using Moving Target Indicator techniques[75]. In MTI the Doppler filters inhibit the signals near zero frequency (DC) and at desired frequencies of wind turbine clutter. In case the radar is located in the turbine and radar interference areas, then employing Moving Target Indicators can solve the problem of the static clutter of WTG; however the problem of fake targets due to the reflected return by turbine blades cannot be removed. The problem for cancelling the Doppler returns will be undertaken next.

5.2.3 Optimizing the Tracker in the Clutter Zone

"Create No Automatic Plot to Track conversion Zone"

In the process towards mitigating the Doppler ambiguities, the first step is to create a "No Automatic plot to Track conversion Zone". Once radar makes detection, which means that the radar receiver has received the echo from a potential target and the track formation takes place based on radar estimations and measurements. The measurements made by radar are in the form of target attributes which include Range, Azimuth, Velocity, and height. Once based on the estimated inputs a target measurement is made, these measurements are co-related and association is done for conversion of plots to tracks. Radar measurements can be co-related and associated with and existing track or a new track in a pre-defined estimated area which is called as Gate.

Algorithms like the Nearest Neighbour (NN) and Global Nearest Neighbour (GNN)are used for co-relation of tracks ensuring that the track numbers are not changed. The GNN has a better performance over Nearest Neighbour algorithm for tracking targets and are more suitable for areas which may have deployment of Wind Turbine Generator (WTG) [20].

In the methodology suggested in this study the creation of “Clutter Zone” of Wind Turbine Generator (WTG) is the first step. This is the sector affected with interference and clutter. This “Clutter Zone” in the radar scope is the area of “No plot to track conversion zone”. In this sector the algorithm of radar which automatically converts the plots to tracks after correlation is disabled. A different correlation and plot to track conversion algorithms will be implemented in the “clutter zone”.

Tracker filter selection

The tracking system of any advanced multifunctional radar is based on estimation theories. Many multifunctional radars search for targets using pre-set rate of rotation, thus allocating a fixed time on target which is due to the fixed time of target illumination by radio waves. In order to undertake tracking of simultaneous targets, radars will make use of estimation techniques. The radar tracking system is capable to track simultaneous targets which may be manoeuvring or accelerating or taking rapid turns by using prediction techniques in filters [76], [77].The choice of filtering techniques in the tracker should be chosen as per the target characteristics and the requirement of data accuracy. The requirement of filtering is for selecting the most accurate data. We will analyse the available choice of filters and see which filter should be applied for the WTG sector.

α-β-γ tracker uses previous measurements and predicts the future positions. The gain of the filter is used to correct the future positions. The difference between the measured and predicted is multiplied with the gain to improve the prediction data [78]. The estimation equations used for the tracker are enumerated below.

$$\hat{x}_K = \hat{x}_{K-1} + T\,\hat{v}_{K-1} \qquad (5.4)$$

$$d_k = z_k - \hat{x}_K \qquad (5.5)$$

$$x_k = \hat{x}_K + \gamma\, d_k \qquad (5.6)$$

$$\hat{v}_K = \hat{v}_{K-1} + \frac{\beta}{\Delta T} d_k \qquad (5.7)$$

$\hat{x}_K$= This is the predicted position at time k

x_k=This is the position estimate at time k

z_k = This is the measurement value of position at time k

$\hat{v}_K$= This is the estimate of the velocity at time k

α and β = These are the system gains and remain constant

The tracker equations can be employed for prediction of targets, however due to the limitation of constant gain which does not change with the filter α-β-γ tracker will not be deemed suitable for tracking an aircraft. The limitation of constant gain can be overcome by use of Kalman filter. The Kalman filtering technique makes use of Bayesian principles while undertaking estimation of targets and predicting the parameters like velocity and acceleration from measurements which are corrupted with noise. Kalman filter predicts the values of these state variables in reference to earlier measurements[76].

Consider the state equation

$$X_k = A_{k-1}X_{k-1} + B_{k-1}U_{k-1} + W_{k-1} \quad (5.8)$$

A_{k-1} Defines the state described by X_{k-1}at time k-1 & state X_k at time k.

B_{k-1}relates the control input vector $U_{k-1}$and$W_{k-1}$is process noise

The measurement vector Z_k is connected to the system state

$$Z_k = H_k X_k + V_k \quad (5.9)$$

where is V_k noise andH_k is observation matrix

The system noise covariance is Q_{k-1}= **E**($W_{k-1}W_{k-1}^T$) (5.10)

Where '**E**'is expected value

$$P_{k\mathrm{I}k} = \mathbf{E}[(X_k - \hat{X}_{K\mathrm{IK}}) (X_k - \hat{X}_{K\mathrm{IK}})^T] \quad (5.11)$$

Estimate $\hat{X}_{K\mathrm{IK}}$ is known as 'Posteriori' estimate and $\hat{X}_{K\mathrm{IK}-1}$is known as the 'Priori' estimate. The kalman filtering starts by undertaking prediction of error covariance and predicting the variables of state matrix. Calculation of Kalman Gain and error covariance is undertaken and a recursive cycle is repeated[79]. To initialize the filter the first step will involve the setting of initial values for state variables and covariance $\widehat{X0}$, P_0

The next step is undertaking the prediction of the state and error covariance.

$$\hat{x}_{k/k-1} = A_{k-1}\hat{x}_{k-1/k-1} \quad (5.12)$$

$$P_{k/k-1} = A_{k-1} P_{k-1/k-1} A^T_{k-1} T + Q_{k-1} \quad (5.13)$$

Calculation of Kalman gain is undertaken

$$K_k = P_{k/k-1} H^T_k \left(H_k P_{k/k-1} H_k^T + R_k \right)^{-1} \quad (5.14)$$

The next step is computation of estimates based on measurement

$$\hat{x}_{k/k} = \hat{x}_{k/k-1} + K_k \left(Z_k - H_k \hat{x}_{k/k-1} \right) \quad (5.15)$$

Calculation or error covariance

$$P_{k/k} = P_{k/k-1} - K_k H_k P_{k/k-1} \quad (5.16)$$

Order of Selected Filter

The order of the filter design will depend upon the expected behaviour of the target. In case the aircraft is expected to have a constant speed and constant heading, the order of the filter for getting the best noise reduction when tracking such a system is a second order filter. However, in case the aircraft is expected to take manoeuvres and accelerate then the filter will be third order, where $x1$ is position, $x2$ velocity, and $x3$ acceleration.

State Models

$$x = [\,x \;\; y \;\; \dot{x} \;\; \dot{y}\,]' \qquad (5.17)$$

The state variables will be defined as per the input of the parameters or the coordinates which are required to be tracked. The state vector will be position x and velocity $\dot{x}$ and their estimates. In a most simple case for explanation for basic Kalman filter, these can be position and velocity in Cartesian coordinates.

State Transition Matrix

The Transition Matrix is required for undertaking the iteration. It is used to determine the next target position. The Kalman filtering will involve prediction of error covariance and state matrix. The Kalman Gain is calculated along with computation of error covariance and cycle is repeated.

Simulated Target Behaviour

Target initialization at t=0, position is initialized

Initial Velocity = 1m/sec

Constant acceleration =0.5 m/sec^2

Number of samples= 200. Random white noise is added to corrupt the data.

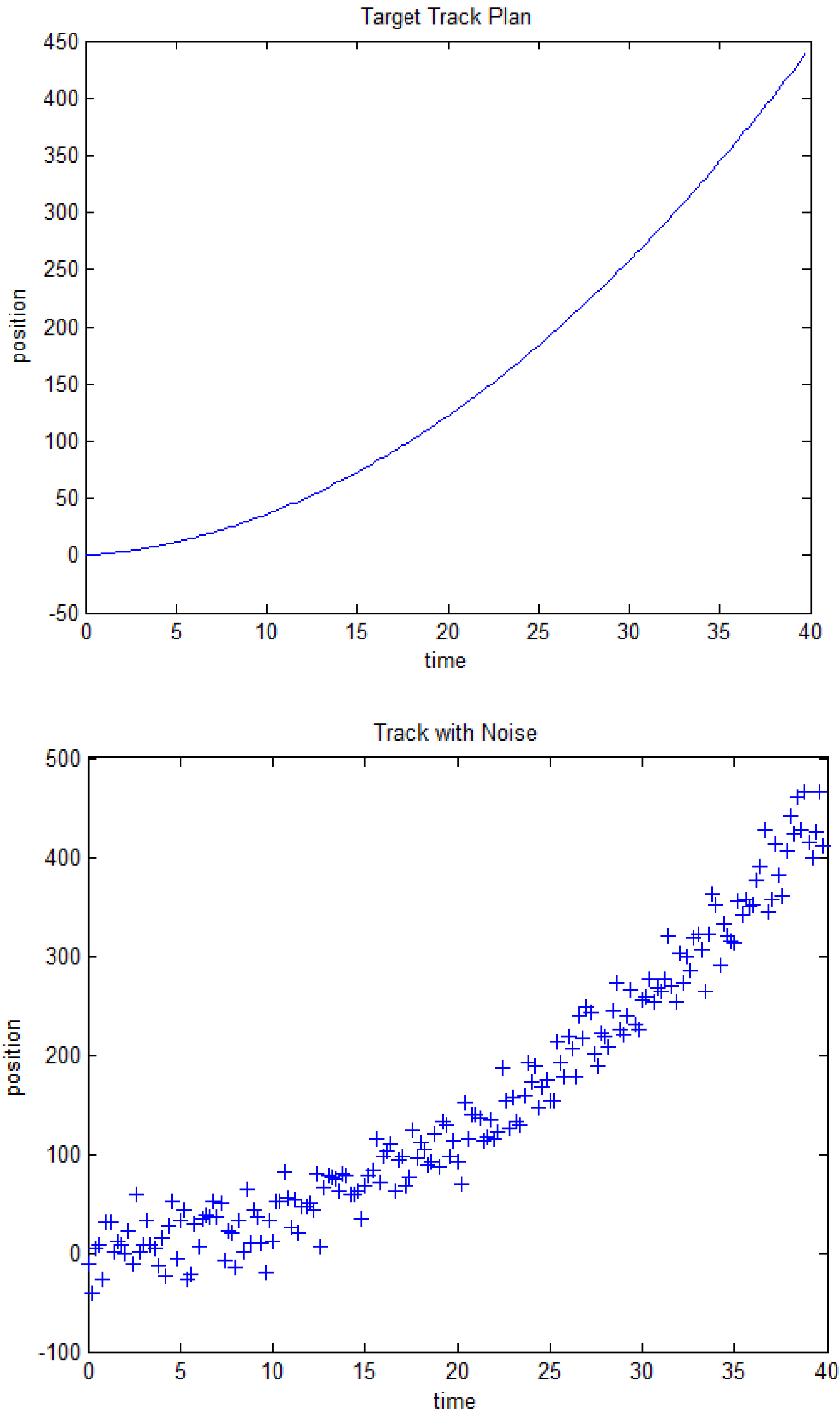

Fig. 5.5 (a) Aircraft track moment plan (b) Track moment with noise

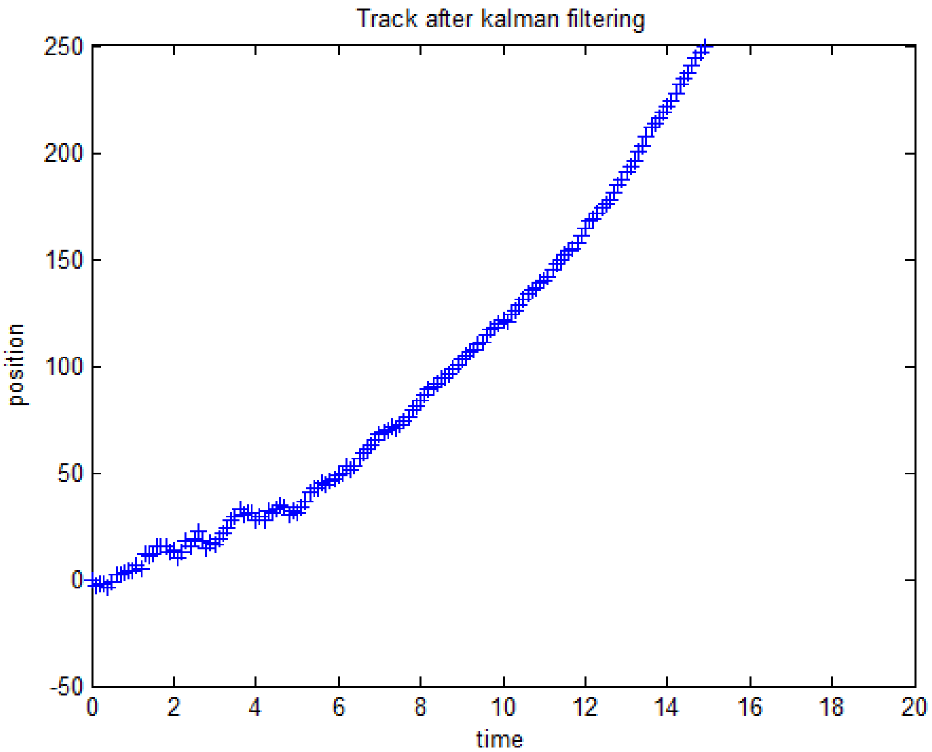

Fig. 5.5 (c) Aircraft Track Noise filtered

The Kalman filter has the advantage over the α-β-γ tracker however; it is limited to linear systems and will not be suitable for radar tracking scenarios. The Kalman filter has limitation for tracking highly dense air situations of high manoeuvrings targets or tracking under ambiguous situations like strong interference–situations. Another filtering technique known as the "Interacting Multiple Model" (IMM) tracker, which employs a number of different models to predict the values of state variables. The model selection depends upon target behaviour which can be a "Constant velocity" model, "Singer model" or "Turn model". The selection for manoeuvrings / non manoeuvrings models is dependent upon the target application, which is based on target behaviour for example Air Traffic Control application. For the estimation purpose, state equations are used to define different modes of operation. The probability for the target and their modes of operation is defined by Markov transition matrix. After each measurement the probability of the likelihood of each model is updated.[80].

Once the aircraft comes near the interference zone, the change of filter is to be undertaken. The IMM filter will undertake the aircraft estimation and select the most suitable filter. In case an Air Traffic Control Radar is deployed near the interference zone, the filter selected will be adapted to handle aircraft flying in a consistent pattern. This case will be different as compared to a case when a military tracking radar is operating. The military aircraft tracking radars will be designed to track fast manoeuvring targets which make quick manoeuvres as compared to civilian aircraft traffic. An Air Traffic Control IMM filter [81] can employ a "Constant velocity model" along with a "manoeuvring model with coordinated turn".

The "Constant velocity model" is defined by

$$x(k+1) = \begin{bmatrix} 1 & T & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & T \\ 0 & 0 & 0 & 1 \end{bmatrix} x(k) + \begin{bmatrix} \frac{1}{2}T^2 & 0 \\ T & 0 \\ 0 & \frac{1}{2}T^2 \\ 0 & T \end{bmatrix} v(k) \tag{5.18}$$

$x = [\ \xi\ \dot{\xi}\ \eta\ \ \dot{\eta}\ ]'$

T is sampling time, x is the target state , ξ and η define the coordinates and $v(k)$ defines the noise for coordinating turn model when Ω defines the turn rate [81].

$x = [\ \xi\ \dot{\xi}\ \eta\ \eta\ \dot{}\Omega]'$

$$x(k+1) = \begin{bmatrix} 1 & \frac{\sin\Omega(k)T}{\Omega(k)} & 0- & \frac{1-\cos\Omega(k)T}{\Omega(k)} & 0 \\ 0 & \cos\Omega(k)T & 0 & -\sin\Omega(k)T & 0 \\ 0 & \frac{1-\cos\Omega(k)T}{\Omega(k)} & 1 & \frac{\sin\Omega(k)T}{\Omega(k)} & 0 \\ 0 & \sin\Omega(k)T & 0 & \cos\Omega(k)T & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} x(k) + \begin{bmatrix} \frac{1}{2}T^2 & 0 & 0 \\ T & 0 & 0 \\ 0 & \frac{1}{2}T^2 & 0 \\ 0 & T & 0 \\ 0 & 0 & T \end{bmatrix} v(k)$$

(5.19)

Interacting Multiple Model (IMM)

The complex target scenarios of the system can be represented by different models as per their behaviour. The transition between various target manoeuvres can be described as Markov models.

$$P_T = \begin{bmatrix} P11 & P12 \\ P21 & P22 \end{bmatrix} = \begin{bmatrix} 0.98 & 0.02 \\ 0.02 & 0.98 \end{bmatrix}$$

The value of these probabilities will depend upon the target behaviour and as an example here $P12 = 0.2$ denotes the probability that the behaviour of the target will be changing from model 1 to model 2 or we can state that this is the probability that the P_{ij} target will make a switch between model i to j.[78].

$\hat{s}_i$ (k-1/k-1) = The filtered estimate of model for scan k-1 at model i at instant k-1.

$\hat{P}_i$ (k/k) = Covariance matrix of model i at instant k.

$\mu_i(k)$ = The probability that the target is in state i during scan k

$\mu_{ij}(k)$ = The probability that target went from state i to state j during scan k

Cj (k) = The probability of the target to be in state j after interaction

Where Cj (k) = $\sum_{i=1}^{r} P_{ij}\mu_i(k)$ where r is the number of models

$\mu_{ij}(k)$ =The conditional probability that the target is in state j and transition occurred from the state i.

$$\mu_{ij}(k) = \frac{P\ ij\ \mu i\ (k)}{Cj\ (k)} \tag{5.20}$$

The IMM process will be based on the model selection for example the first model can be a target with non-manoeuvring trajectory and the second model can be a target taking coordinated turn.

$$S^1 = \begin{vmatrix} x \\ y \\ vx \\ vy \end{vmatrix} \qquad S^2 = \begin{vmatrix} x \\ y \\ vx \\ vy \\ \Omega \end{vmatrix} \tag{5.21}$$

Since the model 2 will have an additional factor of turn therefore the fifth state vector is additionally included (Ω). The state vectors are for each model as per their weighted probability of transition.

In order to undertake mitigation techniques for Air Traffic Control Radar a combination of two models i.e the ‘constant velocity model’ and ‘coordinating turn model’ will be most suitable. The selection among the type of manoeuvring model selection and total number of filter models is to be employed depending on the aircraft flying profiles. The model probabilities are to be chosen, mixing to be carried out and consistently updated. It is also suggested to employ other confirmation techniques for the wind turbine clutter zone. The study compared a number of filters in order to suggest most optimum filter. In addition to completely assure the removal of Doppler ambiguity and removal of wind turbine clutter the use of "Micro-Doppler techniques" is suggested to be employed.

5.2.4 Use of Micro -Doppler in the Wind Turbine clutter zone

As per the Doppler principle, when a target is mobile and moving either away or towards the radar, the velocity of the returned signal has a shift in the frequency. This shift depends upon its relative velocity and wavelength of the moving aircraft and the receiver of radar. The shift in frequency is also dependent on whether the aircraft /target are inbound or outbound with respect to radar receiver. If the aircraft/target has structures having vibrations or rotational motion, then this rotational motion induces frequency modulations which generate side-bands. These side-bands generated have the Doppler frequency and is called as "Micro-Doppler" effect.

The Fourier Transform can be used to calculate the frequency shift to get the estimate of velocity dispersion because of the micro-Doppler effect [82], [83]. In our study we have suggested the utilization of same concept for removal of WTG clutter. For matter of convenience, the wind turbine blades can be compared to rotor blade of helicopter. The time domain signature for the rotating blades can be determined by equation 5.22[84].

$$s(t) = \sum_{k=0}^{n-1} Lsinc(\frac{4\pi}{\lambda}\frac{L}{2}cos\beta \sin(\Omega t + \theta o + k2\frac{\pi}{N}) \quad (5.22)$$

Ω is Rotation rate of blade, L is the turbine blade length, β is the elevation angle of rotor, θo is the blade scatter angle.

Simulation Data

The simulation data is required to capture the blade flashes. The azimuth and elevation angles will be with respect to the rotor of the WTG blades form the radar. The f_c is the carrier frequency of the radar, which will be varied between 2Ghz to 8Ghz. The respective wavelength for the cases will be 15cm & 3.75 cm. The elevation angle β can be varied from 0 to 90 Deg. The length of the rotor blades has been varied from 35 m to 70 mts. The θo is the scatter angle and Ω is rotation speed of rotor, which can be varied. In our simulations 2 cases of 20 RPM and 45 RPM have been considered. The velocity of radio wave propagation is considered as $2.9 * 10^8$ and sample rate is 10000.The FFT plot in Matlab is using fftshift function to centre the results around 0, however the amplitude in frequency domain doesn't have any significance in our study. The amplitude in time domain will depend upon the length of the blade. The dimension of Amplitude is (m) in time domain The Amplitude of the blade flashes will depend upon the length of the blade in time domain. The blade length is varied from 35 m to 70 mts.

Case 1: **Doppler returns for S-Band radar at 20 RPM**

Radar Carrier Frequency	Blade Length	Speed of WTG blades	No of WTG blades
2 Ghz (S-Band)	35 Mts	20 RPM	3

The wind turbine blades flash rate is dependent on the rate of rotation of turbine blades. The flash duration will depend upon the blade length, wavelength and RPM. The radar flashes from returns of turbine blades with radars of various frequency ranges is calculated and depicted through various simulation results.

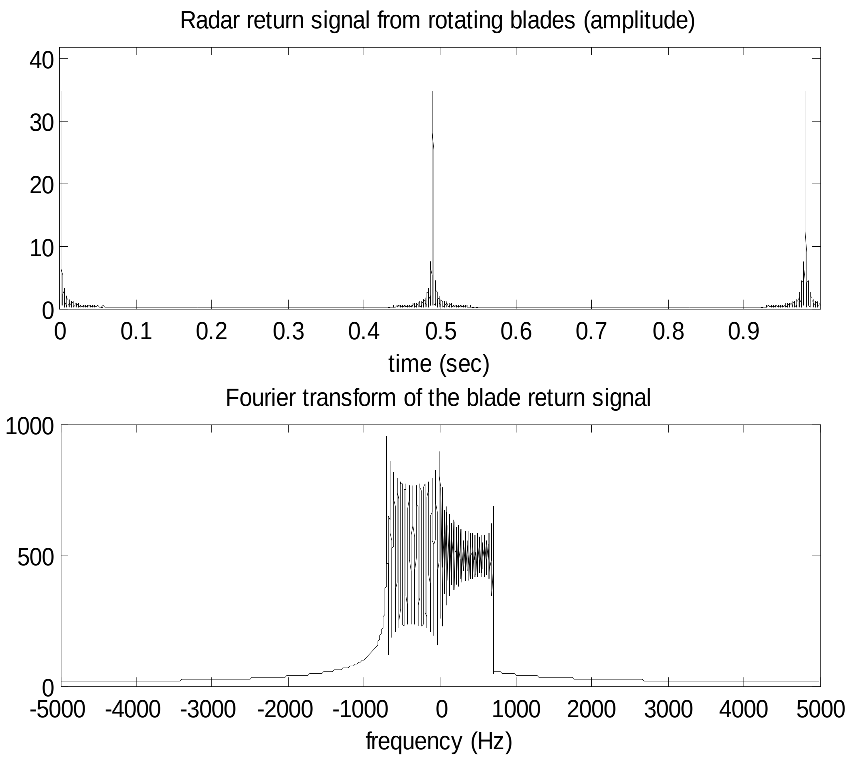

Fig. 5.6 Radar returns from WTG for 20 RPM and 2 Ghz Freq

Case 2: Doppler returns for S Band radar at 45 RPM

Radar Carrier Frequency	Blade Length	Speed of WTG blades	No of WTG blades
2 Ghz (S-Band)	35 Mts	45 RPM	3

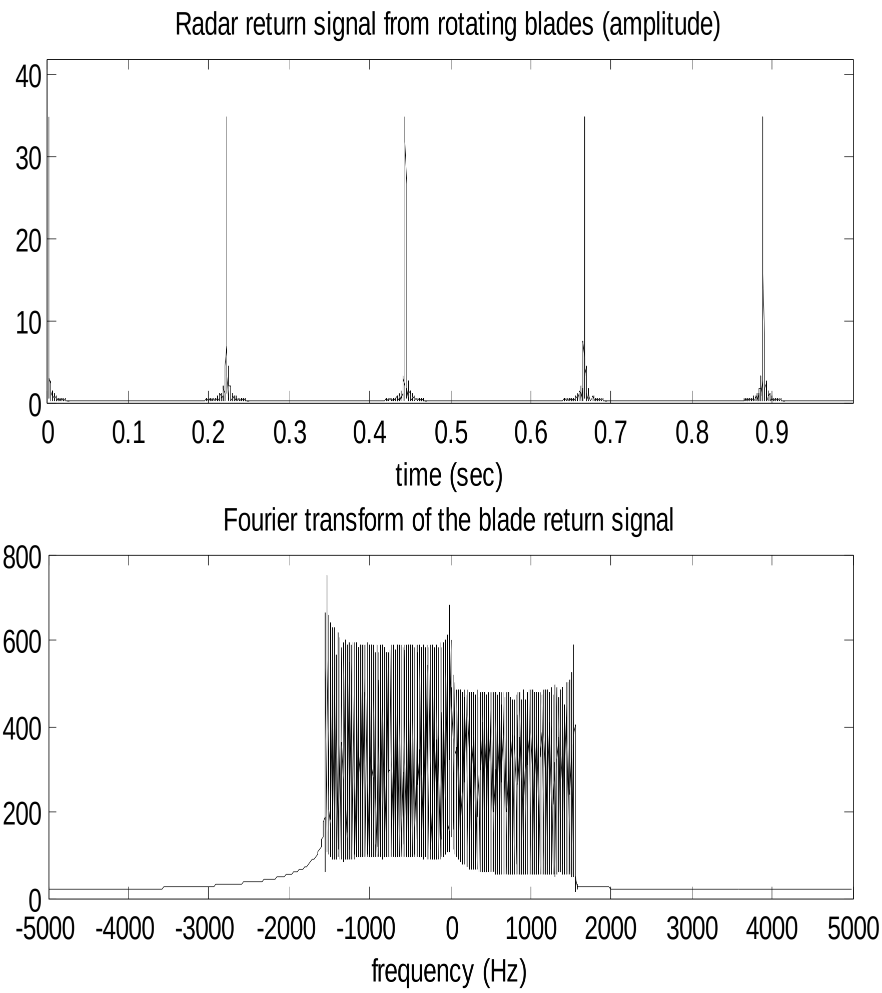

Fig. 5.7 Radar returns from WTG for 45 RPM and 2 GhzFreq

Case 3 Doppler returns for X- Band radar at 45 RPM

Radar Carrier Frequency	Blade Length	Speed of WTG blades	No of WTG blades
8 Ghz (X-Band)	35 Mts	45 RPM	3

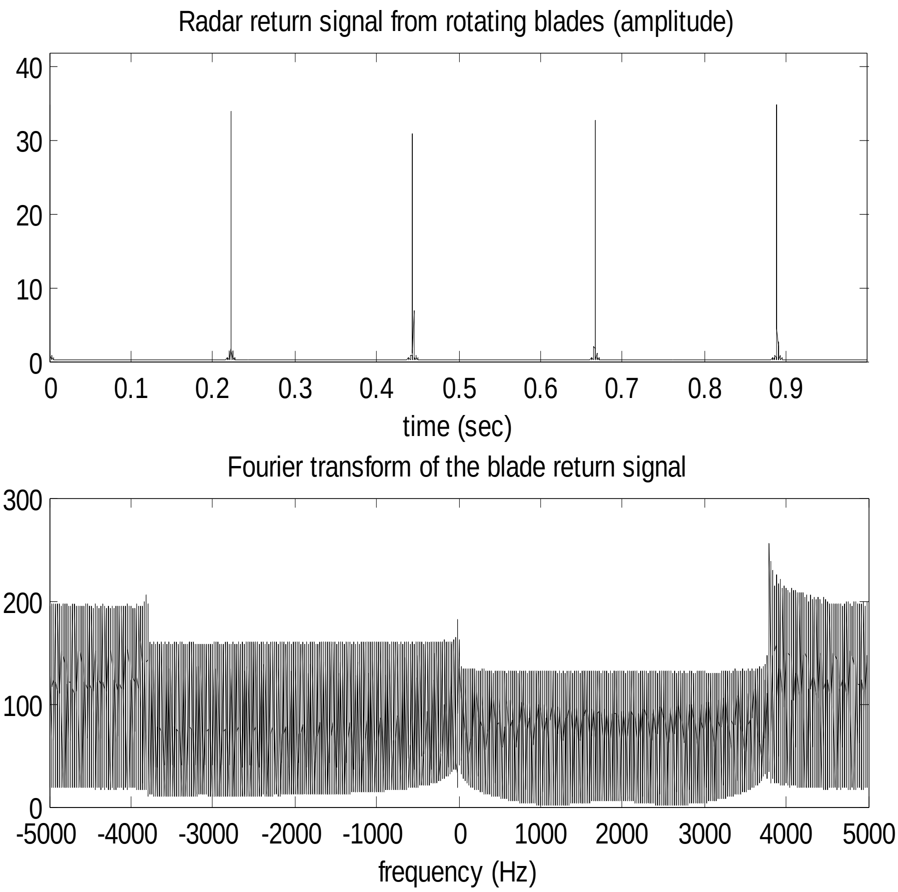

Fig.5.8 Radar returns from WTG for 45 RPM and 8 Ghz Freq

Case 4 Doppler Returns for X Band radar at 20 RPM

Radar Carrier Frequency	Blade Length	Speed of WTG blades	No of WTG blades
8 Ghz (X-Band)	35 Mts	20 RPM	3

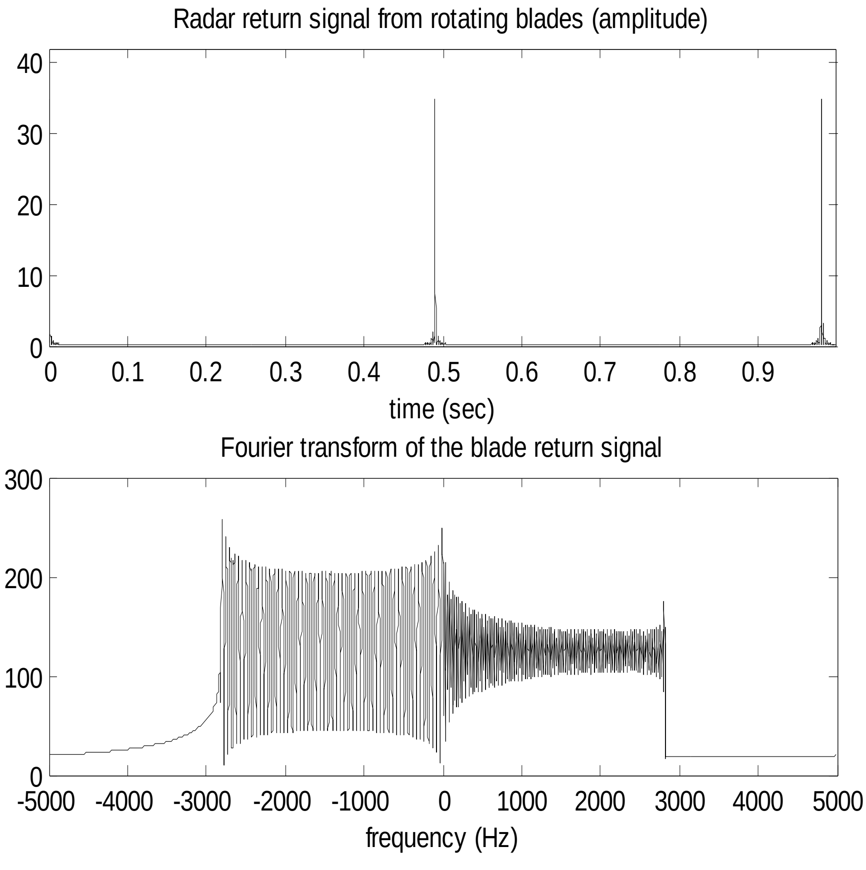

Fig.5.9 Radar returns from WTG for 20 RPM and 8 Ghz Freq

Effect on Radar returns by varying WTG parameters

The analysis was undertaken by varying the radar parameters and the parameters of WTG were considered to be constant. Simulation results for obtaining the Doppler returns for various WTG profiles can also be considered

Case 1 Effect of varying the WTG blades

Radar Carrier Frequency	Blade Length	Speed of WTG blades	No of WTG blades
8 Ghz (X-Band)	35 Mts	45 RPM	5

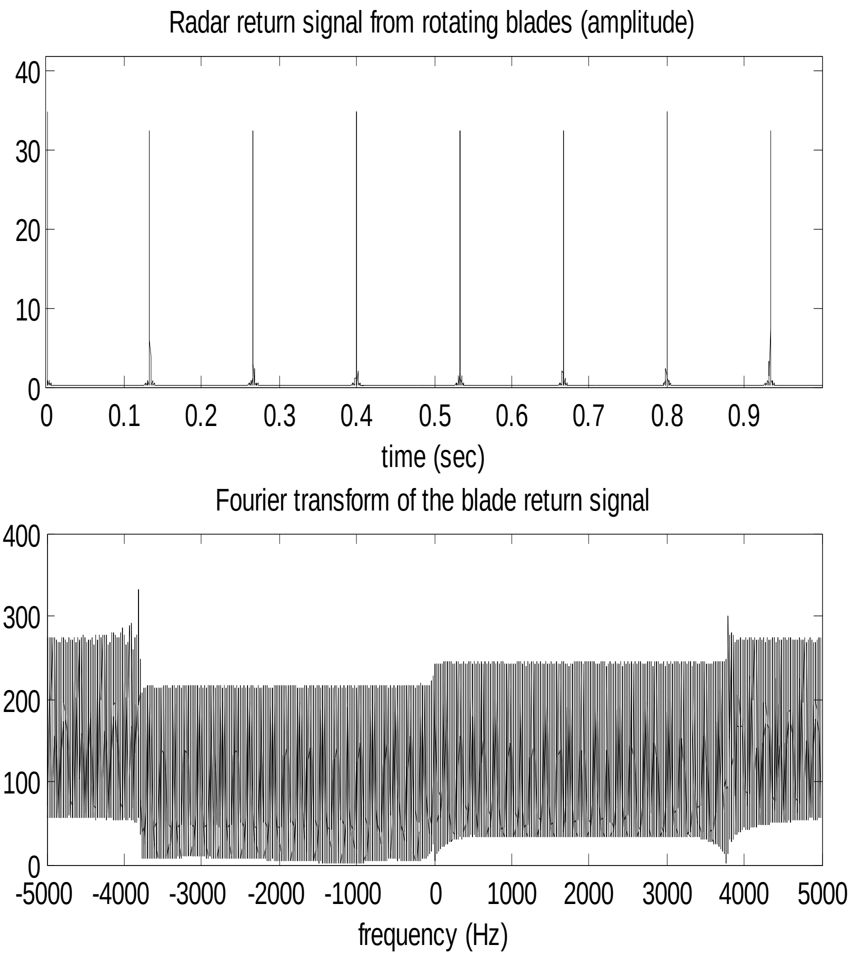

Fig. 5.10. Radar returns by increasing the no WTG blades(45 RPM & 5 Blades)

Case 2 Effect by varying the length of WTG blades

Radar Carrier Frequency	Blade Length	Speed of WTG blades	No of WTG blades
8 Ghz (X-Band)	70 Mts	20 RPM	3

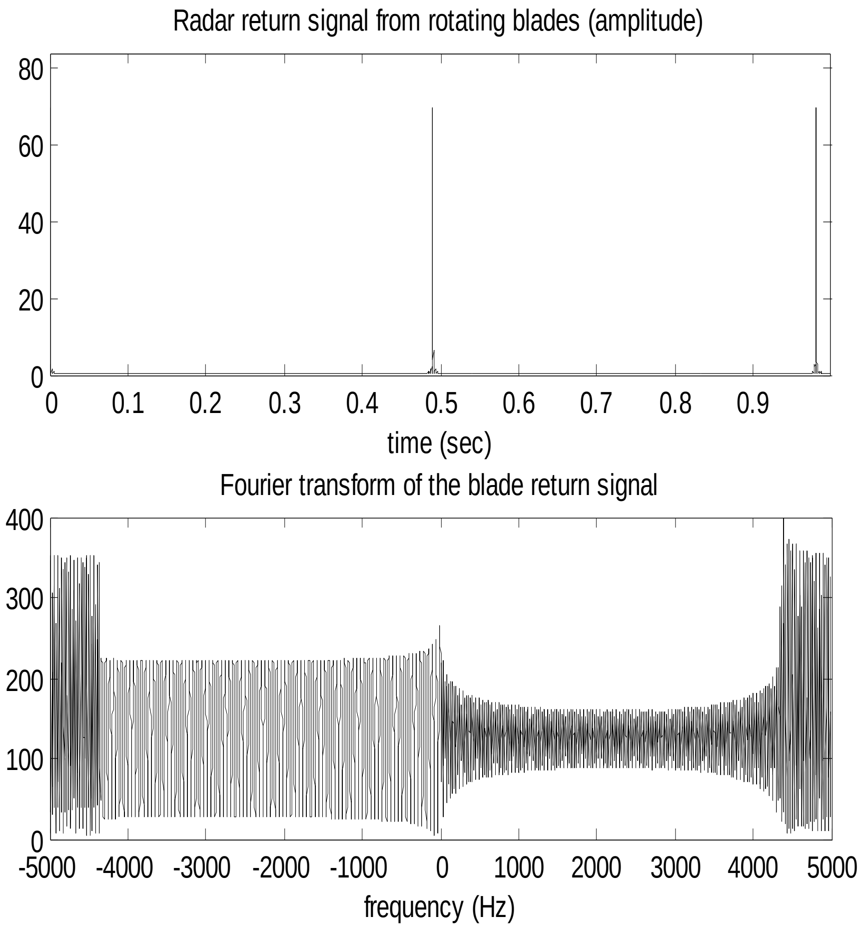

Fig. 5.11 Radar returns by increasing the length of WTG blades 20 rpm 70 mts

5.3 DISCUSSIONS

The purpose of the simulations was to explain the potential of capturing the Doppler returns and using them for identification of WTGs returns for radars. It is also understood that since we are concerned with only the Doppler returns, therefore the static areas of wind turbines will not be considered. The Doppler returns of the turbine blades signify time domain returns with radars having different frequency of operation. The rate of rotor blade returns will be dependent upon the rotation speed of the turbine rotor. The turbine blade length and frequency determines the turbine flashes duration[85].

<u>Deductions</u> : The increase in size of WTG tower although will not provide any change in Doppler returns, however it will present more static clutter due to the large area of tower, which will have to be cleared by Moving Target Indicators (MTI) as mentioned in the study. The increase in the length of blades or the number of WTG blades will definitely present stronger returns and more Doppler flashes into the radar receiver. It is therefore necessary that the profile of the wind turbines is known and there radar returns are captured and stored in the radar which can be identified and separated out. The study establishes that each wind turbine will generate specific return which can be stored in the radar processor and matched during operations and suitably cancelled as false target.

CHAPTER 6

STANDARD OPERATING PROCEDURE (SOP) FOR CO-LOCATING RADARS AND WINDFARMS TO MITIGATE INTERFERENCE

6.1 LINE OF SIGHT (LOS) SURVEY FOR SELECTED SITE

The simplest of the mitigation techniques for removing the radar interference with the Windfarms is to undertake the siting of the WTGs by siting them outside the Line of Sight (LOS) of the radar. This can be achieved by circumventing the radar waveform areas in the LOS. The radars beam forming, frequency and other design parameters are based on the type of application for which the radar has been designed. The radars are designed for applications such as Air Traffic Control (ATC) radars, Low Level radars, surveillance radars, Missile tracking radars, Air Defence radars, Mountain radars etc. Based on the types of roles and applications the radar-beams are designed for detecting the targets.

The curvature of earth enforces the restrictions in terms of LOS on the propagation of radio beams. The Radio Frequencies (RF) employed in the beam forming travel in straight line. To improve the siting conditions for mitigating the WTG and RF wave interference, the Line of Sight equations can be used. A Wind turbine having a height (h_m) and Radar with height (h_r) are positioned at a distance of $d_r + d_m$ as shown in Fig.6.1[86].

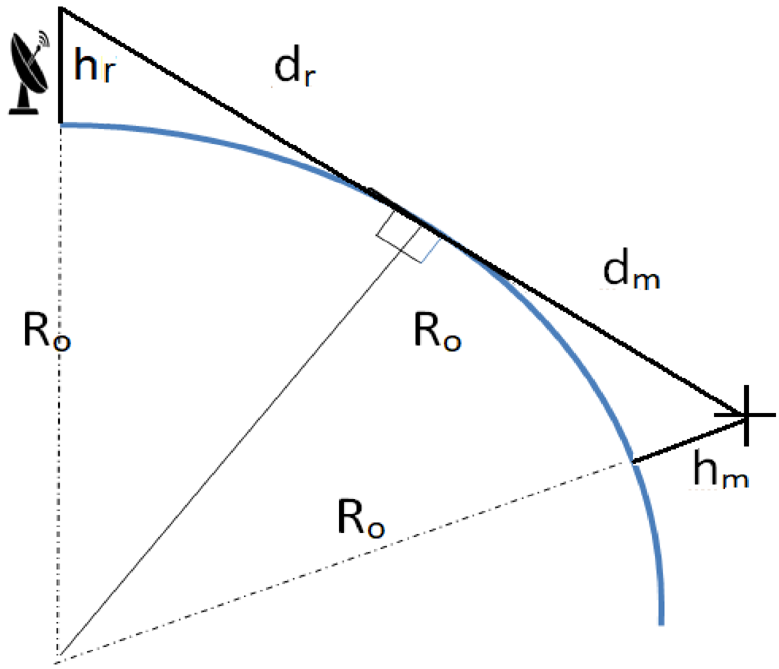

Fig. 6.1 LOS calculation between WTG and Radar

R_o= Radius of Earth ; R_o=3,959 miles

$$d_r^2 + R_o^2 = (R_o + h_r)^2 \qquad (6.1)$$

$$d_r^2 + R_o^2 = R_o^2 + \ h_r^2 + 2\ R_o h_r \qquad (6.2)$$

$$d_r = \sqrt{h_r^2 \ + 2\ R_o h_r} \qquad (6.3)$$

$$d_m = \sqrt{h_m^2 + 2\,R_o h_m} \qquad (6.4)$$

Since h_r and h_m are small, sod_r can be approximated as

$$d_r = \sqrt{2\,R_o h_r} \qquad (6.5)$$

$$d_m = \sqrt{2\,R_o h_m} \qquad (6.6)$$

$$\text{LOS} = d_r + d_m \qquad (6.7)$$

As per the 4/3 atmospheric refraction earth model R_o= 4/3 R_o to cater for earth's atmospheric refraction [75].

$$\text{LOS}= \sqrt{\frac{8}{3}\,R_o h_r} + \sqrt{\frac{8}{3}\,R_o h_m} \qquad (6.8)$$

The average height of any Wind Turbine Generator WTG (h_m) varies anywhere between (200 feet to 400 feet). The largely used (GE1.5-megawatt) has 115ft blade length and the tower length is 212ft, which results into total height of 328 feet. Similarly WTGs up to height of 400 feet are also currently in use [87].

6.2 LINE OF SIGHT (LOS) - CASE STUDY

The long range static radars are usually sited on higher platforms or on artificially made ramps in order to prevent reflections from ground which can result in ground clutter and for improving the LOS performance. On the other hand the transportable mobile radars are used for defence applications and are placed at sites with sufficient ground clearance and with least urban clutter. These can be placed at artificially made ramps, hilltops or raised grounds with improved LOS clearance. In order to provide a demonstrative example a site in Gujarat (India) is depicted in Fig 6.2[88].

This is a perfect site, for our case study which will be subject to ideal conditions for likely interference between radar and WTGs. This site is inside one of the areas having high wind potential in India. Since this place is in the vicinity of international border, it makes it a suitable site for placing military radars. The placement of military radars at this site which has a high density of WTGs creates a perfect scenario for case study on interference between radars and WTGs.

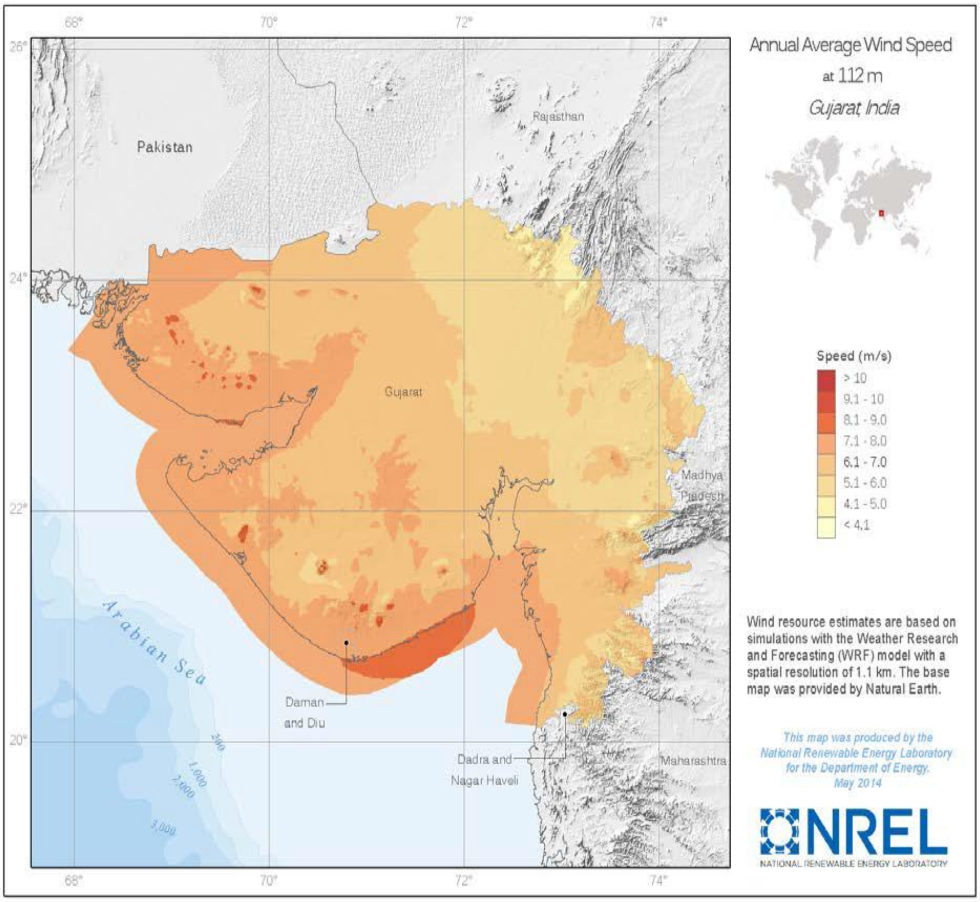

Fig. 6.2 Wind Potential map representing wind potential of Gujarat[88]

In this case study the height of WTGs (h_m) is assumed as 400 feet and the radar height (h_r) as 150 feet. Substituting the height of WTG and radar in equation 6.8 will give the LOS distance for the example under consideration.

LOS= $\sqrt{\frac{8}{3}\,R_o h_r} + \sqrt{\frac{8}{3}\,R_o h_m}$

=17.26 + 28.26

= 45.52 miles.

In the case study, if the LOS distance of 45 miles is maintained between the WTGs and the radars, then there should be no interference between them. However, this distance will also depend upon a number of other factors like the obstructions and the type of terrain shadowing or masking. In our case study the area is plain wetland which has no man-made structures or natural terrain undulations/obstructions, which makes the analysis simple. The terrain type may also hide the WTG tower and blades, thus avoiding direct reflections from radars. This also brings forth the requirement of digital terrain maps for the areas/sites where deployment is to be sought.

The type of terrain and the distance between the WTGs and the radar can help into the classification of Zones, which will help in undertaking the potential threat of interference at the site. The Federal Aviation Administration (FAA) of US, has developed a preliminary tool for undertaking screening which helps in calculating the potential impact of WTGs radars sited near the windfarms. Once the radar type and its site are marked in the map, the FAA tool helps in calculating the impact of WTGs on radars. The FAA tool creates a zonal classification map for the coordinates of the site. The FAA preliminary screening tool predicts the impact for Air Defence (AD) radars and weather Doppler radar within US [89]. Fig.6.3. depicts the preliminary results.

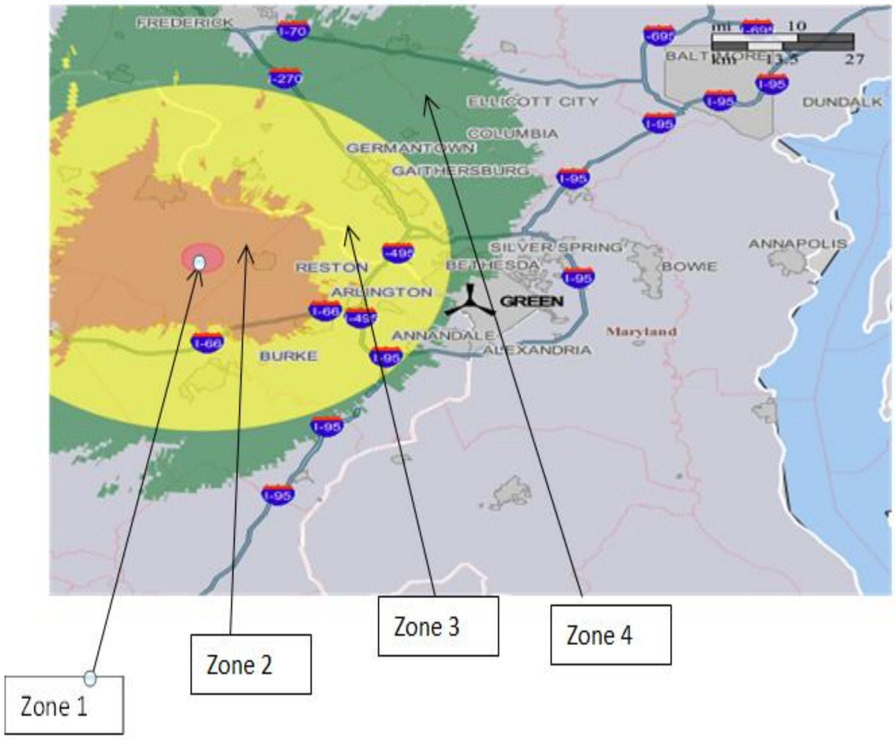

Fig. 6.3 Zone classification for radar and WTGs interference

The figure 6.3 illustrates the zones for the radar and WTGs interference potential for the selected site coordinates. The figure shows the impact zones. The Zone 1 is the most critical zone where the radar and WTGs cannot be sited due to high interference between the WTGs and radar. The Zone 2 falls under the area where it will require an analysis based upon the radar design parameters and the WTGs. The next Zone 3 will have less interference due to the increased distance and the Zone 4 and the areas further to Zone 4 are likely to have minimal or no interference.

Based on the results it is evident that the radars and WTGs should be sited based on the Line Of Sight (LOS) analysis. However, in case due to any reasons the radars have to be placed inside Zone 1 to Zone 3, then the interference reduction methods will have to be taken into consideration. One of the causes of the WTG clutter into the radar scope is the size of the WTG tower which is responsible for strong reflections back into the radar receivers thus saturating the radar receiver and creating clutter for the radar operators. If the effective area i.e the RCS (Radar Cross-Section) is reduced, then it will decrease the amount of radio waves reflected from the WTGs and will invariably reduce the interference. It is hence imperative that the parameters contributing in the RCS are analysed before choosing the radar site which is in close proximity to WTGs. In our study we have seen that the clutter which is caused by the WTG tower can be removed after use of MTI, however the clutter due to the returns from the rotating blades is difficult to remove and therefore efforts should be made to reduce this clutter. One of the easiest ways for reduction of clutter is to reduce the Radar Cross-Section, which will directly reduce the radar clutter.

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6.3 EFFECT OF SITE VARIABLES ON RADAR CROSS-SECTION

6.3.1 Effect on RCS due to variation in Azimuth

The RCS is directly related to the clutter, larger the area of the WTG structure, larger will be the windfarm clutter. The WTG yaws in the direction depending upon the direction of the wind in order to increase the efficiency. As a result due to the change in direction of the WTG blades in respect to radar axis of radiation will result in a change in RCS.[16]. The resultant change is in term of aspect angle which is measured from radar centre to yaw axis of turbine.

The fluctuation of RCS due to the variation of variables like frequency and aspect angle can be calculated by considering isotropic point scatters along the radar sight[74]. The aim is to reduce the windfarm clutter by making a reduction in the radar cross-section. There are several techniques for calculating the Radar Cross-section. Amongst various methods which can be used for calculating the RCS, the Physical Optics (PO) is one the easiest method which can be used for calculating the scattered fields to determine the RCS.

POFACETS is a software option which employs the Physical Optics method for determining the RCS [90]. POFACETS can be employed for investigating the effect of variable factors like incident variation of the observation angles, change in frequency and polarization, and the efficacy of Radar Absorbent Materials (RAM) on RCS of wind turbines. The WTG tower is the major contributor towards the RCS. The same can be calculated by making a variation in variable parameters like incident frequency, polarization and observation angles.

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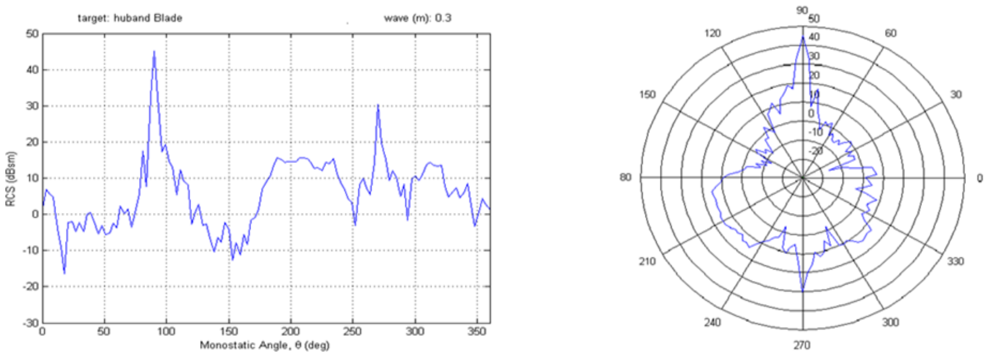

Fig. 6.4 (a) Effect of observation angle on RCS (wavelength 0.3m) ; (b) Polar plot

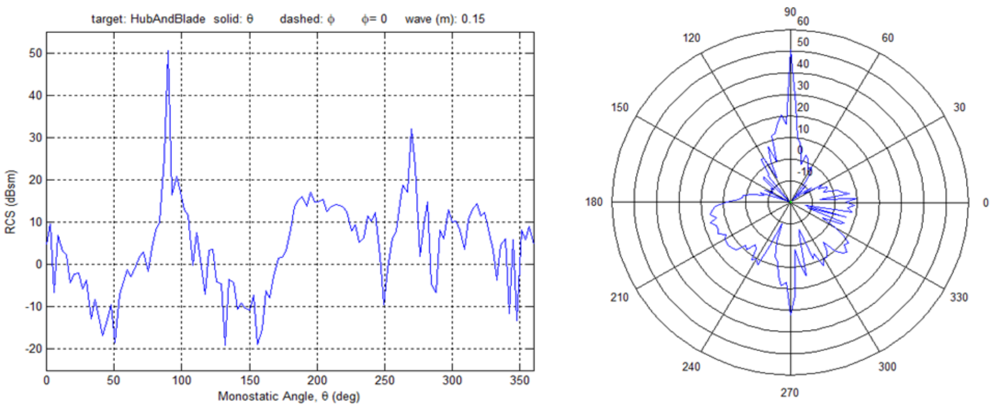

Fig. 6.4 (c) Effect of observation angle on RCS (wavlength 0.15m) ; (d) Polar plot

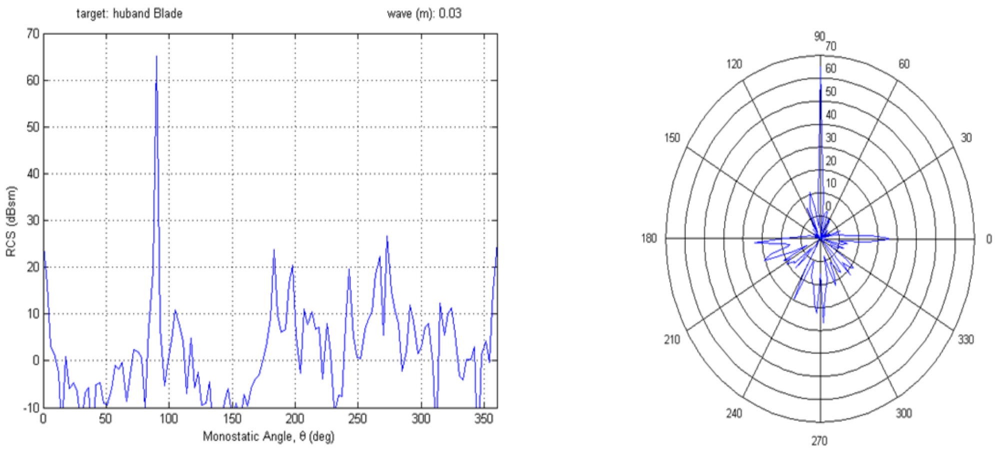

Fig. 6.4 (e) Effect of observation angle on RCS (wavlength 0.03m) ; (f) Polar plot

The simulations are carried out for the wavelength (Frequencies) of tracking and surveillance radars. The frequencies used are (1 GHz, 2 GHz and 10 GHz) covering all the commonly used ranges for tracking and surveillance radars. The POFACETS is used with an assumption that wind turbine material is Perfectly Electric Conductor (PEC). The blade material of wind turbines is made of composites, the relative permittivity in our simulations is taken as 4 and effect of ground reflections is neglected. The observation angles are varied from 0 to 360 deg and the effect on RCS is shown in Fig 6.4.

The angle at which the RF energy illuminates the WTG has a considerable effect on the Radar Cross-section. The variation of RCS with change in angle of observation is simulated for several radar frequency bands. The simulation results show a wide non- linear variation in RCS with change in Observation angle. These fluctuations in RCS will have a direct bearing on the radar clutter.

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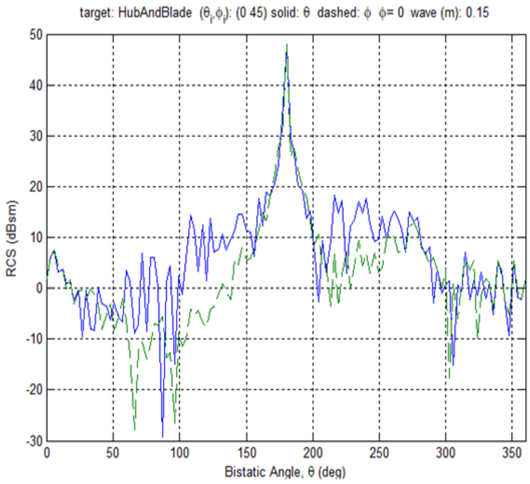

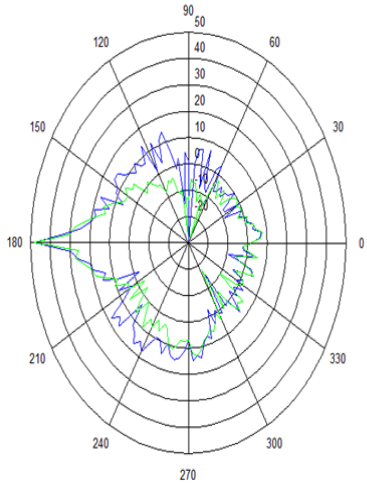

Fig. 6.5 (a) Variation in RCS by changing the bi-static angle (wavelength 0.15m) (b) Polar plot

The change of RCS by varying the bi-Static angle of radar with a fixed angle of incidence is depicted in Fig. 6.5. The change of RCS with incidence angle at 45 Deg for radar with a wavelength of (0.15m) is shown with the help of simulation. The S-band radars are the most commonly used multifunctional radar and is therefore the choice of frequency for our simulation.

6.4 EFFECT ON RCS DUE TO CHANGE IN FREQUENCY

The choice of selection of carrier frequencies is one of the most critical factors for the radar designers. The change in the radar cross-section with change in frequency of radar should be studied. The change in frequency plotted with respect to RCS on a logarithmic scale dBsm is depicted in Fig. 6.6. The fluctuations of RCS with frequency will largely depend upon the scatter spacing, frequency and physical shape. In the optical regions, the effect is negligible. The effect of change in frequency on the RCS is simulated on POFACETS software[86]. The results for simulation of RCS variation with frequency is undertaken for (0.1 GHz to 10 GHz) as this covers all the frequencies used in radar.

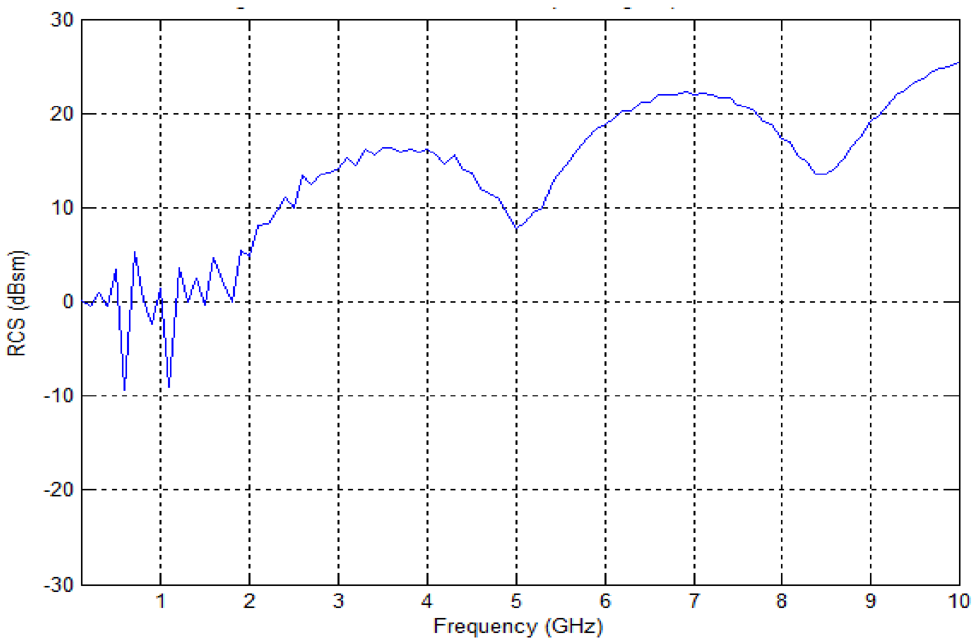

Fig. 6.6 Variation of RCS with frequency

6.5 EFFECT OF SPACING BETWEEN WTGs

The selection of spacing between the wind turbines is based upon many factors like aerodynamics, type of turbine and terrain. It may also be noted that the spacing between the turbines and the clutter produced by wind turbines will depend upon the type of radar and its design parameters. The long range older radars used of surveillance have wider pulse widths, which makes them capable of providing longer range with low resolution. The wide pulses may cause the adjacent wind turbines to fall within the same pulse. The modern radars employ pulse compression techniques for improving the capability of radars to resolve between two adjacent turbines. The higher spacing between adjacent turbines makes it easier for the removal of the WTG clutter by signal processing[16]. The summary of effect of varying parameters on Radar Cross-section is summarized in Table 6.1.

Table 6.1 Effects on RCS due to change in variable

Sl No	Variable	Effect on wind turbine RCS
1	Observation Angle	There is sharp fluctuation of RCS with respect to aspect angle due to constructive and destructive interference which depend upon frequency and scatter spacing.
2	Range and Wind	The increase in spacing between turbines

	turbine spacing	makes it easier for radar waveforms to resolve the turbines through signal processing and will lead to less clutter.
3	Effect of RCS with change in frequency	With an increase in frequency the RCS increases as shown on a logarithmic scale. The fluctuations in RCS with increase infrequency depends upon the scatter spacing frequency range and shape of the wind turbine.
4	Shape and Material	Shape of target and material reflectivity will play a major role in determining the radar cross-section.
Deductions: The relationship of RCS for three dimensional targets with respect to variables is complex and does not exhibit a linear pattern. The effect of observation angle, incident angle for Bi-Static radar, frequency, and shape and target material will have significant effect on target reflectivity. However, the relationships of these variables with RCS are complex and interdependent.		

The simulation plots for calculating the effect of variables which are related to the RCS revealed that factors like frequency, azimuth of radar, shape, scatter spacing, type of material have a considerable effect on the RCS of the radar, which is directly linked to the WTG clutter. It is therefore imperative that in case due to some unavoidable reasons, the radar is to be operated near the wind turbines, then the effect of these variables can play a significant role in optimizing the positioning of the radar, which will provide least interference.

CHAPTER 7

MITIGATION PROCESS FLOW

7.1 DISCUSSION

The effect of variables like azimuth, observation angles and range have a considerable effect on the interference and clutter, which was shown with the help of simulation results. Characteristic wavelength and frequencies used for different types of military and Air Traffic control radars were selected for undertaking the simulation. The selection of frequencies from 1 Ghz to 10 Ghz covers a wide range of frequencies used for tracking and surveillance. The effect for changing the azimuth and its effect on RCS were carried by changing the observation angles between 0 to 360 deg. It was also shown with the help of simulations that change in Azimuth has a considerable effect on RCS. The change of RCS with azimuth angles and corresponding change in RCS has significant changes in WTG clutter.

The simulations for ascertaining the effect of radar frequency on the RCS for frequencies between 0.1 Ghz to 30 Ghz were plotted on a logarithmic scale showing that there is a considerable increase in RCS with increase in Radar frequencies.

The simulation results showed that the variable factors like azimuth and frequencies have a significant effect on the Radar Cross-section which has a direct bearing on the WTG clutter. The simulation results bring forth the fact that in case the radars and WTGs are to be operated in close proximity then analysis of effect of azimuth and frequency should be studied. The analysis of these variables needs to be a part of the standard operating procedure for siting the radars near wind turbines.

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7.2 RADAR AND WTG CO-LOCATING (SOP)

The Standard Operating Procedure (SOP) for radars with WTGs co-location involves the steps depicted in Fig 7.1. The first step in the SOP is to try maintaining the Line of Sight (LOS) distance between the radars and WTGs. This activity can be undertaken by use of 3- Dimensional terrain maps/digital maps. The terrain maps will be useful for analysing the shadowing effect between the radar and WTG structures.

In case the radar siting cannot be avoided near wind turbines due to operational constraints, then they can be sited together after optimizing the effect of variables like frequency and Azimuth. The data given in (Table 7.1) can be used for siting.

Table 7.1 WTG/Radar siting data.

Site Data	Radar Data	Windfarm Data
Terrain profile	Type of radar (Weather, Surveillance, Tracking, Air Traffic Control)	Number of windfarms, type of windfarm
Distance between radar and windfarm	Frequency, polarisation	Height of windfarms, windfarm spacing
LOS clearance	Signal processing employed	Angle with respect to radar
Reflectivity profiles	Antenna height	Blade length, tower height
Shadow regions	Bi-static, Monostatic	Number of blades

The siting of radars as discussed will depend upon the variable factors like radar frequency of operation and radar azimuth. Similarly the mitigation techniques have to consider the radar parameters, signal processing techniques as these will have a different impact on the WTG clutter. After the radar siting has been finalised, then appropriate mitigation techniques can be suitably considered.

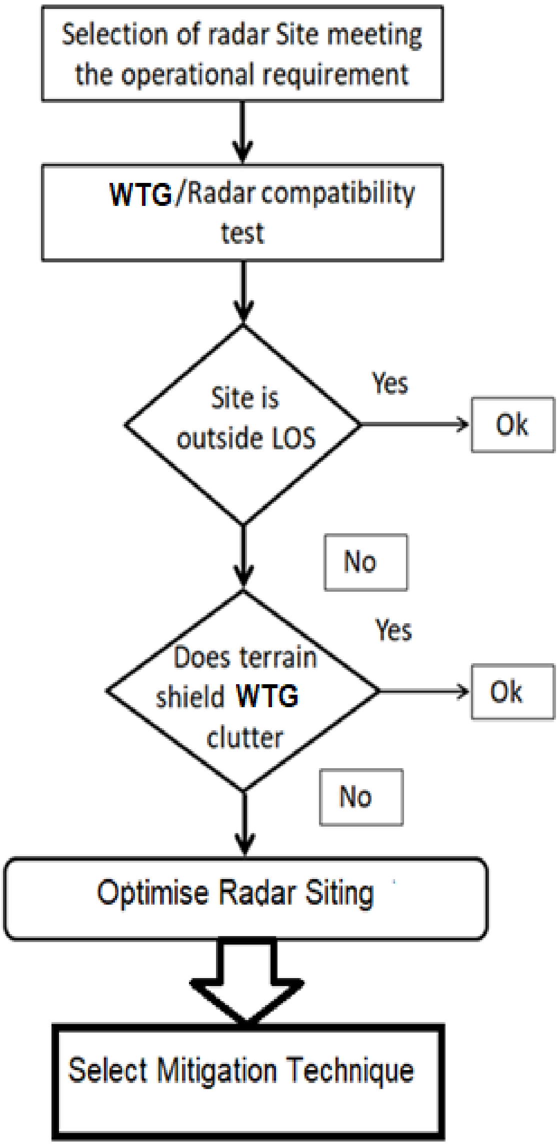

Fig. 7.1 Flow chart for siting strategy

7.3 PROCESS FLOW FOR MITIGATION TECHNIQUES

Once the Radar siting has been done in accordance to the siting strategy formulated in the study with the help of simulations, the interference/clutter mitigation is undertaken as depicted in Fig 7.1. The process flow chart will involve the reduction of static clutter due to the WTG tower. The clutter mapping is undertaken to identify the static clutter which can be eliminated using the Moving Target Indicator (MTI). This step will eliminate the static clutter of WTG. The next step towards the mitigation process is the removal of Doppler ambiguity which arises due to the interference effect of WTG blades.

The process will involve use of Range Angle Gates for the sector which has interference with the WTG. The sector will not have automatic track initiation and the Interacting Multiple Mode (IMM) filter is recommended to be applied due to the limitation of other filters. The expected target behaviour will determine the model selection and the correlation and association algorithm can be applied for track conversion. After the filtering process, the next step is the use of Micro Doppler filtering for eliminating the WTG Doppler returns. The Doppler frequency shift will create specific returns for each Wind turbine which is the characteristic of speed of blades, number of blades and the frequency of the radar. These characteristic Micro-Doppler returns from the wind turbines will be kept in the memory of radar computer and can be easily identified and filtered out. The mitigation process flow is depicted in the flow chart in Fig.7.2.

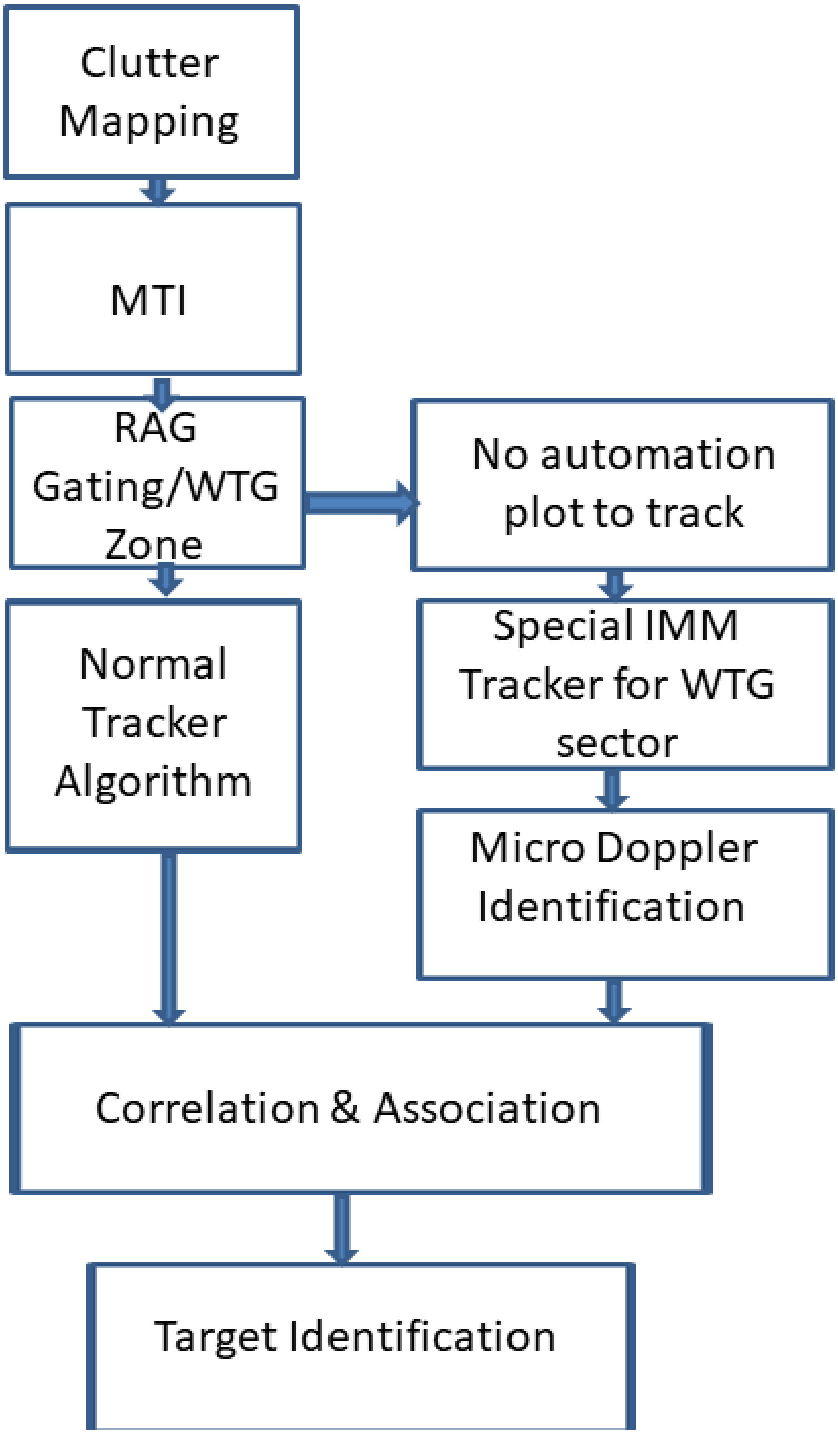

Fig. 7.2 Mitigation of Clutter Flow-Chart

CHAPTER 8

CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

8.1 CONCLUSION

The research is aimed to provide solutions for the live technical problem of Radar interference with windfarms. The objectives were to suggest mitigating techniques to overcome this technical glitch. The sub objectives of the study aimed to overcome the limitation of existing techniques with help of simulations and formulate a co-location methodology for windfarms and radars.

The study formulated a process flow chart towards siting radars and windfarms. The first step towards mitigating the interference between radars and WTGs is to undertake an assessment of the potential interferences considering the terrain of the site where the radar and the wind turbines are sited. The terrain shadowing and the Line of Sight (LOS) distance are to be considered while undertaking the assessment. The study suggested siting guidelines, use of terrain maps as the prerequisites before undertaking co-location of radars and wind turbines. Use of modern terrain analysis techniques by using 3-D maps for evaluating the effect of shadowing and masking is an important step before selection of appropriate mitigation techniques. The characteristic features of terrain like masking and shadowing will have a considerable impact. The radar variables like frequency of operation, azimuth and aspect angles have a considerable impact on the interference due to the constructive and destructive interference behaviour. These variables were shown to have a substantial impact on the Radar Cross-section. The selection of suitable azimuth angle can considerably lessen the Radar Cross-section thus reducing the effect on radar clutter. The simulation studies showed that the angle at which the RF energy illuminates the WTG has a considerable effect on the Radar Cross-section. The simulation results show a wide non- linear variation in RCS with change in observation angle. These fluctuations in RCS will have a direct bearing on the radar clutter

In case there is an operational requirement of siting the radar within the high interference zones, then mitigation process as depicted in “Mitigation of Clutter Flow-chart” is to be adopted. Modelling and simulation studies can be used to suitably select the most appropriate technique for reducing the interference effects; this will require analysis of radar and WTG site data as shown in the study. A case for LOS siting efficacy is shown for the Indian state of Gujarat. The study shows that if the distance between both radar and turbines is 45.52 miles, for the selected terrain and known radar and turbine heights, there should be no interference between the turbine and radar. This will also largely depend upon the contours of terrain as these factors are likely to obstruct the radar beam.

The study suggested a novel signal processing methodology by employing available features within radars for resolving the interference problem. The study recommended use of Moving Target Indicators for removing the static WTG clutter by formulating a clutter map on the radar scope for the site and afterwards subtracting the static returns using MTI. For management of the WTG blade clutter, the study recommended use of Interacting Multiple Model filters along with the employment of micro-Doppler techniques, where the returns from each turbine are stored in the radar processor and are cancelled subsequently.

The study focused on practical solutions for the problem in hand. Implementing complex modification in Air Traffic Radars/military radars may take years due to flight safety concerns; therefore the study demonstrated easily implementable solutions. The study demonstrated that by tweaking the inbuilt design capabilities of radars and formulating Standard Operating Procedures (SOPs) the interference issues can be mitigated and the problem can be managed.

8.2 FUTURE WORK

Due to the expansion of renewable energy requirements and growth of wind energy, co-existence of windfarms with military and civil radars is an inescapable requirement. In consonance to these requirements, there will always be scope of improvement with new technologies and techniques. The following work in this field can be undertaken in future:-

(a) Employment of Cost effective radar absorbing material, which can absorb radar waves and is cost effective. Complete absorption of radar waves will resolve the problem.

(b) Deflection of radar waves by employing active and passive techniques on wind turbine blades. The waves if deflected away from the radar will not cause any interference.

(c) Development of "Screening Tool" using 3D terrain digital maps for India as developed by US. This will help the windfarm operators to get quick clearances and will also facilitate aviation industry and IAF.

APPENDIX – ‘A’

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