Condition Monitoring of Wind Farm based on Wireless Mesh Network

Lorenzo Ciani, Alessandro Bartolini, Giulia Guidi, Gabriele Patrizi

Department of Information Engineering,
University of Florence,
via di S. Marta 3, 50139, Florence (Italy)
lorenzo.ciani@unifi.it

Abstract **– Since the last years of twentieth century the use of wind energy rapidly increased and it is imposed as one of the best alternatives to burning fossil fuels. Nowadays, in renewable energy resources, wind energy is the leading candidate for electricity production due to its lower investment cost and well-developed technology in manufacturing high-power wind turbines. Basing on a Reliability Centred Maintenance (RCM) analysis, this paper focuses on the use of a Wireless Mesh Network in order to monitoring several condition parameters to identify possible incipient failures analysing the health-status of the turbine. The objective of the RCM is to identify the appropriate maintenance task for each item. Condition Monitoring is one of the possible task choices and represents a cost-effective solution to minimize the plant downtime. The case study identifies the most critical components of wind turbine and propose a set of possible sensors that could be included in the Wireless Mesh Network to monitor the condition parameters of the turbine.**

Keywords **– Wireless Sensor Network, Wireless Mesh Network, Condition Monitoring, Wind Turbine, Maintenance**

I. INTRODUCTION

Nowadays, all the diagnostics process plays a fundamental role in industrial engineering representing an essential part of performance requirements. One of the easiest and widely used maintenance task is condition monitoring (CM): it is the process of monitoring one or more condition parameters in machinery to identify some changes that are indicative of an incipient fault or equipment health degradation [1]. In the past, condition monitoring was applied simply through routine manual diagnostic actions but, with the introduction of low-cost sensors and automated monitoring systems, online condition monitoring was adopted.

Condition monitoring is a type of condition-based maintenance used to select and survey parameters from the sensors placed in the system in order to detect a change in the health machine condition [2], [3]. CM, as well as reliability and availability, is mandatory in several manufacturing fields, such as energy and industry applications where products are forced to endure extreme process and environmental conditions [4]–[6].

II. RELIABILITY CENTERED MAINTENANCE

Reliability centred maintenance (RCM) is a method to identify and select failure management policies to efficiently and effectively achieve the required safety, availability and economy of operation. Failure management policies can include maintenance activities, operational changes, design modifications or other actions in order to mitigate the consequences of failure. RCM provides a decision process to identify applicable and effective preventive maintenance requirements, or management actions, for equipment in accordance with the safety, operational and economic consequences of identifiable failures, and the degradation mechanisms responsible for those failures.

The end result of working through the process is a judgement as to the necessity of performing a maintenance task, design change or other alternatives to effect improvements. The basic steps of an RCM programme are as follows [7]–[10]:

- Initiation and planning;
- Functional failure analysis;
- Task selection;
- Implementation;
- Continuous improvement.

Maximum benefit can be obtained from an RCM analysis if it is conducted at the design stage, so that feedback from the analysis can influence design. However, RCM is also worthwhile during the operation and maintenance phase to improve existing maintenance tasks, make necessary modifications or other alternatives.

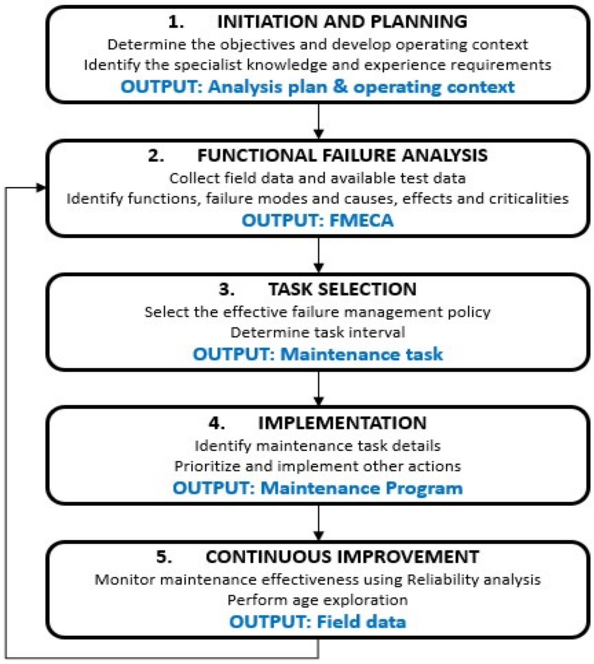

Fig. 1. Overview of the RCM process

According to [10], Fig. 1 presents a summary of the overall RCM process, divided into five steps. As can be seen from the figure, RCM provides a comprehensive programme that addresses not just the analysis process but also the preliminary and follow-on activities necessary to ensure that the RCM effort achieves the desired results[10].

The process starts with "Initiation & Planning" step, it is an important stage in order to analyse the operating context and to assess the optimal work order. A "Functional failure analysis" is crucial in the RCM process because understanding the effects of each failure mode leads to an optimization of the maintenance policies. The output of the second step is the Failure Mode, Effect and Criticality Analysis (FMECA), which is a systematic procedure for the analysis of a system to identify the potential failure modes, their causes and effects on system performance. FMECA is a method to identify the severity of potential failure modes and to provide an input to mitigating measures to reduce risk. In some applications it includes a means of ranking the severity of the failure modes (S), the frequency of occurrence (O) and the possibility of diagnose the failure mode before its effects are manifested on the system (D) to produce a metric called Risk Priority Number (RPN) [11]–[13].

By using the FMECA report it is possible to implement the third step ("task selection") in order to select the most appropriate and effective failure management policy. There are several different maintenance tasks that could be selected using an RCM decision diagram [10]:

- Condition monitoring: it is a continuous or periodic task to evaluate the condition of an item in operation against pre-set parameters in order to monitor its deterioration. It may consist of inspection tasks, which are an examination of an item against a specific standard.
- Scheduled restoration: it is the work necessary to return the item to a specific standard. Since restoration may vary from cleaning to the replacement of multiple parts, the scope of each assigned restoration task has to be specified.
- Scheduled replacement: it is the removal from service of an item at a specified life limit and replacement by an item meeting all the required performance standards.
- Failure-finding: it is a task to determine whether or not an item is able to fulfil its intended function. It is solely intended to reveal hidden failures. A failure-finding task may vary from a visual check to a quantitative evaluation against a specific performance standard. Some applications restrict the ability to conduct a complete functional test: in such cases, a partial functional test may be applicable.
- No preventive maintenance: in some situations no task is required, depending on the effect of failure. The result of this failure management policy is corrective maintenance or no maintenance at all. Sometimes, this approach is called "Run-To-Failure".
- Alternative actions: it can include redesign; modifications to existing equipment, such as more reliable components; maintenance procedure changes; pre-use or after-use checks; additional operator or maintainer training.

III. WIRELESS SENSOR NETWORK

Wireless Sensor Network (WSN) is a network characterized by a distributed architecture of small nodes (or motes). Each node can host multiple sensors and is equipped with computational and wireless communication capability. Recently, Wireless Mesh Networks (WMNs) have become an optimal solution to provide broadband internet access to large geographical areas [14]. The difference between a traditional WSN and Mesh network is [15], [16]:

- A traditional WSN (Fig. 2) is a point-to-multipoint (star) network where a single central node, known as the access point (AP), is directly connected to all other nodes known as stations. Traditional infrastructure Wi-Fi networks have the disadvantage of limited coverage area because every station must be in a range directly connected with the AP. Furthermore, overloading is another relevant drawback of traditional Wi-Fi networks because the maximum number of stations permitted in the network is limited by the capacity of the AP.

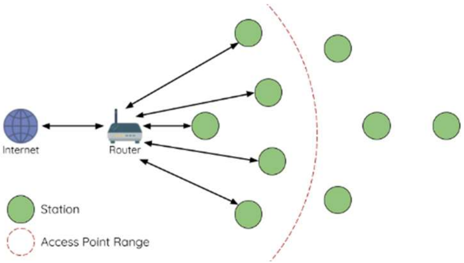

Fig. 2. Traditional Wireless Network

- A WMN (Fig. 3) is a self-organized and self-configured network. Nodes are mutually responsible for relaying each others transmissions. This allows MESH networks to have larger coverage area because nodes can still achieve interconnectivity, even if they are out of the central node cover range. Therefore, MESH network is also less susceptible to overloading. Another advantage of this network is the fault tolerance, when a node stops working, the whole network does not fail, but the access point can be reached by different paths [14].

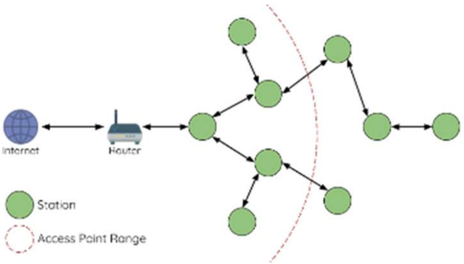

Fig. 3. Wireless Mesh Network

The block diagram of the typical sensor node is shown in Fig. 4. The picture highlights the main components that make up this system, as follow:

- *Sensing Unit:* It could include several different kind of transducer, such as thermal, vibration, magnetic sensor, etc. based on the physical quantities under analysis. If one or more sensors provide analogue signals, then they will be converted to digital form using ADC (Analog to Digital converter).
- *Processing Unit:* It process the sensors output using pre-defined instructions or programs loaded.
- *Communication Unit:* Once the elaboration of sensor information is completed, the data are relayed to the central Base Station using the communication unit. It consists of RF transceiver and antenna for transmitting and receiving packets. In order to optimize the energy efficiency of the sensor node, in addition to the traditional transmit and receive modes the communication unit could be set also as idle and sleep mode.
- *Power Unit:* It provides power to all the other units of sensor mote using one or more batteries.

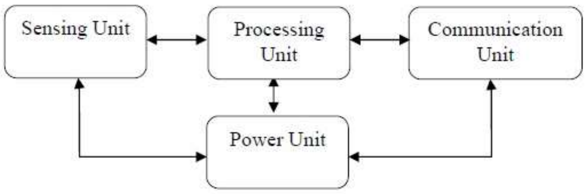

Fig. 4. Block Diagram of Sensor Node

WSN monitoring provides continuous and near real-time data acquisition and autonomous data acquisition. It can be used to [17]:

- maintain process tolerances;
- verify and protect machine, systems and process stability;
- detect maintenance requirements;
- minimize downtime;
- prevent failures saving Operation&Maintenance cost and time;
- request maintenance based on the prediction of failure rather than maintenance running to a standard schedule or being requested following an actual failure.

IV. WIND TURBINE COMPONENT FAILURES

A wind turbine (WT) is a device that converts the wind's kinetic energy into electrical energy, it has evolved from generating a few kilowatts in the 1980s to several megawatts today [18]–[20].

A wind farm, sometimes called wind park, is a group of wind turbines in the same location used to produce electricity. A large wind farm may consist of several hundred individual wind turbines and cover an extended area of hundreds of square kilometres, but the land between the turbines may be used for agricultural or other purposes [21].

WT is a very complex system composed by both mechanical and electrical/electronic components. The efficiency and practicality of horizontal-axis, three-blade turbines have resulted in domination of the market and, in almost all the new installations of wind farms, this is the only type that is employed for energy generation. This kind of wind turbine is comprised of four major components: Rotor, Tower, Blades and Nacelle, that is an enclosure which contains the electrical and mechanical components needed to produce electricity (e.g. gearbox, brake, yaw mechanism, generator, control system, etc.).

The functional failure analysis carried out on the wind turbine highlighted several different type of failure modes. Many causes can influence on electronic and mechanical components that make up the wind turbine; for instance, the failures of the mechanical items may be affected by the high vibration level on the shafts, the very extreme temperature generated during the rotation speed conversion by the gearbox, corrosion and fatigue.

While the damage of the electrical and electronic components may be affected by the environmental conditions, such as the temperature, humidity and vibration.

V. CM NETWORK FOR WIND FARM

When the wind turbine is damaged, the maintenance costs and the economic losses caused by downtime are enormous, so repairs must be carried out quickly [22]. For this purpose, it is necessary to use a real-time monitoring system. In particular, thanks also to the greater capacity of the wind farm in the distribution network, an excellent solution is given by the mesh sensor networks [23].

After a preliminary Reliability Centred Maintenance analysis, the work focuses only on the blocks for which the procedure suggests to implement the Condition Monitoring as the optimal maintenance task. The CM is implemented using a Wireless Mesh Network, where each sensor node is provided by several different type of sensing element (Fig. 5). The use of a Wireless Sensor Network to monitor a wind farm is a powerful and low-cost solution that allows infrastructure modification and increasing the amount of sensor nodes after the plant installation compared to the higher cost of the changes in classical wired network.

Fig. 6 shows the architecture of the Wireless Mesh Network used to monitor the wind farm under test, where the blue lines stands for the direction of the wireless communications in standard configuration. In case a node fails, the other nodes have to identify a different communication path in order to ensure a complete monitoring of the farm. The LAN protocol used in the CM network is the IEEE 802.11n that represents a trade-off between geographical coverage, transmission of great amount of data and power dissipation [24].

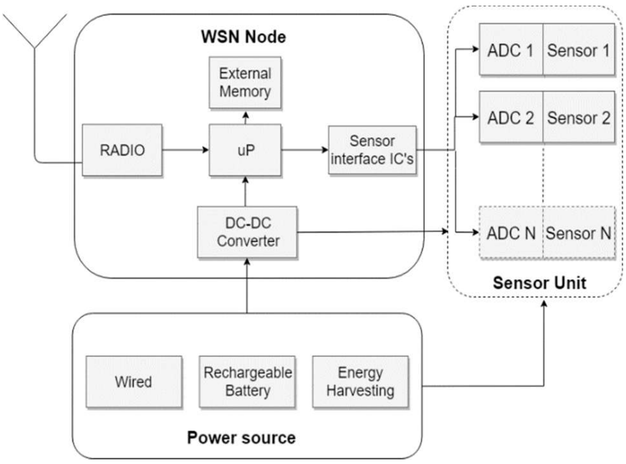

Fig. 5. Architecture of WMN node used for condition monitoring

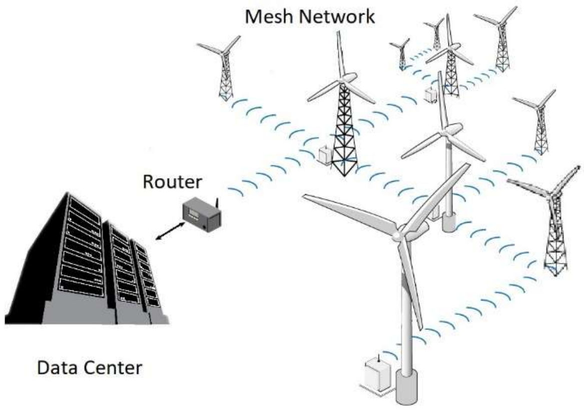

Fig. 6. Architecture of the network used to monitor the wind farm

Table 1 presents an extract of the CM assessment designed for the wind farm under test. The table contains:

- a description of the functionality of the items useful for the functional failure analysis;
- a list of the main failure modes (how we can observe the inability of the item to perform a required function) and mechanisms (the physical, chemical, or other processes that have led to a failure);
- The types of measurements used to monitor the item;
- The proposed sensor technology for the relative measurement.

In compliance to [1], [25] the electrical and electronic components are characterized by several failure modes, all due to electrical causes, that are mainly subjected to variation according to the environmental condition of the nacelle. For this reason, a Resistance Temperature Detector (RTD), a humidity sensor and a Piezoelectric accelerometer are used to monitor this kind of components.

The other types of considered items, like blades, gearbox and tower are subjected to mechanical failure mechanisms, such as fatigue, corrosion, sticking etc. that could be monitored using different types of sensing units [26], [27]. For instance, a large amount of heat is generated in the gearbox due to the friction between the gears, therefore it is advisable to use a thermocouple in spite of an RTD because the thermocouples have characterized by a larger measurement range. The acceleration, pitch, roll and yaw of the blades are monitored using a MEMS inertial module that integrates one triaxial accelerometer, one triaxial gyroscope and one triaxial magnetometer to provide a measure of the acceleration and of the angular position with a unique small and cheap device. The other vibration measurement (such as the vibration on the gearbox or on the electronic boards) are implemented using a single triaxial MEMS accelerometer that provides information only on the acceleration.

Table 1. Extract of Condition Monitoring assessment for Wind Turbine

Item	Description/Function	Failure modes and mechanisms	Measurement	Sensors
Blades	Power source of the wind turbine that catch the wind energy and convert it in mechanical motion.	.Fatigue failure .Lightning damage .Corrosion .Delamination	Crack/Fatigue detection	Acoustic Emission
			Wind speed/direction	Anemometer
			Acceleration, pitch, roll and yaw	Inertial module
			Microdeformation	Extensometer
Gearbox	Increases the rotor speed up to the appropriate generator speed using gears, pinions and shafts.	.Binding/Sticking .Excessive Wear .Fails to move .Mechanical damage	Vibration	MEMS accelerometer
			Temperature	Thermocouple
			Motion	Displacement transducer
			Stress	Strain gauge
Electrical/Electronic system	Contains all the electrical components in the turbine, such as power converter, PFC system, transformers, contactors etc.	.Parameter drifts .No output .Short/Open circuit . Error in data elaboration/storage	Temperature	Resistance temperature detector
			Humidity	Humidity sensor
			Vibration	MEMS accelerometer
Hydraulics system	Moves the nacelle towards the yaw axis (wind direction)	.Leakage .Contamination .Improper flow .Stuck valve	Pressure	Piezoelectric pressure transmitter
			Flow	Ultrasonic meter
			Level	Magnetic level meter
			Contamination	Contamination sensor
Tower	Supports the other parts and holds them off the ground.	.Fatigue failure .Corrosion .Fracture	Crack/Fatigue detection	Acoustic Emission
			Microdeformation	Extensometer
UPS	Provides emergency power when the input power source or mains power fails.	.Aging battery	Temperature	Resistance temperature detector
			Current	Hall effect integrated current sensor

The tower is monitored using an extensometer to detect the micro-deformation of the structure and an acoustic emission sensor which uses ultrasounds to investigate the fatigue of the construction.

Piezoelectric pressure transmitter, ultrasonic flow meter, magnetic level meter and contamination sensor are used to investigate the characteristics of the oil in the hydraulic system.

VI. CONCLUSION

Wireless sensor network and condition monitoring represent the optimal maintenance solution for extended wind farm because of the limited installation and management cost. The use of only human employee in turbine monitoring becomes a high-cost solution when the wind farm covers a very large area. Using CM network preventive maintenance tasks are minimized because the maintenance and management policies are addressed to the network. The operator performs corrective maintenance only in case the system identifies an intervention request. WMN provides a great amount of reliable and low-cost wearing data, allowing significant decreasing in the Operation&Maintenance cost and turbine downtime.

REFERENCES

[1] MIL-HDB-338B, "Electronic Reliability Design Handbook." US Department of Defense, Whasington DC, 1998.

[2] Y. Wang, Z. Zhu, H. Song, and K. Shi, "Wind turbine gearbox condition monitoring based on extreme gradient boosting," in *IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society*, 2017, vol. 2017-Janua, pp. 6017–6023.

[3] K. Singh, H. Malik, and R. Sharma, "Condition monitoring of wind turbine gearbox using electrical signatures," in *2017 International conference on Microelectronic Devices, Circuits and Systems (ICMDCS)*, 2017, vol. 2017-Janua, pp. 1–6.

[4] A. Reatti, M. K. Kazimierczuk, M. Catelani, and L. Ciani, "Monitoring and field data acquisition system for hybrid static concentrator plant," *Measurement*, vol. 98, pp. 384–392, Feb. 2017.

[5] M. Catelani, L. Ciani, and A. Reatti, "Critical components test and reliability issues for photovoltaic inverter," in *20th IMEKO TC4 Symposium on Measurements of Electrical Quantities: Research on Electrical and Electronic Measurement for the Economic Upturn, Together with 18th TC4 International Workshop on ADC and DCA Modeling and Testing, IWADC 2014*, 2014, pp. 592–596.

[6] L. Albertoni *et al.*, "Analysis and design of full-bridge Class-DE inverter at fixed duty cycle," in *IECON 2016 - 42nd Annual Conference of the IEEE Industrial Electronics Society*, 2016, pp. 5609–5614.

[7] J. Moubray, *Reliability Centered Maintenance*, Second. Butterworth-Heinemann, 1997.
[8] N. B. Bloom, *Reliability Centered Maintenance: Implementation made simple*. McGraw-Hill Companies, 2006.
[9] NASA Headquarters, "Reliability Centered Maintenance guide for facilities and collateral equipment." 2000.
[10] IEC 60300-3-11, "Dependability management – Part 3-11 - Application guide – Reliability centred maintenance." International Electrotechnical Commission, 2009.
[11] M. Catelani, L. Ciani, and M. Venzi, "Failure modes, mechanisms and effect analysis on temperature redundant sensor stage," *Reliab. Eng. Syst. Saf.*, vol. 180, pp. 425–433, Dec. 2018.
[12] IEC 60812, "Failure modes and effects analysis (FMEA and FMECA)." International Electrotechnical Commission, 2018.
[13] Mil-Std-1629A, "Military standard procedures for performing a failure mode, effects and criticality analysis." US Department of Defense, Whasington DC, 1980.
[14] Karthika K.C, "Wireless mesh network: A survey," in *2016 International Conference on Wireless Communications, Signal Processing and Networking (WiSPNET)*, 2016, pp. 1966–1970.
[15] A. Hać, *Wireless Sensor Network Designs*. Chichester, UK: John Wiley & Sons, Ltd, 2003.
[16] Y. Zhang, L. Jijun, and H. Hu, *Wireless Mesh Networking: Architectures, Protocols and Standards*. Tailor & Francis Group, 2007.
[17] V. J. Hodge, S. O'Keefe, M. Weeks, and A. Moulds, "Wireless Sensor Networks for Condition Monitoring in the Railway Industry: A Survey," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 3, pp. 1088–1106, Jun. 2015.
[18] I. Munteanu, A. I. Bratcu, N. A. Cutululis, and E. Ceanga, *Optimal Control of WInd ENergy Systems Towards a Global Approach*. Springer, 2008.
[19] T. Burton, D. Sharpe, N. Jenkins, and E. Bossanyi, *Wind Energy Handbook*. John Wiley & Sons, 2001.
[20] A. González and D. Galar, "Condition monitoring of wind turbine pitch controller: A maintenance approach," in *15th IMEKO TC10 Workshop on Technical Diagnostics: Technical Diagnostics in Cyber-Physical Era*, 2017, pp. 200–206.
[21] A. Hemami, *Wind Turbine technology*. Cengage Learning, 2012.
[22] Z. Fu, Y. Luo, C. Gu, F. Li, and Y. Yuan, "Reliability analysis of condition monitoring network of wind turbine blade based on wireless sensor networks," *IEEE Trans. Sustain. Energy*, vol. 3029, no. c, pp. 1–1, 2018.
[23] C. Na, Z. Haixiang, and D. Huizhu, "Dynamic Behavior of Integrated Wind Turbines during Fault Condition and Impact on Relay Settings of Distribution Network Feeders," in *2006 International Conference on Power System Technology*, 2006, pp. 1–8.
[24] J. Jansons and T. Dorins, "Analyzing IEEE 802.11n standard: outdoor performanace," in *2012 Second International Conference on Digital Information Processing and Communications (ICDIPC)*, 2012, pp. 26–30.
[25] IEC TR 62380, "Reliability data handbook – Universal model for reliability prediction of electronics components, PCBs and equipment," vol. 2004. International Electrotechnical Commission, 2005.
[26] NSWC-11, "Handbook of Reliability Prediction Procedures for Mechanical Equipment," no. May. Naval Surface Warfare Center Carderock Division, West Bethesda, Maryland, 2011.
[27] W. Denson, G. Chandler, W. Crowell, and R. Wanner, "NPRD-91 Nonelectronic Parts Reliability Data." Reliability Analysis Center, p. 632, 1991.