BLADE HEALTH MONITORING OF WIND TURBINES AND A CASE STUDY OF BHM IN 9FA GAS TURBINE COMPRESSOR BLADES AT RGPPL

By

Debashis Das , Hemant and Rajat Bhawsar

Control & Instrumentation

Ratnagiri Gas & Power Pvt. Ltd.

A. WIND TURBINE

A1. Abstract

Growing concern for environmental degradation and the urge to get clean energy has made wind energy to be a viable source both commercially and operationally. In addition to being green power wind turbine projects also have the advantages of having the fastest payback period, minimum investment in manpower and the cheapest source of electrical energy (20 years levelized cost basis). Maturity of wind turbine technology has also led NTPC Ltd. foray a joint venture with wind turbine manufacturing company M/s Inox Wind with headquarters at Noida. The company will be installing DFIG100 class 2MW machines for a project capacity of 50MW in the first quarter of 2017-18.

In order to harvest wind energy more efficiently, wind turbine size have become physically larger making it difficult to carry out maintenance & repair work. Monitoring of wind turbine health – especially for the blades - on a real time basis have become important to improve safety, minimize downtime and bring down associated maintenance and logistics costs.

Blade health monitoring of compressor and turbine blades in Gas Turbines shall also serve the purpose of preempting corrective action before catastrophic failures. Usually this is done through extrapolative techniques by real time monitoring of temperature and vibration, but for GE9FA machine, deployed at RGPPL Ratnagiri, same is being done through magnetic probes facing various stages of compressor blades and a data acquisition system (Bentley Nevada system).

This paper is an attempt in understanding the various BHM techniques available for wind turbines and detailing the process by which it is done in 9FA Gas Turbine of GE make

A2. Introduction

Urge for clean energy to mitigate Greenhouse effect has been a major driver for research in wind energy. In India development of wind power began in the 1990s. With Denmark and USA leading the table, India has the fifth largest installed wind power capacity in the world.

India has an estimated gross wind power potential of 1,02,000 MW (assessed at 80 m height) which has been arrived at with certain practical assumptions. This potential is mainly in the states of Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan and Tamil Nadu. A total capacity of over 20,000 MW of wind power has so far been installed in the country.

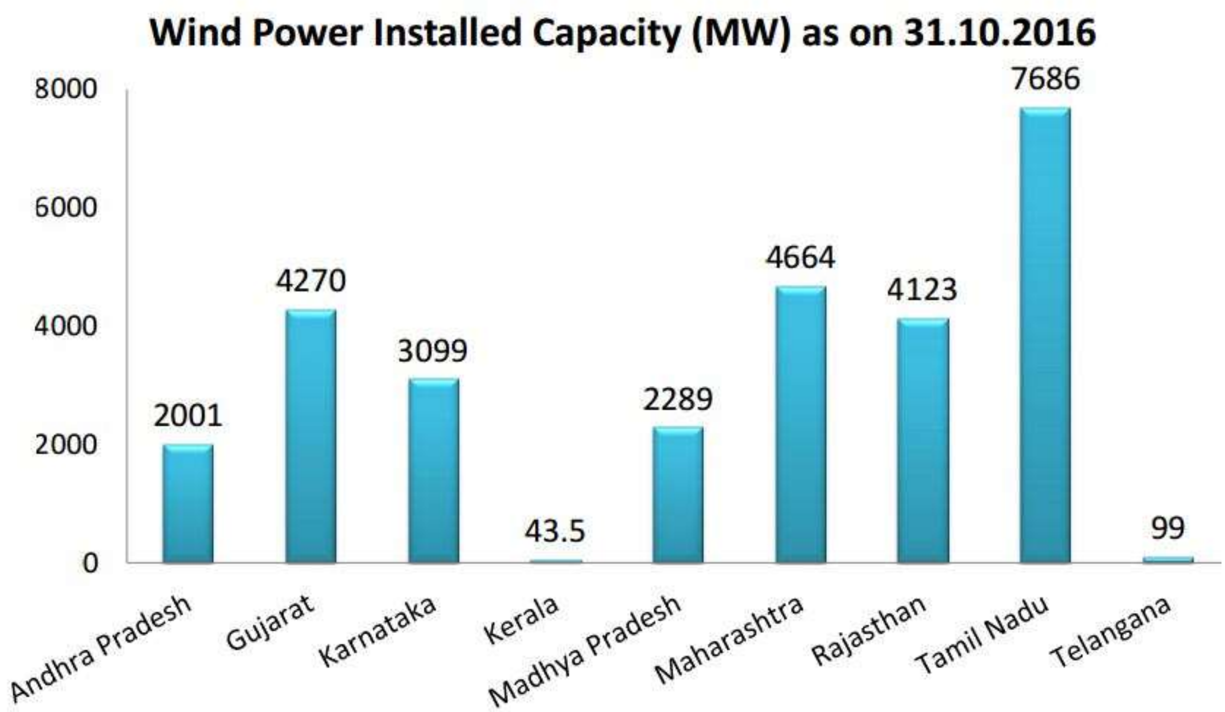


Fig.1 – Installed capacity in India

Most wind machines have blades attached to a horizontal shaft. This shaft transmits power through a series of gears, which provide power to a water pump or electric generator. These are called horizontal axis wind turbines.

There are also vertical axis machines, such as the Darrieus wind machine, which has two, three, or four long curved blades on a vertical shaft and resembles a giant eggbeater in shape.

The amount of energy produced by a wind machine depends upon the wind speed and the size of the blades in the machine. In general, when the wind speed doubles, the power produced increases eight times. Larger blades capture more wind. As the diameter of the circle formed by the blade doubles, the power increases four times.

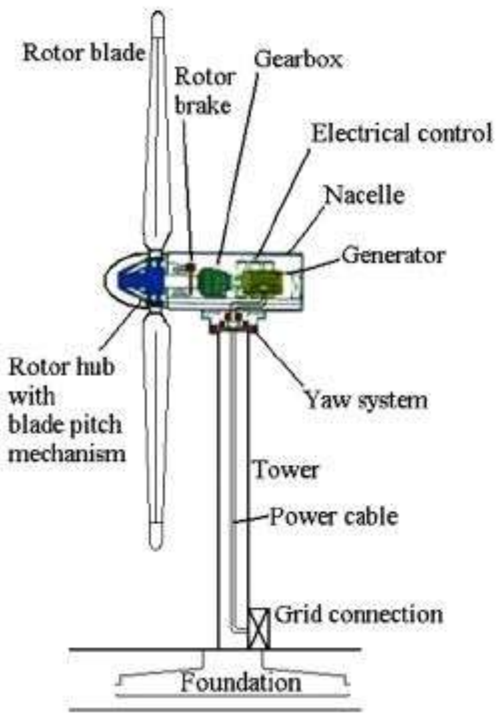


Fig.2 – Typical configuration of Horizontal Axis wind turbine system

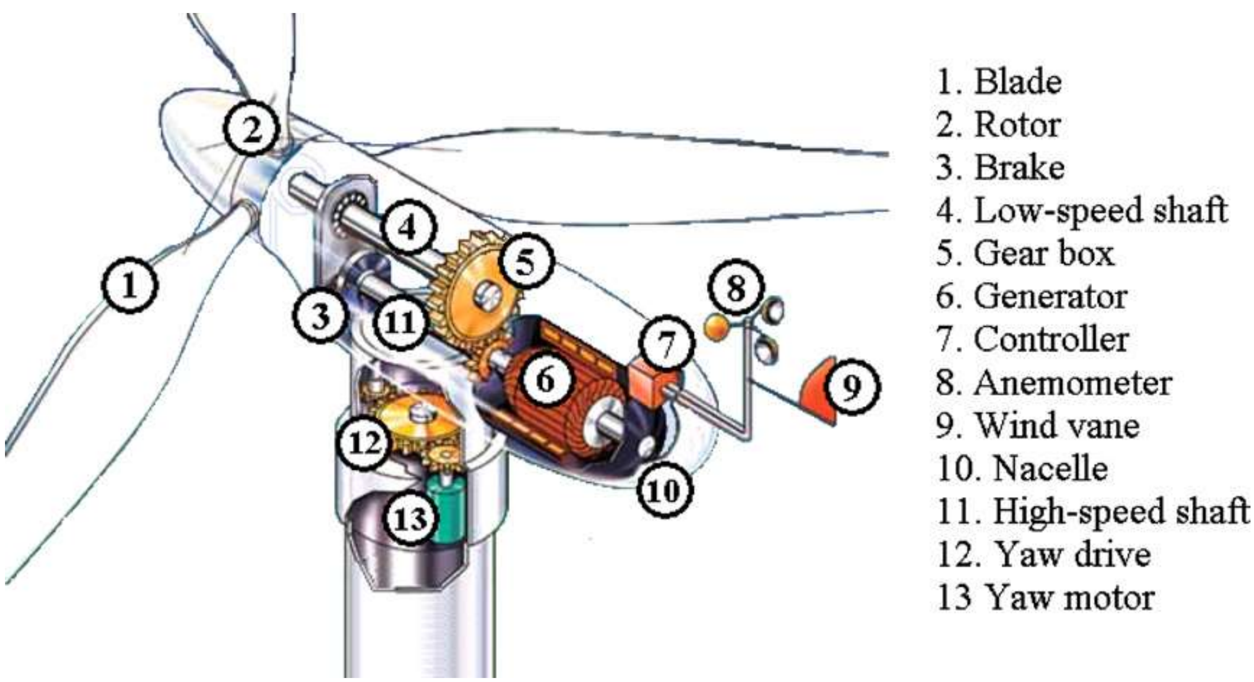


Fig.3 – Components inside a wind turbine nacelle

Some of the problems faced by the wind turbine industry are as follows:

1. Difficult to carry out inspection and maintenance work on account of height
2. Location of wind turbine, many a times in mountainous or rough sea regions makes maintenance more difficult
3. Fatal accidents have been reported globally a number of times
4. Advanced class lifting and handling equipment are required for erection and maintenance activities
5. Stake becomes higher with increase in capacity, hence tower and turbine size
6. Routine monitoring from remote location involves high maintenance and logistics cost

A structural health monitoring system is important as structural damage may initiate catastrophic damage to the whole wind turbine system. A monitoring system that is reliable, low cost and integrated into the wind turbine system may reduce wind turbine life cycle costs thus making wind energy more affordable. There are many causes of structural damage such as moisture absorption, fatigue, wind gusts, thermal stress, corrosion, fire and even lightning strikes. Wind turbine blades manufactured of non-conducting fiber composite materials without any conducting components are frequently struck by lightning, particularly at the outermost part of the blade. In general, the development of successful SHM methods depends on two key factors: sensing technology and the associated signal analysis and interpretation algorithm. The components of the SHM are made up of system state definition, data acquisition, data filtration, feature extraction, data reduction, pattern recognition and decision making. Each of these components is equally important in determining the state of health of a structure.
The SHM process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements and the statistical analysis of these features to determine the current state of structural health. For long term SHM, the output of this process gives periodically updated information regarding the ability of the structure to perform its intended function in light of the inevitable ageing and degradation resulting from operational environments.

Function	Advantages	Benefits
Early warning	Avoid breakdown	Avoid repair cost
	Better planning of maintenance	Minimized downtime
Problem identification	Right service at the right time	Prolong lifetime
	Minimize unnecessary replacements	Lowered maintenance costs
	Problems resolved before the time of guarantee expires	Quality control operations during time of guarantee
Continuous monitoring	Constant information that the system is working	Security; less stress

Table.1 – Wind turbine health monitoring systems categorized by characteristics

The benefits of having a fault detection system are as follows :
(a) *Avoidance of premature breakdown*: prevent catastrophic failures and secondary defects
(b) *Reduced maintenance cost*: inspection interval can be increased with on-line inspection, and replacement of intact parts is avoided by condition-based maintenance
(c) *Supervision at remote sides and remote diagnosis*: large turbines are usually built at remote sites.
(d) *Improvement of capacity factor*: with early warning of impending failures, repair action can be taken during low wind season and hence will not affect the capacity factor
(e) *Support for further development of a turbine*: the data obtained can be used to improve designs for the next generation of turbines

With a reliable SHM system, a promising maintenance and repair strategy for wind turbines, especially those offshore, can be planned. Maintenance and repair actions can be worked out on demand and during suitable weather conditions. Mobilization costs for staff, materials and craning equipment can be optimized.

Assembly	Possible defects
Rotor blade	Surface damage, cracks, structural discontinuities Damage to the lightning protection system
Drive train	Leakages, corrosion
Nacelle and force- and moment-transmitting components	Corrosion, cracks
Hydraulic system, pneumatic system	Leakages, corrosion
Tower and foundation	Corrosion, cracks
Safety devices, sensors and braking systems	Damage, wear
Control system and electrics including transformer station and switchgear	Terminals, fastenings, function, corrosion, dirt

Table.2 – Possible wind turbine damage

Damage can occur at any component or part of the wind turbine; it can be anything from a failure in the concrete base to a failure of the blades themselves, a bolt shears, a load-bearing brace buckles and so on. Cases of structural damage are reported from time to time from places such as Wales, Scotland, Spain, Germany, France, Denmark, Japan and New Zealand. In Germany, 2002, a blade broke in mid-turn with an audible ‘crack’. Pieces were found scattered throughout surrounding fields. In another case, a blade torn off flew as far as 8 km and through the window of a house. The possible types of damage that can occur are tabulated in table 2.

A3. Structural Damage

Although structural damage can happen to any structural component, the most common type of damage is rotor or blade damage and tower damage. Extensive attention has been given to the structural health of blades as they are the key elements of a wind power generation system, and also because the cost of the blades can account for 15–20% of the total turbine cost. It has been shown that the blade damage is the most expensive type of damage to repair and also has the greatest repair time. Furthermore, rotating mass unbalance due to minor blade damage can cause serious secondary damage to the whole wind turbine system if prompt repair action is not taken and this can result in the collapse of the whole tower.

In order to understand the blade damage, the anatomy of a blade must first be understood. The main elements of a wind turbine blade are shown in figures 4 and 5. The materials of the contemporary blades are usually fiber-reinforced composites with the majority of wind turbine blades being made of glass fiber/epoxy, glass fiber/polyester, wood/epoxy or carbon fiber/epoxy composites. The use of carbon-fib rereinforced plastic (CFRP) to manufacture the turbine blade has also increased with increasing rotor size. There is a main spar tube, and the upwind side and downwind side of the blade are constructed and joined together at both the leading edge and the trailing edge using adhesive. Damage to a blade can occur in various ways. Typical damage in turbine blades is listed in table 3 and a sketch of the damage types is available in figure 6.

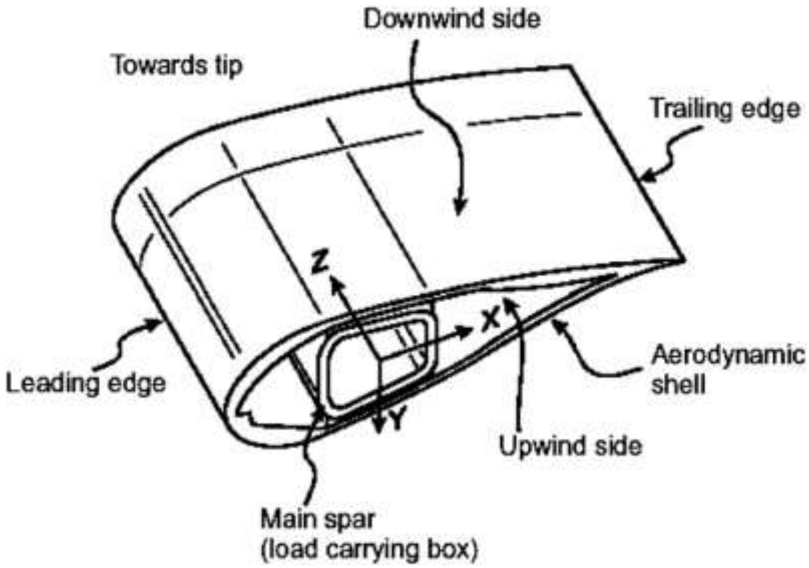


Fig.4 – Main elements of a wind turbine blade

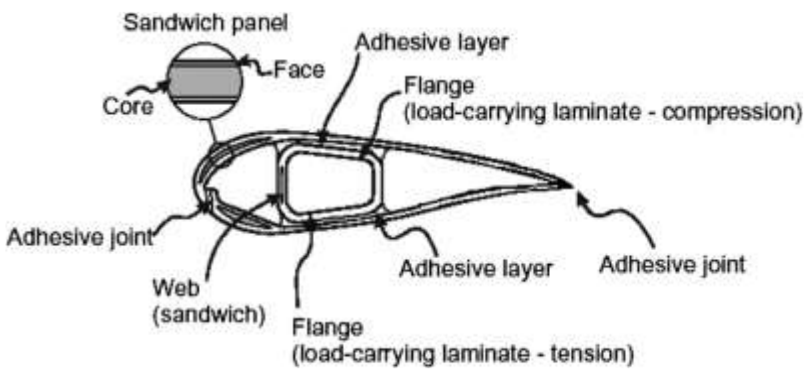


Fig.5 – Nomenclature of different blade construction elements

Type	Description
Type 1	Damage formation and growth in the adhesive layer joining skin and main spar flanges (skin/adhesive debonding and/or main spar/adhesive layer debonding)
Type 2	Damage formation and growth in the adhesive layer joining the up- and downwind skins along leading and/or trailing edges (adhesive joint failure between skins)
Type 3	Damage formation and growth at the interface between face and core in sandwich panels in skins and main spar web (sandwich panel face/core debonding)
Type 4	Internal damage formation and growth in laminates in skin and/or main spar flanges, under a tensile or compression load (delamination driven by a tensional or a buckling load)
Type 5	Splitting and fracture of separate fibres in laminates of the skin and main spar (fibre failure in tension; laminate failure in compression)
Type 6	Buckling of the skin due to damage formation and growth in the bond between skin and main spar under compressive load (skin/adhesive debonding induced by buckling, a specific type 1 case)
Type 7	Formation and growth of cracks in the gel-coat; debonding of the gel-coat from the skin (gel-coat cracking and gel-coat/skin debonding)

Table 3 – Typical damage of wind turbine blades

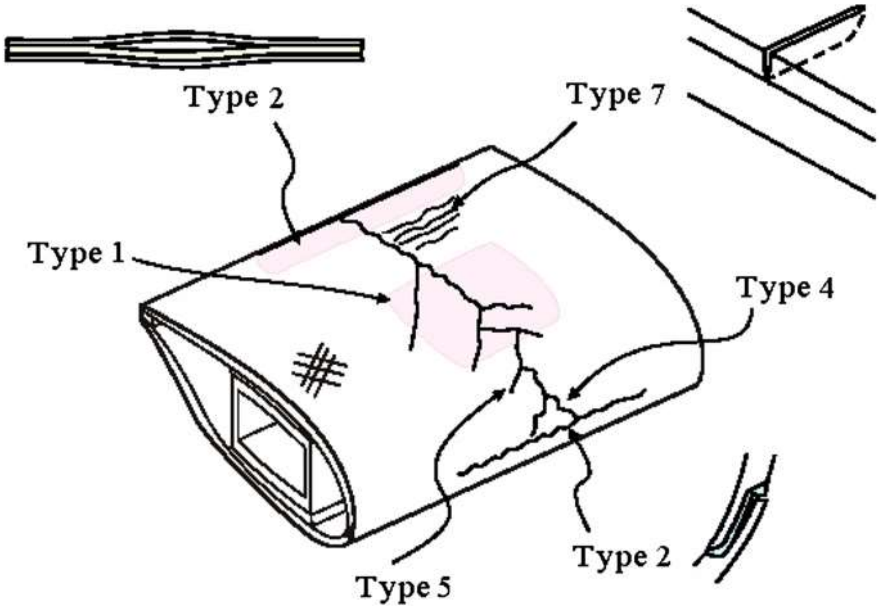


Fig.6 – Sketch illustrating common damage types on wind turbine blades

Fig.7 – An example of blade damage at 30% from root

A4. Damage detection techniques

An ideal SHM system typically consists of two major components: a built-in network of sensors for collecting response measurements, and a data analysis algorithm/software for interpretation of the measurements in terms of the physical condition of the structures. Some of the methods which are applicable or may have promising application in the near future to the wind turbine system are:

4.1. Acoustic emission events detection method

Processes such as cracking, deformation, de-bonding, delamination, impacts, crushing and others, all produce localized transient changes in stored elastic energy with a broad spectral content. Acoustic emission (AE) monitoring during loading of wind turbine blades has offered considerable advantages towards the understanding of the complex damage mechanisms which occur on a turbine blade, and have enhanced the tester's ability to evaluate damage. Tests revealed an audible cracking sound from the blade and identified the damage area of failure with the use of piezoelectric sensors to detect the high-frequency component of the elastic waves (or stress release waves) generated by the energy loss processes within materials and structures.

4.2. Thermal imaging method
Thermal imaging method is a subsurface defects or anomalies detection method owing to temperature differences observed on the investigated surface, such as the wind turbine blade, during monitoring by using infrared sensors or cameras. The temperature difference when compared to the sound part is related to the difference of thermal diffusivity and hence indicates material irregularity or damage.

4.3. Ultrasonic methods
Ultrasound is a well-established method for investigating the inner structures of solid objects. Ultrasonic scanning is also very useful for investigating composite structures. The basic principle of the technique is that an ultrasonic wave is passed through the material and is then reflected and/or mode converted by a defect. A transmitter transfers ultrasound waves into the material and the signal from this is picked up by a receiver once it has passed through the material. In the simplest arrangement, the transmitter and receiver are placed on opposite surfaces of the material. The technique may also be applied with a single transmitter/receiver transducer in a pulse-echo mode or with separate transmitter and receiver transducers placed on the same side of the material. Ultrasound probing will typically reveal planar cracks (e.g. delaminations) oriented perpendicular to the direction of sound wave propagation. The transmit time and/or amplitude of the ultrasound is usually monitored. The transit time can be used to determine the position of the defect relative to the position of the transducers while the amplitude can be used to assess the severity of the defect. Damage of length as small as a few millimeters can be detected.

4.4. Algorithms
Many of the damage detection techniques discussed above require algorithms to function, ranging from simple and direct to complex with learning capability. These algorithms are capable of processing the signals from the sensors for damage identification, damage localization, severity assessment, and can be further extended to the prediction of failure, estimation of the remaining service life and decision making to determine the action required for the damage detected. There are also many global monitoring algorithms developed based on the general turbine parameters, and then implemented by keeping in view the main characteristics of the wind turbine

B. 9FA GAS TURBINE

B1. Abstract

Compressor blades of a heavy duty industrial gas turbine need to sustain long period mechanical stress and vibration induced by high speed rotation and high pressure mass flow. High stress coupled with erosion and corrosion damage during operation is the main driver for blade cracking. Material separation of cracked rotating blade is a serious safety and reliability concern, which not only affects compressor health, but may also cause costly secondary damage at downstream. Early detection of blade anomaly and incipient crack is critical to ensure blade and compressor health and minimize service disruption. In this paper we will introduce a blade health monitoring (BHM) system developed by GE Power. BHM adopts distributed system architecture and operates continuously 24x7 to provide real time rotor blade health assessment. BHM sensors and data acquisition (DAQ) system are installed on the gas turbine to capture blade passing signals (BPS) and assess time of arrival (TOA) for each blade. Advanced signal processing algorithms process the signals locally to calculate key features that associated with blade health. Then finally, a central anomaly detection module, which is fully integrated with GE Power monitoring system, is developed to assess blade health condition and generate anomaly alarms to alert diagnostic engineer.

B2. Introduction

Heavy duty industrial gas turbines are widely used in power generation plants worldwide. Axial flow compressor is a key subsystem of the gas turbine. Due to inlet air flow aero dynamic load and rotor rotation, various mode displacement and vibration on the compressor blades are excited. Excessive vibration may accumulate high cycle fatigue and thermal mechanical stress on a rotor blade, and cracks may initiate and propagate over time. To detect and monitor blade cracks and provide early warning before material liberation is the main focus for any blade health monitoring system.

Blade tip sensing based approaches have been the primary method widely adopted for rotor blade vibration analysis and crack detection (Heath, 1998 and Von Flotow et al. 2000). In this approach, one or multiple non-contacting blade tip sensors are inserted through drilled holes in compressor casing at an axial location directly above the trajectory of blade tips. The sensor can sense the approaching or departure of rotating blades and produce a pulse voltage when the blade passes the sensor midpoint. Two families of blade tip sensors are typically used, eddy current sensors (ECS) and variable reluctance magnetic sensors (VRS). Both sensor types operate based on the principal of perturbed magnetic field caused by blade passing. ECS sensor uses special circuit to produce an active magnetic field, while the VRS sensor uses permanent magnet to produce a static magnetic field. In comparison, the latter one is less expensive since no complex circuit and signal conditioning is required to maintain the active field. On the other hand, ECS sensor can operate for blades of different conductive materials, whereas VRS only works with ferrous materials. Other sensing system such as acoustic pressure sensor and bearing vibration sensor have also been studied.

B3. Preventable Gas Turbine Failures via BHM

Example of Gas Turbine compressor blade liberation
followed by extensive secondary damage

Typical failure drivers & mechanisms for turbine blades

1. High cycle fatigue (HCF)
   - Normal corrosion can initiate tiny pits in metal
   - Continuous flexing of blades during operation can grow cracks from pits (high cycle fatigue)
   - When a crack gets large enough, the centrifugal force can pull blade apart (liberation)
2. Foreign Object Damage (FOD):
   - Debris gets sucked in and damages blades
3. Rubs
4. Liberation could cause significant secondary damage -> Millions of dollars.

BHM at RGPPL

In this system, two data sources are utilized in blade health calculation:

1. TOA data: It is time of arrival data. A local DAQ is installed to collect TOA data.

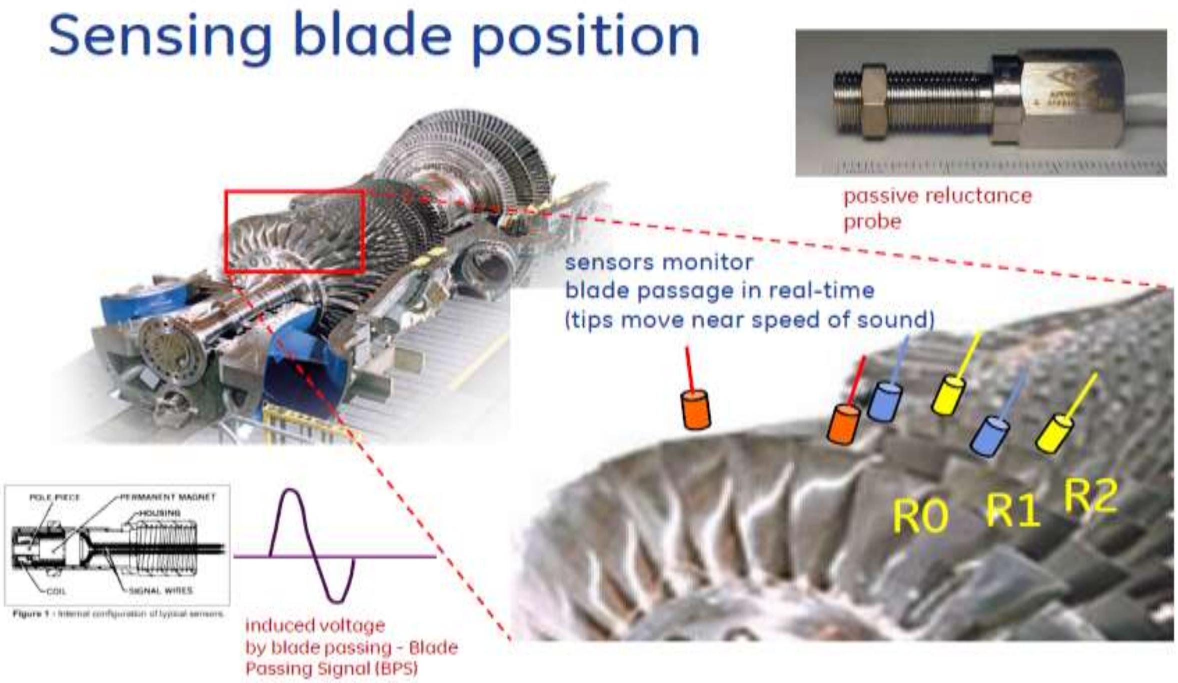
2. Turbine operation data: The data from turbine control system is logged in an on-site-monitor (OSM) computer.

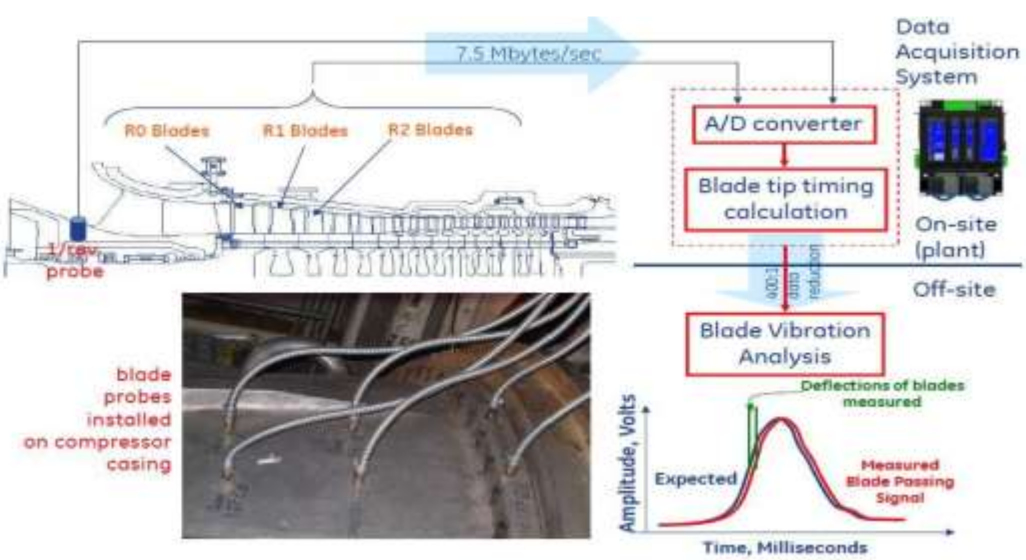
Both data streams are transferred as data files to a central calculation server for feature extraction and anomaly detection. The data transfer is time based and run once a day for each unit. In the central calculation server, BHM feature calculation is performed.

Depending on the operating mode based on turbine speed, TOA data is classified into two categories:

i. Steady state: for steady state static deflection is calculated.
ii. Transient state: For transient mode, blade resonance frequency and magnitude is calculated.

An anomaly detection or alarming module is also hosted in the central calculation server, which will generate alarms if resonance detuning during start up or shut down, or shift in static deflection in steady state is detected.





B4. A Case Study at RGPPL

RGPPL Unit GT1A BHM Observation R1 Blade 19 and 24

During routine monitoring by M&D Centre following observations were noted from the data captured by R1 – LE1/LE2 BHM sensors:

1. Delta TOA shift on Stage R1 Blade # 19 (80 mils) and 24 (40 mils) when on steady state.
2. Clearance shifted in positive direction (Blade # 19 and 24 by approximately 0.8 and 0.6 volts respectively).
3. No vibration shift.
4. No Axial shift.

GE Engineering recommended performing detailed borescope inspection.

After inspection it was observed that FOD event occurred in R1 blades-19 and 24 chipping off portion of the blade tip at the leading edge. Thus, catastrophic failure was saved with the help of BHM.

B4. Conclusion

This paper has introduced a real-time remote monitoring system for compressor blade health in gas turbines. BHM system not only monitors rotor blade health, but also able to monitor its local and central system health. It can alert on faulty BHM sensor, DAQ issue, data transfer or data delay issue, etc.
Remote monitoring is rapidly growing in the power generation industry, and BHM is doing its part to take care of its customers. BHM provides data acquisition, analysis, storage, and versatile reporting capabilities that are used to help in the early detection of abnormal operating conditions of gas turbines. This information, along with associated recommendations, makes it possible to make more informed business decisions about the course of action regarding diagnostics issues.

For wind turbines, adding BHM sensors may adversely affect the performance of the turbine, number and location of blade monitoring sensors also becomes critical to ensure optimum monitoring without compromising turbine efficiency. In addition, wired and wireless networking between the rotating turbine blades and the nacelle is still challenging. A robust, reliable and minimum maintenance BHM system will be imperative to accurately predict wind turbine failures and minimise downtime.

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