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Wind energy : site characterization and application of remote sensing

Safar ALHILAL[1], Siraj AHMED[2]

[1]*(Department of Electrical – Electronic Engineering, Faculty of Engineering/ Zirve University, Gaziantep 27260, Turkey)*

[2] *(Department of Mechanical Engineering (Head), Maulana Azad National Institute of Technology, Bhopal-462003, India)*

ABSTRACT

Wind energy is becoming popular source of renewable energy based power generation for electricity in windy areas. The wind resource assessment is essential and necessary step for appropriate wind turbine selection. Any wind energy development project has mainly three important aspects: quantification of available wind resource, site geographical and geological conditions and wind turbine power curve. In this paper initial two aspects are discussed along with the application of remote sensing techniques. The remote sensing application is important due increasing hub height of modern wind turbines in on shore and off shore sites, mountainous and complex terrain.

Keywords: *lidar, remote sensing, scaterrometry, site characterization, sodar, Wind energy.*

1. INTRODUCTION

Wind is air in motion relative to the surface of the earth. Wind power density (WPD) is a truer indication of a site's wind energy potential than average wind speed alone. Its value combines the effect of a site's wind speed distribution and its dependence on air density and wind speed. The direction changes of wind vector are depicted by wind rose. The variation of wind speed with elevation is referred to as the vertical profile. The time variations in wind speed and direction with periods less than about 1/10 hour are generally considered to be turbulence. The most common indicator of turbulence for sitting purposes is the standard deviation **(σ)** of wind speed. Normalizing this value with the mean wind speed gives the turbulence intensity (TI) [1].

In recent times, the wind turbines are being installed at an increasing rate in hilly, forested and complex mountainous terrain as well as in off-shore sites with ever increasing hub heights. The conventional method of accredited wind resource assessment is to mount cup-anemometers and direction sensors on tall metrological (met) mast. Due to increasing hub height of modern wind turbine the cost of met towers are increasing approximately to the third power of height. Then licensing permission of installation of high met mast is time consuming to obtain.

The measurement of wind speed at 100 m height for a modern 5 MW wind turbine hub level at a single point by cup-anemometer is no longer a representative speed of wind for a rotor diameter spanning more than 120 m. The rotor blade tip from lower most point to upper most point for such wind turbine will be at a height from 50 m to 200 m. Cup anemometer is a point measurement device whereas using a sodar or lidar at 100 m height probes a sampling volume in order of 1000 m^3 [2]. Remote sensing application in wind energy is used to supplement as well as to replace tall met mast measurement for the following purpose:

- Wind resource assessment: global wind resource is mapped on-shore, plains, over hilly and mountainous terrain, coastal area, off-shore et cetera.
- Evaluating various wind flow models and developing wind atlases of micro, macro and global scale.

- Power performance verification of wind turbines.
- Wind turbine online and forward-feed controls.

IEC 61400-12-1 standard for power curve measurement specify that a calibrated cup-anemometer at hub height and two to four rotor diameter up-wind in front of wind turbine is to be mounted [3]. With this arrangement the wind speed measurement is based which is only at a single point measurement. For a modern wind turbine of rotor diameter spanning 120 m, the wind field over the entire plane cannot be represented by a single point measurement that too especially in mountainous and complex terrain. Wind turbines operate in atmospheric boundary layer which is having high turbulence levels due to wind shear caused by roughness of the earth surface. To characterize the wind flow over the entire rotor plane multi-point and multi-height wind measurement will be required. The remote sensing application is now available commercially to fulfill above requirement.

The remote sensing technique based on sound and light waves propagation and backscatter detection such as sound detection and ranging (sodar), light detection and ranging (lidar), satellite based sea surface micro-wave scatterometry and synthetic aperture radar (SAR) find useful replacement of expensive met mast based sensors. It also replaces the time consuming erection and installation of high met mast. Sodar and lidar are direct measurement of wind speed based on Doppler shift and SAR is based on proxy-empirical calibration methods [2, 4].

2. POTENTIAL PARAMETERS

The most common objectives of wind characteristics measurement are:

- Determine or verify whether sufficient wind resources exist within the area to justify further site-specific investigations
- Compare areas to distinguish relative development potential
- Obtain representative data for estimating the performance and/or the economic viability of selected wind turbines
- Screen for potential wind turbine installation sites.

Micro-sitting is used to position one or more wind turbines on a parcel of land to maximize the overall energy output of the wind farm. The topographic screening should attempt to identify features that are likely to experience a greater mean wind speed than the general surroundings. Topographic maps also provide the analyst with a preliminary look at other site attributes, including [5, 6]:

- Available land area
- Positions of existing roads and dwellings
- Land cover (e.g. forests)
- Political/administrative boundaries
- Parks/national parks, forest reserves, restricted areas
- Proximity to transmission lines
- Location of obstructions
- Potential impact on local aesthetics
- Cellular phone service reliability for data transfers

For the development of wind energy the site characterization has to include following parameters and information:

- Main parameters
- Annual average wind speed
- Wind power density
- Wind rose
- Wind resource map

- Prevailing wind direction
- Speed frequency distribution and persistence
- Vertical wind speed profile
- Wind shear exponent (α)
- Weibull parameters: shape parameter (k) and scale parameter (c)
- Turbulence intensity (TI)
- Wind density (ρ) and its variation vertically and seasonally
- Historical wind data (including frequency and intensity of storms)

Other associated information:

- Power curve of the turbine
- Capacity Factor
- Annual energy production
- Economics
- Topographical map, contour map
- Roughness class of the site
- Grid related Studies
- Transmission line map
- Approach Road
- Other infrastructural Facilities

How wind is being reliably and cost-effectively integrated? The major goal is to maximize energy capture and thereby reduce the unit cost of generating electricity. Progress has to be made on the following aspects in managing the variable nature of wind energy [6]:

- Predicting wind power output hours and days in advance with increasing accuracy and confidence with advanced computer software
- Higher capacity factors and penetration levels for wind energy
- Selection of larger rotor diameter turbines and building wind farms in strategic areas to maximize output
- Balance between load and generation in the grid while integrating larger amounts of variable wind power
- Wind power plants are an integral part of the power system and are expected to ride through disturbances and provide power control and voltage control.

3. REMOTE SENSING APPLICATION

The remote sensing techniques of lidar (light detection and ranging), SAR (synthetic-aperture radar (radio detection and ranging)), scatterometer, RASS (remote access service), sodar (sound detection and ranging) etc. both ground and satellite based are recent advances in wind energy technology [2]. The application and usefulness of these techniques in wind resource mapping, wind profiling, power curve verification, determination of wind loads and wind turbine control are becoming usual practices.

3.1 SODAR

Sodar are developed and based on audio-frequent technology. In sodar technique a ground based instrument transmits sequence of short bursts of sound waves of audible range frequencies from 2000 to 4000 Hz aloft at various heights in the atmosphere in three directions. A small fraction of transmitted sound wave propagation is scattered and reflected in all directions from the temperature differences and turbulence in the atmosphere. A very small fraction of scattered waves received back into the receiver or detector of sodar instrument. The height, at which the wind speed is measured, will be determined by the delay in time in the back scatter of the transmitted pulse. In standard atmospheric conditions the speed of sound propagation is about 340 m/s. For Example the back scatter of sound wave from a height of 170 m above the ground will be received back into the detector after delay of 1 s. The wind speed is determined as a function of Doppler shift observed from the frequency difference between the transmitted sound wave or light beam and frequency of back scattered received by the sodar or lidar instrument.

Sodar are typically applicable for measuring 10 min averaged vertical profile from 20 m to 200 m height all of for following parameters: mean wind speed, mean wind direction and turbulence in three directions [2].

Sodar can be used for direct control of wind turbine by installing in the spinner of the hub. It can also work as gust warning system and for power optimization.

There are two types of sodar systems available: mono-static and bi-static. In mono-static system, transmitter and receiver are co-located on the ground. In bi-static system the transmitter and receiver are separated 100 to 200 m apart on the ground. The carrier to noise ratio (C/N) is higher for bi-static system as compared to mono-static system. Bi-static continuous wave (CW) sodar system is preferred due to higher accuracy considered for wind energy applications [2].

In number of applications it is shown that mean wind speed and direction measurement by sodar is within and accuracy of ±3 percent as compared to cup-anemometer. It is to note that 1 percent uncertainty in mean wind speed results in 3 percent uncertainty in mean wind power. Sodar relatively cheaper option compared to lidar with low power consumption of about 10 W per unit [2]. Some of the manufacturers of sodar system are Remtech, Atmospheric System Corporation, Metek, Scientec, Second Wind, AQ System et cetera.

3.2 LIDAR

It is remote sensing of wind parameter like speed, direction and turbulence by using laser light. A lidar is used to measure wind speed and direction by probing the wind flow in the atmosphere from a ground based instrument using laser beams. The wind measurement is achieved by detecting the Doppler shift in the back scattered light. The Doppler shift is directly proportional to wind speed in the direction of laser beam in the adjustable measurement volume in the atmosphere. The lidar can be used at various ranges, angles and different heights. In lidar system electromagnetic radiation of light in the form of laser of wavelength of about 1.5 µm near infra-red is transmitted in the atmosphere at the point of interest [2]. The back scattering of light from many small aerosols suspended and moving with the wind will be detected by receiver of lidar in the form of small frequency shifts or Doppler shifts. Wind lidars are working in two measurement principles, namely: continuous wave (CW) lidar and pulsed lidar.

3.2.1 Continuous Wave (Cw) Lidar

A continuous laser beam is transmitted aloft in the atmosphere from lidar system and backscattering is received continuously at the receiver to record Doppler shift at a particular height. It focuses beam at different heights for measuring wind speeds. The measurement heights or range of measurement and spatial resolution of a continuous wave lidar is controlled by focal properties of the telescope. It works like a photographic camera to control the aperture, more for shorter distances and less for longer distances.

3.2.2 Pulsed Lidar

It transmits a sequence of short pulses of laser beam in the order about 30 m wave length and detects back scattered light. The measurement of wind speed in the direction of beam is related to Doppler shift.

Comparatively CW lidar showed higher spatial resolution and faster data acquisition than pulsed lidar and therefore former is preferred for turbulence measurements. Pulsed lidar is preferred for wind speed measurements at multiple heights simultaneously with higher ranges.

3.2.3 Wind Profiler

A wind profiler measures average parameters of vertical wind speed profiles, vertical direction profiles, vertical turbulence profiles through a series of radial direction measurement of several components of wind speed normally based on 10 min data sampling aloft in the atmosphere in beam direction. It is a ground based system transmitting a continuous or pulsed laser beam. It works on the same principle of Doppler shift detection in back scattered radiation. A wind profiler has transmitter and receiving antennas and both are combined in a single optical telescope.

Lidars system of measurement shows higher accuracy due to following features:

- Nature of light which is 10^6 times faster than a sound wave
- Antenna aperture size of lidar is based on the wave length of light. The ratio of its lens diameter to wavelength is more than 1000 which results in better beam control and higher data sampling rate.
- Both types of lidars, continuous and pulsed wave are based on the assumption that measured wind speed is proportional to Doppler shift and also that the aerosols are homogeneously distributed and follow the mean wind flow.
- Lidars can be mounted on hub at the spinner or in the blades. The lidar can see the wind front 300 m to 400 m ahead of wind turbine and by the time wind strikes the blades it can activate the pitch of the blade for appropriate angle of attack for optimum aerodynamic performance. It works on active control of blade pitch and nacelle yaw movement as forward-feed control strategy. It also reduces the fatigue damage from extreme wind speeds and wind shear due to forward-feed control which results in prolonging the life of wind turbine. Improve power performance results due to enhanced yaw control and lead-time control of blade pitching for approaching wind front.
- The lidar system is based on volume-averaged wind measurement and therefore more representative than point based cup-anemometer.
- Wind lidars are mobile instruments as compared to fixed location met mast mounted cup anemometers and better suited for onshore as well as offshore applications.

3.3 SCATTEROMETRY

Scatterometry is technique used for remote sensing the wind characteristics like speed, direction and turbulence aloft the sea surface. Scaterrometers are active radars that send pulses towards the surface of sea and measure the back scattered signal due to small scale waves in the order of 20 mm. Post processing of back scattered signals relate to wind speed. An instrument known as synthetic aperture radar (SAR) is based on similar working principle and measures the back scattered signals related to wind speed. Sun synchronous satellite over the ocean fitted with radar scatterometers operating at different sub-bands of micro-wave are widely used to measure near-surface wind speed and direction.

Radars operate at different sub-bands within the micro-wave range of electromagnetic radiation spectrum. As per IEC standard [3] radar band spectrum (2002) given in Table below scaterrometers are typically based on C and Ku sub bands. Indian Space Research Organization (ISRO) launched satellite Oceansat-2 in 2009 with Ku band scatterometer.

Table IEC standard radar band spectrum [3].

Designation	Frequency (GHz)	Wavelength(mm)
C-band	4-8	75-37.5
Ku-band	12-18	25-16.7

4. CONCLUSION

The following points are specifically important to take care for recent advances in wind energy technology:

- Usefulness of remote sensing for on-shore and off-shore applications as the size and hub height of wind turbines are increasing (10 MW capacity wind turbine with rotor diameter 180 m and hub height of 165 m is in design stage)
- Meteorological towers measures wind characteristics at a point and very expensive above 100 m. Remote sensing offers cost effectiveness and accuracy in measurements in a volume of space.
- The temperature variations and fluctuations play an important role in turbulence of wind in the atmosphere and remote sensing can measure temperature profile and turbulence very effectively.
- When recorded wind data by cup anemometer (reference instrument) is compared with lidar recorded data it shows closeness within 1 percent.
- Both pulsed lidar and continuous wave lidar are used in wind energy applications.
- Sitting of wind turbine in complex terrain requires careful understanding of the inhomogeneous wind pattern due to uneven topography and differential sun shine levels.
- For off shore wind energy development marine atmospheric boundary layer is to be analyzed.
- Signal processing in remote sensing involves Doppler shift, time to travel, pattern matching, fast Fourier transform, strength of scattering, pulse coding, travel time tomography etc.
- Studies of mixing layer height in the atmospheric boundary layer is very important due to low level jet effects at different times of the day due to synoptic situation changes in 12 hours period. For example the difference in wind shear profile above and below 160 m level is significant for multi-MW wind turbine.
- Temperature inversion in the atmosphere affects back scatter which eventually affects application remote sensing of wind characteristics.
- Usually maximum output of a wind farm is occurring at night time as compared to day time due to lower level of turbulence. It offers integration of solar photo voltaic energy in existing wind farms to normalize the difference in output.
- Sodar technique can be used for measurement in the range of 200 m to 600 m and lidar technique can be used upto 2000 m.
- Recent advances in sodar are bistatic sodar and narrow beam sodar.
- By using pulsed coherent lidars for remote sensing of wind the measurement is performed in the slice of atmosphere instead of a point.
- Lidar offers power curve verification of wind turbines through remote sensing.
- Buoy and floating plate form mounted lidars are useful for off shore applications.
- Wind scanner can be used for pro-active control of wind turbine. For example nacelle mounted lidars can sense approaching wind front say at 300 m ahead of rotor. By the time the wind front strikes the rotor, the blade pitching takes place to optimum angle. The feed forward control of wind turbine is thus achieved.
- Concept of rotor equivalent wind speed (REWS) is more realistic than hub height single point reference wind speed for power curve verification as well as for assessment and quantification of kinetic energy

in wind. Lidar/sodar is used with a met mast for initialization and calibration for measuring wind characteristics even up to the tip of blade in vertical position.

- Even 1 percent inaccuracy in wind resource measurement over a period of one year leads to substantial generation revenue loss for 1 MW wind turbine due to cubic relationship.
- For off shore application sea-state instrumentation is required which is costlier and sophisticated than normal instrumentation.

Wind energy is becoming one of the major elements in renewable energy based power generation for electricity. The size and sophistication in wind turbine is improving day by day with the introduction of new design concepts and newer materials. The technology have been evolved to present status with tremendous inputs from many other well established technological best practices like instruments and measurements, power electronics, electrical engineering, aerodynamics, statistical and probabilistic modeling, flow analysis, power drives et cetera and now laser based technology is introduced in the form remote sensing.

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