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Lifetime Extension of Wind Farms by a Low-Cost Energy-Autonomous IoT-Based Structural Health Monitoring System

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Abstract. The latest results of a research project pursuing an energy-autonomous Structural Health Monitoring (SHM) system for wind farms are presented. The SHM system is based on the development of low-power IoT wireless nodes and electromagnetic harvesters to capture energy from low-frequency vibrations of wind towers. Computationally efficient operational modal analysis methods suited to the low-cost IoT edge nodes are also explored. The work carried out aims to extend the lifetime of existing wind farms by properly monitoring their structural integrity.

Key words. Wind farms, Structural Health Monitoring, IoT.

1. Introduction

A large part of Europe's wind farms will come to the end of its designed lifetime within the next 10-15 years, especially in countries like Spain where this technology was deployed early. In order to fulfill Europe's long-term decarbonization agenda, the share of wind energy in the energy mix needs to grow further, and this generation capacity will have to be maintained as much as possible. The war in Ukraine has also pushed energy security and sovereignty in the forefront, demanding increased local wind power generation. Hence lifetime extension of the wind farms is a strategic priority. Of the 22 GW power generated by wind farms reaching their economic end of life, WindEurope estimates that 17.8 GW will receive a lifetime extension [1]. However, the economic advantage of using already amortized wind turbines requires keeping the increase of maintenance cost moderate. In particular, global onshore wind operations and maintenance costs reached nearly $15 billion in 2019. Of that number, $8.5 billion was spent on unplanned repairs and correctives caused by component failures [2]. In this regard, the IEC standard "IEC-61400-28 Through life management and life extension of wind farms" rates wind power SHM systems as essential for keeping maintenance costs low, managing assets more effectively throughout their lives, and estimating more accurately the potential for life extension.

Guaranteeing the structural integrity of the wind turbines is a challenge, as they have become increasingly flexible structures, highly prone to damage due to resonance phenomena and rapid wear [3]. Wind turbines experience enormous and fluctuating mechanical loads, the most important of which are caused by the wind and by the nacelle and blades rotation. The guiding principle behind SHM is that a continuous tracking of the natural frequencies and damping coefficients of the structure makes it possible to predict the occurrence of potentially destructive phenomena. Nevertheless, based on the authors' work with companies in the wind sector, we have identified that commercial wind turbine SHM solutions are often based on general approaches designed for use mainly in buildings, not very adequate for the application at hand [4]. Some limitations of current solutions are:

- General purpose commercial equipment is usually wired to the SCADA system of the wind turbine [5]. This solution lacks flexibility and scalability, involving a complex installation and dependence on the wind farm's owner for the deployment.
- Current commercial equipment gets its electrical supply from separate modules that are also sold by the manufacturer, increasing cost.
- Commercial equipment can monitor the wind turbine during operation but not in other critical phases of the life cycle such as transport and assembly, where parts are very prone to damage.
- Any intervention is usually so complex that it can only be carried out during scheduled maintenance periods.

A promising alternative for SHM of wind turbines is the use of wireless Internet of Things (IoT) technologies, which are revolutionizing other monitoring tasks [6, 7]. However, substantial research is still needed for efficient real-time IoT monitoring of wind turbine towers to reduce human intervention as much as possible. Some of the most critical challenges are adapting conventional SHM techniques to the specific requirements of wind farms [8] and making these IoT systems self-powered using energy harvesting techniques, in order to drastically reduce maintenance costs and increase availability [9]. In addition, applying advanced data analysis and machine learning techniques to complement traditional signal analysis appears to be a promising possibility [10, 11, 12, 13].

In this paper we present the main results of a research project funded by the Spanish Ministry of Science and Innovation and currently carried out by our research group and another group from the University of Seville (Spain). The project is aimed to addressing the issues mentioned in the previous section. In particular, our starting hypothesis is that an IoT SHM system specifically designed for wind farms with a wise combination of wireless technologies, sensors, IoT nodes capable of harvesting energy from the environment (if required) and specific signal processing and artificial intelligence techniques can overcome previous unsolved limitations.

2. Proposed Approach

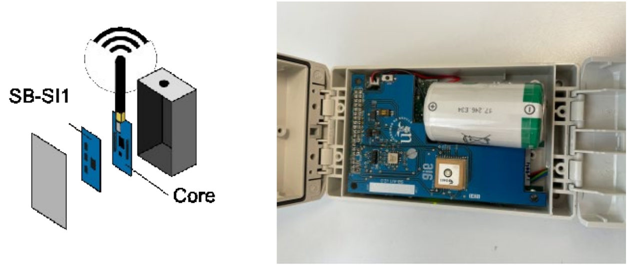
In this section, the main results obtained in the project for the wireless IoT edge node, energy harvester and Operational Modal Analysis (OMA) methods are described.

2.1. Design of IoT Nodes

In order to fulfil the requirements of the application at hand, different wireless communication protocols can be considered, such as Bluetooh, Zigbee, LoraWAN, SigFox, NB-IoT or 4G/5G to name a few common ones [14, 15]. Bluetooth and Zigbee are attractive alternatives due to their low power consumption, but their limited coverage complicates monitoring of large wind farms. Both LoraWAN and NB-IoT are adequate for SHM of large infrastructures such as wind farms. LoraWAN provides large coverage with low power consumption, is cost-effective and allows a flexible deployment particularly in rural areas. However, NB-IoT leverages the existing cellular infrastructure, providing lower latency, higher data rates and secure data transmission. For these reasons we chose NB-IoT as wireless transmission technology for the IoT nodes.

Regarding the hardware design of the IoT edge nodes for SHM, a modular architecture was employed. A main printed circuit board was designed that controls the node and manages all the signal processing, storage, power management and communication tasks. An ARM Cortex-M3 microcontroller from STMicroelectronics was chosen due to its versatility and low power consumption. The main board also includes a power-efficient NB-IoT transceiver from SIMCOM with power saving mode.

Another auxiliary printed circuit board houses specific sensors for various monitoring needs (accelerometer, temperature, humidity, pressure, strain gauges, etc.) and can be easily customized to the particular SHM application of interest. In particular, for SHM of wind farms it includes the ADXL355 triaxial accelerometer from Analog Devices, which features low power consumption and 20-bit resolution, corresponding to less than 4 μg resolution in acceleration. This flexible architecture allows monitoring of diverse structures with simple modifications to the sensor board. The IoT node efficiently utilizes low-power modes in the microcontroller, NBIoT transceiver, and sensors, achieving over 10 years of autonomy [16] (see Figure 1).



(a) (b)

Figure 1. IoT node developed (a) Diagram (b) Photograph

Furthermore, a control center has been developed, consisting of a set of microservices deployed for the reception, storage, processing, and presentation of information. The main microservices, deployed in Docker containers, include the non-relational database, the backend (node.js), the processing service (Python), and the frontend (VUE).

2.2. Design of the Energy Harvester

Energy autonomy of the IoT nodes monitoring the wind turbine is highly desirable as it avoids wired connection to the power supplied by the tower. This way, such autonomy simplifies the installation and maintenance of the nodes and allows placement of the sensors in moving parts of the turbine. Moreover, it enables monitoring during the assembly and transportation of the wind tower, which is often not possible with existing commercial solutions as mentioned earlier.

In order to provide energy autonomy to the IoT nodes, some form of energy harvesting must be employed. There are several potential external energy sources that can be employed in wireless IoT nodes, such as solar, kinetic, thermal, electromagnetic and mechanical vibrations [17]. However, since the SHM IoT nodes are embedded within the wind tower structure, mechanical vibrations of the tower become usually the only feasible choice [9].

There are several energy harvesters proposed in the literature to obtain electrical energy from mechanical vibrations, usually employing piezoelectric or electromagnetic transducers. However, most of conventional harvesters are not suitable for modern wind towers due to the very low frequency and amplitude of the vibrations experienced by the structure. These vibrations are often dominated by the first and second mechanical modes of the structure (typically about 0.35 Hz and 1.5 Hz) and the harmonics of the rotation speed (typically at 0.25 Hz and 0.75 Hz) [9]. Concerning displacement of the nacelle in normal operation of on-shore wind towers, it is typically restricted to ±10 cm, leading to accelerations under 0.1*g*. Moreover, displacement of the wind tower is not only in the wind direction, thus requiring a multidirectional harvesting system. There are few ultra-low frequency vibration harvesters able to operate in this extreme scenario [9].

Considering these requirements, a multidirectional electromagnetic harvester prototype has been developed to supply the SHM IoT nodes of the wind towers. It is essentially a radial (non-rotating) moving structure with three masses of magnets that oscillate depending on the external excitation and adapt to movement in any direction within a plane. The developed prototype is shown in Figure 2, and details of the inner structure can be seen in the 3D image of Figure 3. The main physical dimensions of the device are shown in Table I. Each of the three moving masses includes an embedded array of magnets in Halbach configuration to optimize the outgoing magnetic field, and 24 coils are configured in the casing that collect the generated voltages. An advantage of this Halbach arrangement is that it produces repulsion between adjacent masses which attenuates mechanical impacts between them and helps to bring them to their steady state (120º apart) [9].

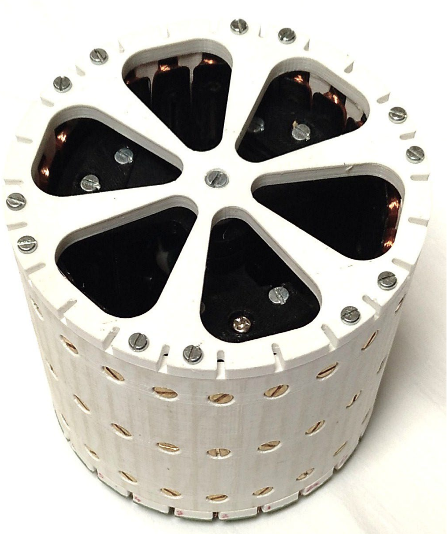


Fig. 2. Energy Harvester developed.

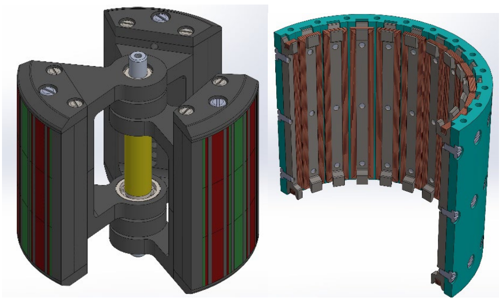


Fig. 3. Detail of the moving masses with the Halbach arrays.

Table I. - Physical dimensions of the electromagnetic harvester

Dimension	**Value**
Diameter	100 mm
Height	90 mm
Single proof mass weight	158 g
Moment of inertia	$20.6 \cdot 10^{-6}$kg mm^2
Weight	612 g

2.3. System Identification Algorithms for IoT-Based SHM

Structural Health Monitoring of wind turbines relies on identifying changes in the system response dynamics of the structure using Operational Modal Analysis (OMA) [18]. However, conventional OMA is often based on computationally intensive techniques such as Stochastic Subspace Identification (SSI) [19]. In an IoT SHM system operating in real-time, edge computing is required [20]. Edge computing refers to a new paradigm in which analysis and (pre)processing takes place on IoT edge nodes. Since such nodes have limited resources in terms of energy, cost and hardware complexity, it is a challenge to optimally distribute the processing between edge computing and the cloud. Hence, techniques to reduce the computational load in IoT edge nodes of OMA methods are required. Moreover, existing approaches for calculating the modal parameters (natural frequencies, damping, modal shapes) of the structure assume that the driving forces are the realization of a stochastic process which can be modelled as white noise. However, the mechanical loads caused by the rotating machinery of the wind turbine have a strong periodic character, reducing the sensitivity of the algorithms.

In order to solve these issues, we have developed a novel approach to harmonic estimation and removal in wind turbines inspired by the techniques which appear in speech and audio signal synthesis and coding [21]. The starting point is to assume a model for the element to be identified, whether it is an isolated harmonic, a vibration mode, or the position (spin speed) corresponding to a non-stationary sinusoidal signal with variable amplitude and/or frequency. If the identification is carried out using a least squares process, a significant reduction in computational load and memory is achieved with respect to algorithms based on SSI. If it is also possible to use linear Kalman filtering, real-time operation is straightforward since it is a recursive procedure with minimum order. Both strategies have been applied alternatively to the aforementioned processes (identification and elimination of harmonics, extraction of modes) with very satisfactory results [22].

In order to reduce the complexity to calculate covariances matrices (whose dimensions make them unfeasible for real-time operation) of SSI-based OMA, the Random Decrement Technique (RDT) has been applied. Since RDT is based on averages, is therefore susceptible to real-time operation [22]. In summary, the combination of techniques that allow isolating and identifying modes and harmonics, and the subsequent application of RDT on them allows the basic parameters (frequency and damping) of a wind turbine to be calculated in real time.

3. Experimental Results

At this stage of the research project the three main elements described of the IoT-Based Structural Health Monitoring System (IoT platform with the designed IoT nodes, electromagnetic energy harvesters and OMA algorithms) have been successfully developed and tested. The next step is system integration in a wind farm demonstrator. However, some preliminary results from a real scenario have been obtained. A wind turbine of 1.5W nominal power and 76 m height has been employed for the experiments. Fig. 4 shows the placement of the device in the nacelle of the wind tower. Actually, an improved version of the electromagnetic harvester of Fig. 2 was installed, using 4 freely-moving masses instead of 3 [23]. In order to capture the generated power and to transfer it to a supercapacitor for storage, the power converter shown in Fig. 5 was employed. It includes one independent self-starting AC/DC boost converter per coil [24]. Moreover, another circuit was included to enforce discharge of the capacitor when a prescribed target voltage level is achieved, allowing to obtain an indirect measure of the average power generated through the charging time readings. Voltage at the supercapacitor is saved and downloaded in 10 min registers (standardized time slot in wind turbines), as well as data of acceleration two wind directions: (fore-aft) and its perpendicular (side-side). Wind speed and power generated by the turbine are also available to correlate power generated by the harvester with operating conditions.

Fig. 6 shows some sample acceleration data obtained. The force-aft data have a period corresponding to the first mode of the wind turbine. The last part of the side-side acceleration also shows the periodicity of the 3P harmonic. These harmonics become clearer in the power spectra shown in Fig. 7. Displacement of tower tips spread over a band of around 2 Hz, with main peaks corresponding to the first structural mode of the tower (approximately 0.37 Hz), together with a first harmonic of around 0.2Hz (1P=rotation speed) and a third harmonic at approximately 0.85 Hz (3P, tower shadow effect).

As expected, the amount of power generated by the harvester strongly depends on the wind speed which influence the vibrations of the nacelle and tower. Figure 8 shows the supercapacitor voltage measured during a record of 10 minutes, showing 22 charge/discharge cycles. Measurement was carried out at nominal wind speed (11 to 20 m/s). In these conditions the average power generated is low (around 20μW), mainly because the energy harvester was not specifically designed to this type of wind tower, which has very low vibration frequencies. Moreover, the power conversion efficiency of the circuit of Fig. 5 is low (less than 30%) due to the very simple circuit employed [24] and should be improved.

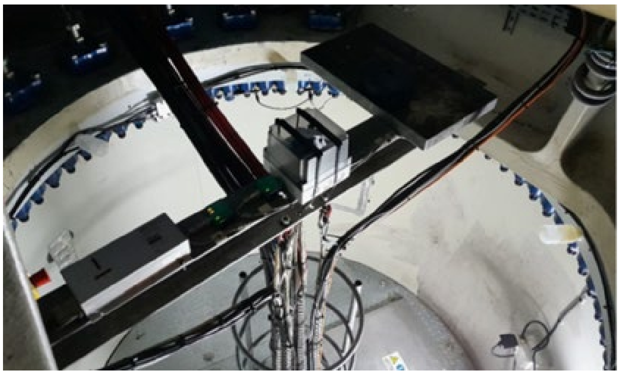


Fig. 4. Test prototype in a wind turbine

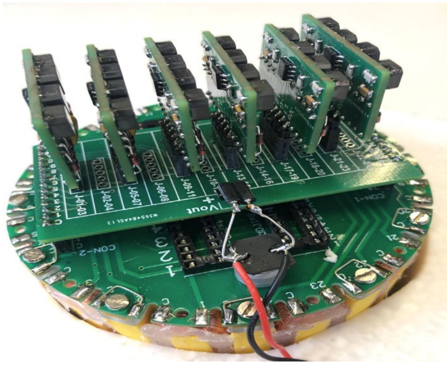


Fig. 5. Power converter of the harvester

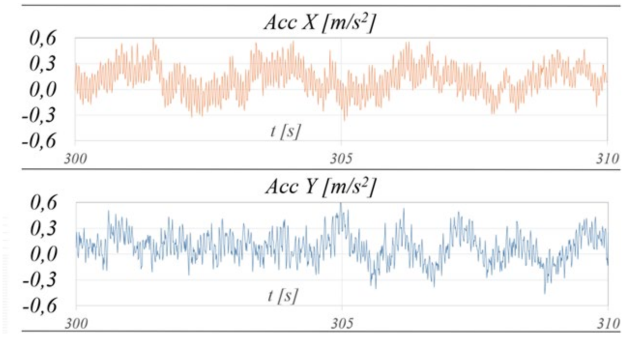


Fig. 6. Measurements of the acceleration at the nacelle: Fore-aft (up) and Side-side (down).

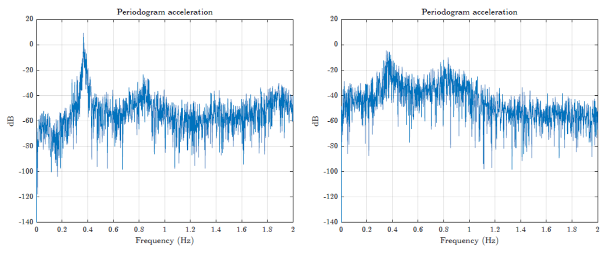


Fig. 7. Tower acceleration spectra: Force-aft acceleration (left) and side-side acceleration (right)

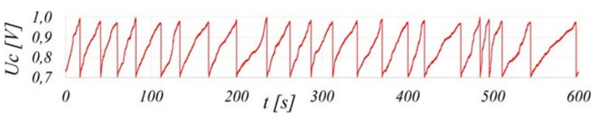


Fig. 8. 10-minute record of supercapacitor voltage.

4. Conclusion

The main hardware and software elements of an IoT platform aimed to provide SHM to wind farms have been described. Vibrational energy harvesting is exploited to provide autonomy to the wireless nodes. Advanced signal processing algorithms have been developed in order to alleviate the computational load of the IoT node. Optimization of the IoT node and power conversion unit of the harvester is still required to guarantee energy autonomy of the node.

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