An IoT condition monitoring system for resilience based on spectral analysis of vibration

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***Abstract*—In these years, the Industry 4.0 paradigm has widespread in worldwide. Smart new automation tools and technologies are rapidly changing the face of manufacturing and industry. The use of new strategies in maintenance management increases the company's competitiveness on the market. The most important task is the reduction of production costs, which can be pursued by reducing downtime and increasing maintenance efficiency. These objectives can be achieved through the widespread use of low-cost smart devices, which can provide a detailed and online view of the operating conditions of the machines. For these reasons, in this paper an IoT system has been proposed. This system analyzes the machinery vibration spectrum, in order to have a conditional and continuous monitoring for the resilience of the machinery after a failure.**

Keywords—Internet of Things, resilience, on-line, vibration, spectral analysis

I. INTRODUCTION

The World Economic Forum [1] discussed that in the coming years 7 million of jobs, considered obsolete, will be lost, but also that there will be 2 million of new jobs. It is therefore important to follow the new technologies, to avoid losing competitiveness.

Industry 4.0 (I4.0) describes the recent evolution in the industrial field, towards a greater computerization and use of connected devices [2]. From a practical point of view I4.0 concerns complete control of the industrial production cycle: all devices are connected to be constantly controlled and monitored in real-time. The connection of the machines and the sharing of information with a fast data network opens new horizons, especially in production.

The main I4.0 advantages concern the development of intelligent and innovative systems, based on four main development lines: (i) data management (based on big data technologies and cloud computing); (ii) automatic data management and improvement of services (machine learning); (iii) human-machine interaction (tablet and new operator panel) and (iv) management and training of data directly from robots (machine to machine) [3].

In the Italian scenario, I4.0 is not so widespread in the sector. From a 2019 study [4], 36 % of smaller companies do not adopt I4.0 solutions and only 24 % of companies are engaged in "high maturity" projects related to new product development. The main reasons are related to the burden of the required investments, and to the related reduced benefits, compared to the effort that should be made for the implementations.

The main protagonists of its implementation are the Internet of Things (IoT) devices, which allow collaboration within a single large structure, through industrial machines, databases, smartphones, tablets, sensors and actuators and taking advantage of concepts such as Big Data, Artificial Intelligence and Data Analysis [5, 6].

The key points are both the interconnection between the devices and the ability to acquire information, customizing each production sector with ad hoc architectures to optimize production objectives. This allowed the application of the same methodologies also in many different sectors such as the healthcare, pharmaceutical or civil sectors. I4.0 has great potential and aims to expand further in the future, as shown in Fig.1 for the global I4.0 market until 2023.

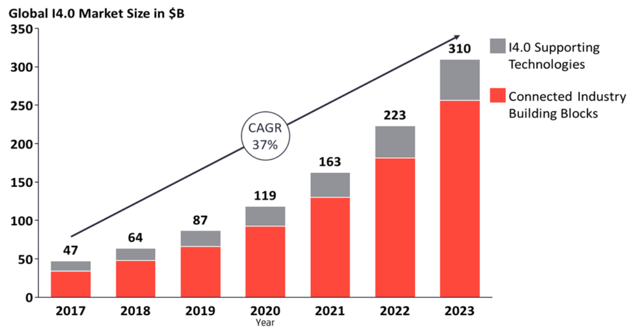

Fig. 1. IOT ANALYTICS: Global I4.0 Market Size in $B 2017-2023

The major obstacle towards the implementation of these new technologies is linked to the need for specific technical skills to manage the relative technological complexities. A help in solving the various problems described is certainly to apply the innovative I4.0 technologies in a widespread way, but without having to make large investments.

Industrial production requires the intensive use of production lines, in order to reduce costs and compete

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internationally. Monitoring and maintenance problems therefore represent the main aspects to pay attention to, especially to improve the performance of existing plants [7-10].

Given the large number of electromechanical systems used in the industrial sector, it is necessary to have low-cost systems capable of monitoring them, in order to optimize maintenance programs and carry out repairs at the right time. In this paper a low-cost IoT condition monitoring system based on spectral analysis of vibration is proposed. The system architecture is described, showing the first experimental results.

II. The Role of Maintenance in the I4.0 Scenario

The role of production operators is evolving, reducing the need for general workers who perform simple operations on products. Today operators supervise each production line via tablet or operator panels, checking and setting the parameters at any time, even by using a remote access.

With I4.0, maintenance is also changing, requiring a different know-how. The new operators must possess notions of mechanics, electrotechnics, pneumatics, computer science and move in an interweaving of procedures.

There was a transition from maintenance where it was "only" necessary to adjust a thermal protection, or replace a fuse, to maintenance that requires expert technicians who must intervene on unscheduled events, modify maintenance plans, improve safety and quality of the new installations.

These trends require changes in the formation of new professional figures. Currently, manufacturers supply machines capable of autonomously generating their own maintenance plan, analysing the information collected with the sensors installed on the machine, counting the operating hours, the number of cycles, measuring all analogue quantities and also correlating all this information between them. Their maintenance is certainly not simple.

Therefore, the qualification and certification of maintenance staff must also be seen from the perspective of I4.0, as reported in the European Standard UNI EN 15628 [11]. This standard defines the profiles of maintenance staff who are called to manage the maintenance to keep the performance of production in the I4.0 scenario. In particular, the figure of the Maintenance Engineer needs not only skills to manage Big Data, but also other skills to control different sectors, such as the IoT and Networking, Cloud Computing. Another important element is the figure of the "Specialist", who is a maintenance technician with a systemic view of the production process based on the analysis and interpretation of the predictive data of the failure.

In this scenario, the maintenance technician plays an important role in the entire production flow. In fact, it must guarantee rapid and precise interventions that reduce downtime [12]. But it must also check, after maintenance following a failure, if the maintenance intervention has completely eliminated the error or if it is necessary to repair other elements. Therefore, a system is required for the acquisition and processing of a large amount of data, to assess whether the error has been eliminated with the increase in the maintenance cost.

Some techniques for monitoring electromechanical systems are based on measuring the electrical power absorbed by the actuator [13]. Given the large number of induction motors, power transformers and actuators installed in the various companies, it is necessary to have a low-cost system capable of providing information on their resilience. By monitoring equipment during operations and then collecting and analysing equipment data, companies can optimize maintenance schedules, to perform repairs at the right time [14].

Using these systems, it is possible to perform vibration monitoring, which can be useful for analysing the working conditions of systems such as power transformers in which, in addition to the magnetostriction, additional mechanical stresses related to harmonics and voltage fluctuations occur. In addition to these phenomena, the transient currents due to sudden load variations and protection interventions must be considered in terms of electrodynamic effects [15].

In this scenario, suitable monitoring techniques represent a good method to study the resilience of the equipment, such as power and insulation transformers, after a repair action or as a part of routine checking [16]. Monitoring of operating conditions mainly uses non-destructive tests, visual inspections and data analysis to know the state of health of the machines, thus avoiding the occurrence of faults and increasing the duration of the components, with the consequent advantages on maintenance costs [17].

In accordance with EN 13306:2010 [18] the Condition-Based Maintenance (CBM) is a maintenance strategy based on monitoring the actual conditions of a system, to decide which maintenance should be performed. CBM is based on the use of data acquired in real-time to prioritize and optimize maintenance resources. Observing the state of the system is known as the condition monitoring. Maintenance should only be performed when some indicators show signs of decreased performance or impending failure.

The health of the component is assessed by correlating one or more physical quantities to the state of the component and identifying a threshold value, beyond which (or below which) the component has a high probability of failure.

For these reasons, a low-cost IoT condition monitoring system based on spectral analysis of vibration has been proposed.

III. The Proposed IoT System

The proposed solution, depicted in Fig.2, is a low-cost IoT condition monitoring system, mainly based on spectral analysis of vibration. The main components are: a STEVAL-IDP005V1 device [19] (left in Fig.2) and a Particle Photon [20], that are connected via a UART full-duplex link.

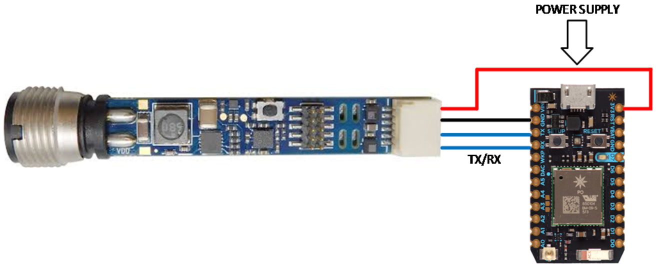

Fig. 2. The proposed IoT condition monitoring system

Vibration data are acquired by means of a three-axis capacitive MEMS transducer, and processed by the IoT system through the ARM Cortex-M4 microprocessor, installed on the STEVAL-IDP005V1 device.

The processed data are compared by the IoT system with those previously acquired and taken as a reference. In more detail, the data acquired in the frequency domain are compared with two masks: one upper and one lower to verify the correct behaviour of the system under monitoring. This allows you to have an always updated "spectral footprint" of the machinery.

The data is then shared by the Particle Photon device, which uses a cloud platform to manage and monitor multiple IoT devices. A LabView client application has been developed to monitor and control the IoT systems.

The elements of the proposed system are described in more detail below.

A. STEVAL-IDP005V1 device

As reported in Fig.3, the STEVAL-IDP005V1 device is composed of the following elements: i) L6984: step-down switching regulator; ii) LDK220: Low-DropOut (LDO) regulator; iii) ISM330DLC: 3D accelerometer and 3D gyroscope; iv) HTS221: humidity and temperature sensor; v) LPS22HB: pressure sensor; vi) L6362A: IO-Link communication transceiver; vii) MP34DT05-A: digital microphone; viii) M95M01-DF: 1-Mbit serial SPI bus EEPROM; ix) STM32F469AI: ARM Cortex-M4 32-bit MCU.

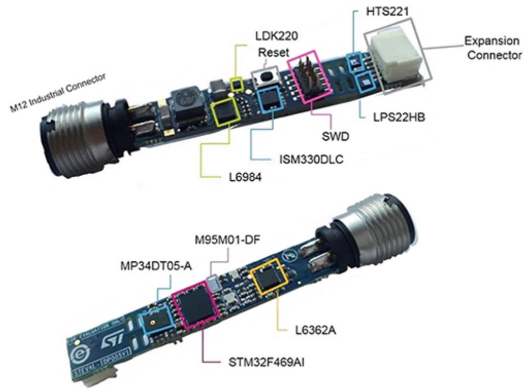

Fig. 3. Components of STEVAL-IDP005V1 device

The main element of the system is the ISM330DLC transducer. Unlike traditional vibration detection instruments based on piezoelectric technology, the one proposed uses capacitive MEMS technology. The reasons for this choice are linked to the advantages it offers such as: i) rapid recovery after a high shock: ii) frequency response starting from DC; iii) good stability over time and for a wide temperature range: iv) digital output: easy wiring and no need for external ADC circuits or other signal conditioning circuits; iv) integrated self-test; v) integrated functionality; vi) low power, small size, low weight.

The device can be connected via an IO-link to the industrial controller, in order to integrate the information into the production cycle. It can also be connected to an external system via a full duplex UART link.

B. Particle Photon device

The Particle Photon device (see Fig.4) is a System on Chip (SOC) where a Broadcom BCM43362 Wi-Fi 802.11b/g/n chip and a STM32F205RGY6 120 MHz ARM Cortex M3 are present in the same chip. The main characteristics are: 1MB flash, 128KB RAM; Real-time operating system (FreeRTOS) and 18 Mixed-signal GPIO. The embedded Wi-Fi module allows the communication over the cloud via an Internet access.

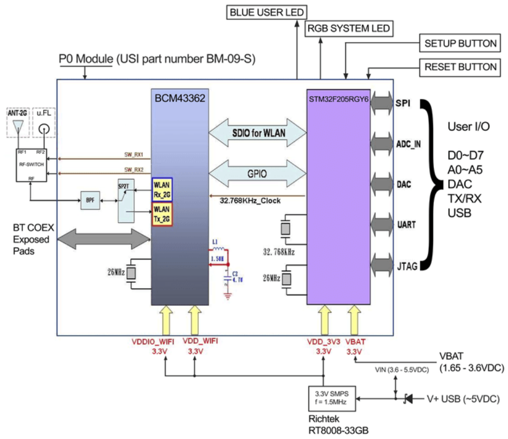

Fig. 4. Elements of Particle Photon device

C. The signal processing flow

The data acquired by the STEVAL-IDP005V1 device are processed to extract the parameters used for the diagnosis. The negative effects of vibrations are related to both the amplitude and frequency of the oscillations. Speed, being a function of these two parameters, is a direct measure of these effects. Acceleration is closely related to dynamic forces and higher forces can occur at higher frequencies, even with reduced velocity values. Speed is commonly used to measure and analyze vibrations at lower frequencies (a few hundred hertz). Acceleration is instead used for vibrations at higher frequencies.

Processing is then performed in both the time and frequency domain. Some steps have been carried out to increase the precision, as reported in Fig. 5.

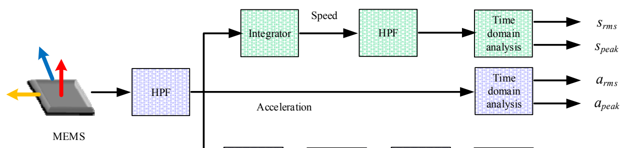

Fig. 5. Data processing flow

The signal acquired by the three-axis MEMS transducer is pre-filtered using a high-pass filter (HPF), to eliminate a small DC bias that may be present. The speed is obtained starting from the acceleration signal through an integration. This operation presents a problem if the initial speed is not precisely known, as the results may have linear drift errors. For this reason, a second high-pass filtering can be performed downstream of the integration.

Speed (s) and acceleration (a) are analyzed in the time domain to provide immediate information for predictive purposes, such as spot or burst events above the established threshold limits. Specifically, peak and rms parameters are measured.

The acceleration data is stored in a circular buffer where 75 % overlaps have been considered to increase accuracy. The data is windowed using a Hanning window, an FFT is performed on a buffer of 2048 samples. To reduce the spectral noise, an average of several spectra is performed on multiple FFT records, calculating the average amplitude for each harmonic component.

D. *Processing performance*

The ISM330DLC capacitive MEMS is the core element of the proposed IoT system. It is a 3D digital accelerometer and 3D digital gyroscope system-in-package with a digital I^{2}C/SPI serial interface standard output. The device provides a sampling frequency of 3.3 kHz with an analogue anti-aliasing filter at 1.5 kHz. The frequency resolution is 1.46 Hz considering a 2048-FFT.

As shown in Fig. 5, the frequency domain processing flow requires several steps to perform frequency analysis. The time required for each activity was assessed in order to define the processing time. From the analysis of the different times detected and shown in Fig. 6, the total execution time is approximately 4.5 s.

The processed data is then transferred to the Particle Photon device via a 230.4 kbps UART connection.

Functions	Excecution time (μs)
HPFiltering on Accelerometer (3D)	1.1
Storage in Circular Buffer (3D)	0.7
Accelerometer Max Peak (3D)	1.2
Accelerometer Integration (3D)	10.6
HPFiltering on Speed (3D)	0.9
FFT Input Buffering from Circular Buffer (1D)	38.7
Input Buffer Filtering with Hanning Window	81.9
FFT processing:	
- arm_rfft_fast_f32 (1D)	973.8
- arm_cmplx_mag_f32 (1D)	354.4
- arm_max_f32 (1D)	46.9

Fig. 6. Time required for analysis

E. *Condition monitoring and (ρ, θ, ϕ) representation*

The most common problems in machinery are caused by shafts, joints and bearings that are not correctly aligned along their central axes. Two types of misalignment are possible: angular and parallel, or a combination of both. Angular misalignment occurs when two shafts are joined at a joint, but their axes are not parallel and a bending force is therefore created on the shaft. Parallel misalignment occurs when the central axes of the shaft are parallel, but displaced from each other.

The possible causes of misalignment are: i) thermal expansion due to a process that works with heat (as with a turbine). Most of the machines are cold aligned, so when they work and heat up, the thermal growth makes them misalign; ii) directly coupled machine not correctly aligned; iii) forces transmitted to the machine from pipes and support members; iv) irregular foundation, displacement or settlement.

Measurements of the FFT spectrum can be used to diagnose misalignment problems. In fact, while angular misalignment causes axial vibrations at the frequency of the travel speed (1x), parallel misalignment produces radial vibrations at twice the frequency of the travel speed (2x). In general, most misalignment is a combination of angular and offset.

FFT analysis has been used to perform conditional monitoring. To verify the behavior of the system under test, a mask was defined in the frequency domain, using upper and lower limit curves. The 2048-FFT points are divided into 64 sub-bands, with a width of 51.5 Hz and a length of 32 points. The maximum is found in each sub-band. If the peak is within the limits of the sub-band, the sub-band does not have a maximum and is not considered in the analysis.

In order to make the 3D positioning of the transducer less binding compared to the system under test, the three-axis FFT analysis was processed to represent the peaks present in each sub-band. In this way, the position of the proposed IoT system is not important because the upper and lower frequency masks have been applied to the resulting spectrum. An example of the proposed approach is illustrated in Fig. 7 where, for one of the sub-bands, the spectra of magnitude (x, y, z) and the peak are shown expressed in polar coordinates (ρ, θ, ϕ).

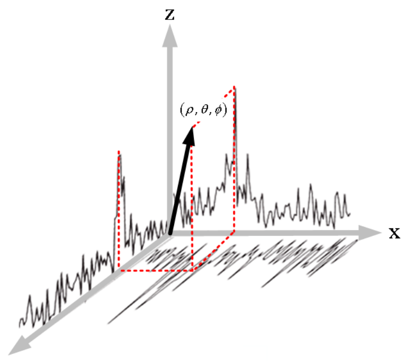

Fig. 7. Polar representation of three-axis FFT analisys

IV. Data Transmission and Network architecture

In Fig. 8, the network architecture of the proposed system has been reported. Each IoT system was implemented using the Particle Proton device as a front end to access the Internet via a Wi-Fi connection. Locally, a router creates the Wi-Fi network through which the IoT device can send data.

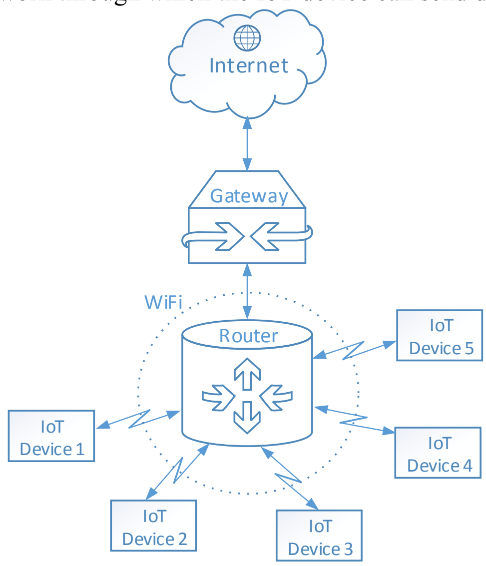

Fig. 8. Network topology of proposed IoT system

Particle provides a complete WEB platform for managing Particle Proton devices. It allows not only to control the status of the IoT system connected to the Internet, but also provides a complete Integrated Development Environment (IDE) to distribute the firmware directly via the WEB. This function is very important because a firmware modification can be remotely applied, without having to connect the device to a PC to download the new firmware. Another important function of Particle is the cloud system through which it is possible to manage and download data. Any IoT system can publish data and can expose the web function to the Internet to create an access point for downloading or uploading data.

In the proposed system the access to the cloud is performed using the API Rest as software architectural style, from which a LabView client can download the latest data published by the IoT system. An example of the mechanism used to access IoT data is shown in Fig. 9, where Particle Cloud is used as a link between the IoT system and a LabView client. Even if the Particle Proton device has an integrated Wi-Fi device that can be used to exchange data locally, the use of the cloud system can increase the availability of the whole system giving much more freedom. In addition, any maintenance operator can reach the IoT device remotely.

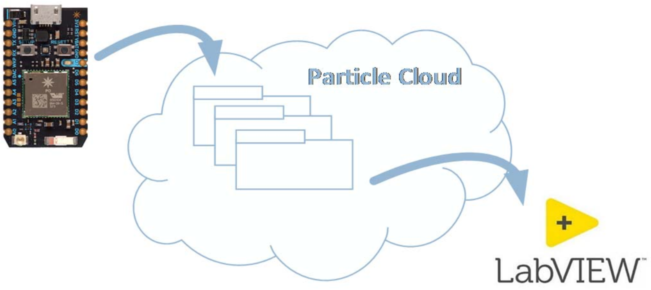

Fig. 9. Network topology of proposed IoT system

A. Security aspects

The API Rest provided by Particle is performed using the https protocol. This means that the SSL layer provides a secure communication system between the two endpoints: IoT system and LabView client. The API Rest adopts an http query string approach to access the web methods published by the IoT device. Although the approach is not so secure, the URL is organized with two main fields: IoT ID and an access token. The IoT ID is 24 characters long and is provided by Particle when the device is mounted in the development center, while the access token is 40 characters long and is associated with the developer. These two fields are not available, so the entire URL is not searchable. Also, a DDoS attack can reduce IoT functionality because the particle is not designed to handle this type of attack.

B. Data published

The data published by the IoT system are organized using the JavaScript Object Notation (JSON). The JSON message is much easier to organize than other mechanisms, due to the reduction in overheads introduced in the message. For this application, the main data to be exchanged are the FFT 3D spectrum, organized into three arrays. An easy way to transfer it is to use the JSON message in which an array can be organized a file of length equal to the number of data. The client parses the JSON message and transforms the text into float data.

C. LabView Client

The LabView client, shown in Fig. 10, accesses the cloud for downloading, saving and viewing the 3D digital accelerometer data. The user interface has several elements: i) three-axis FFT graph showing the acceleration RMS value, displayed in decibels; ii) 3D graph for the spatial visualization of the components of the disturbance frequency; iii) card for system configuration, connection and setup.

The board is divided into three panels:

i) the first panel shows the IoT system configuration. Using a Ring Menu, it is possible to choose the IoT system for data download. The user interface accesses the INI file which contains all the IoT system information (name, IoT ID and access token). The operator can check the connection between the user interface and the IoT system and download the data. In this panel is included a section that performs the download of the data automatically, setting both time and update mode. The operator can also limit the frequency range of the 3D spectrum by configuring a parameter on the IoT system. This parameter only limits the JSON array data and does not change the sampling rate, spectral resolution or FFT points. By shrinking the JSON array data, the client is much more efficient because the download time is shorter. This parameter can be selected if the total spectrum does not present important harmonics at high frequencies.

ii) In the second panel you can apply the condition monitoring settings. A threshold level can be set in order to limit the frequency analysis as a sub-band and window number applied to the spectrum.

iii) At the end a Log Data panel is used to set the file path for saving all the FFT data.

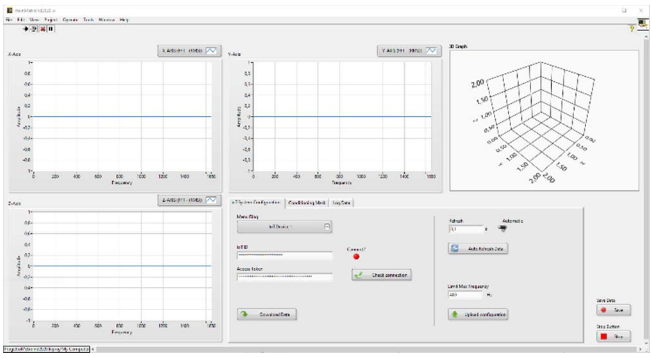

Fig. 10. LabView User Interface

V. Results

As part of the development phase, the implemented IoT has been applied to an induction motor rotating at 3000 RPM and connected to a test bench system coupled via a corrupt ball bearing. In Fig. 11 a screenshot of the client is presented,

The defect is a ball pass frequency multiplier of the outer race (BPFO). The vibration frequencies are created when all the rolling elements roll across a defect in the outer race. During the test, the IoT system has been placed near the ball bearing. The analysis shows the three-FFT spectrum limited to the range of 0-400 Hz. The IoT system perform a continuous data downloading.

In Fig. 12 a particular of the X-axis FFT spectrum is reported. The figure shows the frequencies of rotation (red circles) and other harmonics (black circles) due to the defect.

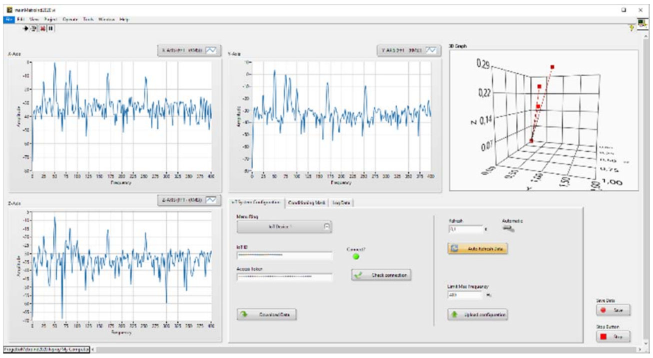

Fig. 11. Result of the proposed IoT system

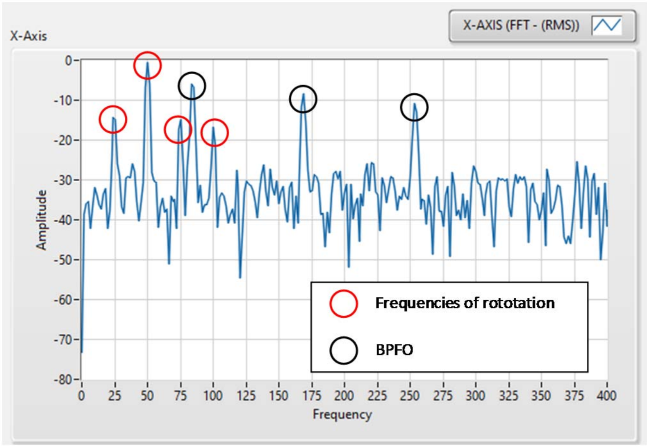

Fig. 12. X-axis FFT graph

In the 3D analysis shown in the user interface all harmonics related to the rotation frequency of the induction motor are filtered. Therefore, only the frequencies present in the sub-bands that have a level higher than the threshold value are taken into consideration. For the frequencies considered, the values (x, y, z) are represented in the 3D graph.

VI. Conclusions

A low-cost IoT measurement system for online monitoring of electromechanical systems based on vibration analysis has been presented. The IoT system is composed of a STEVAL-IDP005V1 device to acquire and process data and a Particle Photon device to perform conditional monitoring activities and publish data on the cloud. The IoT system can be used for conditional monitoring application, but the data produced can also be used for predictive maintenance. The technique used to publish data in the cloud and the LabVIEW client application have been described. Some experimental results, obtained with the proposed system, have been also presented.

The cost of each monitoring unit is less than 150 $. Other commercially available solutions are based on wireless sensors, such as the Fluke 3561 FC [21] which costs around 1000 $ for the sensor alone and around 120 $ for the gateway. More expensive systems are vibration analyzers, such as the Digivibe M30 [22], a portable high-performance system designed to individually analyze machine vibrations, the cost of which is around 3000 $.

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