On-condition maintenance of wind generators - from prediction algorithms to hardware for data acquisition and transmission

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Abstract: Maintenance management is a subject that, instead of reducing importance, with the increase of equipment reliability, it increases its role in the companies and obliges the increase of the level of demand of professionals involved because of the new technical and environmental demands. Sometimes, scientific developments anticipate the company's needs while other times it is the company that challenges science. The maintenance area is an example that offers challenges to both science and companies in order to optimize the performance of equipment and facilities. This is also the case of wind generators, because their expansion, evolution, maintenance and reliability guarantee, needs to be adequately articulated in order to maximize production time and, obviously, to optimize maintenance interventions.
It is because of this kind of challenge that the authors are developing new methodologies in the area of wind generators that aims to optimize the cycles of production and, consequently, reduce other kinds of energy production. The new features include on-line measures and the corresponding on-time treatment, using algorithms based on time-series forecasting and wireless technology to transmit the signals.
The prediction models uses regression techniques based on SVR, ARMA and ARIMA models, modified according to this specific case. The weather conditions and the technical and construction characteristics of wind generators are only some variables that we have in account in the models that are under development.
But, if these conditions are important, it is also very important to collect, read and treat data from sensors placed in wind generators that, because their geographic dispersion, and difficulty of transmission, must be solved adequately and conjugated with the above referred algorithms, in order to implement an adequate system.
This is the ambit of the present article that reports a wide approach of a subject that usually is managed separately, this is, the hardware from one side and the prediction algorithms from other side. This is possible because the team has being researching and developing algorithms and an information system, since many years ago, around the terology subject that is a wider vision of maintenance. Then, the new methodologies, above mentioned, will be, later, incorporated through new predictive maintenance modules in an integrated maintenance management system called SMIT (Terology Integrated Modular System). The base of SMIT is accessed through a client-server system and a browser system that includes the main modules of a traditional system, as well as a fault diagnosis module, a non-periodic maintenance planning module and a generic on-condition maintenance module, among other innovations.

Key-Words: Maintenance management; Predictive maintenance; Wind generators.

1 Introduction

After many years since the appearance of first information systems for maintenance management, the basic maintenance problems remain, but with new boundaries.

The concept began from maintenance itself, continued throughout Terotechnology, Total Productive Maintenance (TPM), Terology, until Reliability Centered Maintenance (RCM).

Although techniques, methodologies and, in general, the research done in this scientific area has developed and provided a lot of knowledge, and because there has not been any scientific society in the specific field of maintenance, this has originated a dispersion of papers of this area within more general scientific areas.

This may be related to the weakness of industrial maintenance. This is usually the first industrial area where the manager reduces costs. In addition, due to the multiplicity of technical skills on the part of technicians, it becomes extremely difficult to find adequate human resource competences.

As a result of these last points or due to the enlargement of challenges made to maintenance, nowadays, new concepts and new background are being developed around the Asset Management concept.

This puts maintenance as the core activity that integrates the global responsibility of all facilities, equipment and installations and, obviously, with the necessary skills to manage them.

It is based on this new background that the scientific community must do more research for new algorithms and develop new methodologies in order to anticipate the new challenges and the solutions to solve the new fragilities of the planet.

It is with an information system for maintenance, called SMIT [1], Terology Integrated Modular System, as a general base to manage the assets, as well as a strategic line of evolution of this system, that on-condition maintenance modules were introduced, and the corresponding research and development is being done around this theme.

The maintenance is one way to manage the life cycle of assets in order to increment its life with maximum reliability and, obviously, reduce the necessity of producing new products and equipments and, consequently, preserve the planet.

We are talking about a new economy, an ecologic economy, having as main objective the sustainability of the planet and, obviously, the maintenance will be or, in other words, is already a very important approach for that goal.

It is because of these reasons that this paper is developed, supported by a strategic way: the maintenance of wind generators, having the system SMIT as a work-base.

The maintenance of wind generators involves new problems, that begin with the traditional operational research methodologies, namely with the optimization of paths and resources but, also with the measurement of operating parameters that have the possibility to minimize faults and increment the optimization of planned maintenance. In this case, we use scheduling techniques and new hardware developed in order to receive and manage the measurement signals that would optimize the planning. The signal measurement, transmission, treatment and the algorithm inserted in SMIT, constitute a new approach in maintenance of wind generators.

These are the global approach that will be developed throughout this paper, beginning with SMIT and, then, with these new on-condition approaches and their integration in the system. Also, we will discuss new trends and new research areas and, finally, the conclusions of this paper.

2 SMIT – main modules

SMIT [1], [4], [5], [6] is a Client/Server program, multi-database, allowing the installation of several clients and its configuration within the same platform. The program is accessed through the Windows environment. SMIT allows the optimization of maintenance resources through the following tools: characterization of maintenance objects; suppliers (of equipments, parts and services); human Resources Management; tools Management; Stocks and Spare Parts Management; Fault Diagnosis; Work Orders; Planned Maintenance Management (including on-condition maintenance); Emission of Reports, Analyses and Improvement Plans.

SMIT always has the advantage to make the maintenance management easy because it includes the complexity of management in its structure but with a front-end that interacts with the user with the minimum complexity and minimum of operations and data. SMIT was developed using the scientific knowledge in this area and it is permanently up-to-date. This approach was used because of the complexity, quantity of variables and diversity of situations that maintenance implies; they are reduced at a minimum with SMIT as explained below:

- To reduce preparation time and emission of Working Orders (WO);
- To print detailed WO with definition of resources and prediction of time for execution of the maintenance interventions;
- To establish priorities, taking in account the importance of equipment, the urgency of intervention and resources available (human and materials);
- To develop daily intervention plans, management of delays and work load, with the objective to minimize the response time, reply time and down time of the maintenance objects;
- To perform planned maintenance through the analysis of historic data and fault diagnosis;
- To perform detailed preventive inspection plans to fulfill all requirements for a good operation of maintenance objects;

- To manage spare parts, taking into account the adequate quantities adjusted in function of the level of equipment importance, the urgency of the intervention and the response of respective suppliers to supply the spare parts, in order to make possible its provision on time;
- To adjust the priorities of interventions, taking into account the evolution of parameters of duration and functioning among other variables, like reliability parameters;
- To compile the provisional costs for budget analysis, filtered by maintenance object, cost centre, location or others;
- To automatically calculate maintenance indicators allowing the emission of reports for periodic control by the responsible persons;
- To carry out the systematic accompaniment between the prevision and real needs for the resources: time, costs, people and suppliers;
- To perform the inventory management (equipment, parts, tools...) and financial calculation of depreciation of goods;
- To perform the management of spare parts, tools, …, and the indent orders to suppliers;
- To perform a dynamic planning of maintenance, updating automatically the maintenance object plan in function of the evolution of WO carried out;

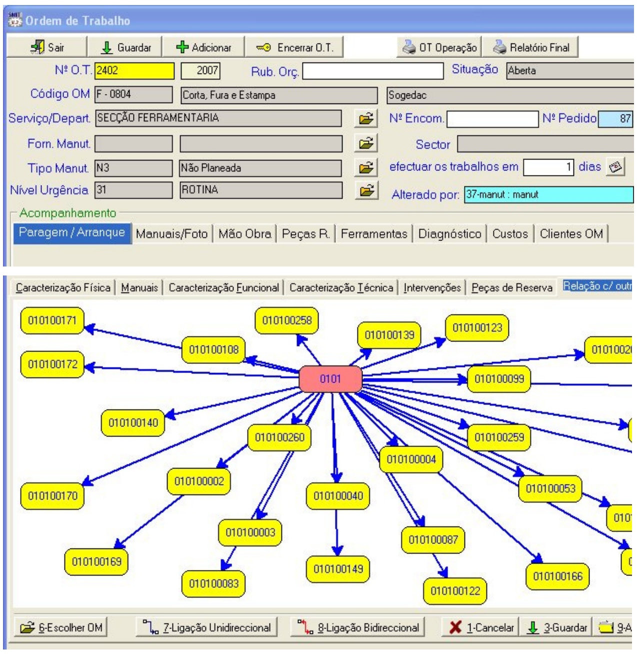

Fig. 1 – Launching a working order in SMIT program, and the Relation between MO-Maintenance Objects (matrix relation)

One of the great advantages of SMIT is the minimum human resources required to work; the use of SMIT could be carried out by a person with basic knowledge of computer science in the user optics.

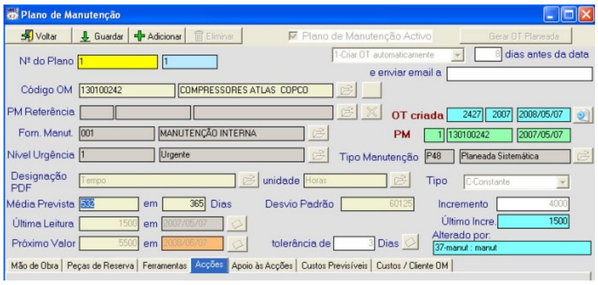

Fig. 2 – Maintenance Plan

In Fig. 1, 2 and 3, some significant SMIT screens are presented as examples. The Planning and the working Orders are basic modules of a maintenance management program.

Fig. 2 represents a maintenance plan. Here, the user can choose the Maintenance Object (MO) in which he wants to implement a maintenance plan.

The Gantt module allows the users to visualize plans in a graphical way, like WO required for interventions. With this interface, it is possible to modify the dates of any plan. The module has the advantage to offer a method of planning the work load of a maintenance department using "drag and drop" techniques.

A general approach and some specific aspects of this system, namely a new research about fault diagnosis and the maintenance training by e-learning using CBR systems, can be seen in [2], [3] e [30].

3 Maintenance of Wind Generators

Wind turbines maintenance uses many techniques similar to other maintenance objects. In this field many authors [7], [8], [9], [10] are working using acoustic techniques, vibration techniques, infrared images, stress measurement, zero crossing current analysis, artificial intelligence, only to name a few. Within this work, the main objective is to perform the fault detection through on-line data instrumentation, acoustic techniques, vibration techniques, infrared images, stress measurement, zero crossing current analysis, and artificial intelligence, among others. Within this work, the main objective is to perform the fault detection through on-line data instrumentation.

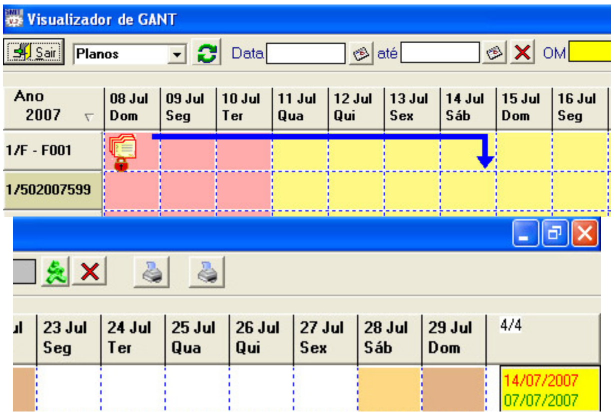

Fig. 3 – Two perspectives of Gantt Module

3.1 The environmental problem

The techniques used for monitoring the wind systems condition are based in the following aspects:

- Vibration monitoring on generator and gearbox;
- Measuring the wind speed, using an analogue anemometer (inexpensive) and a ultrasonic anemometer WMT50 from Vaisala Company (for geographic signature of normal wind behavior);
- Active power measurement;
- Weather forecast using information from weather sites, tracking the wind velocity (using time series analysis);
- Classification using artificial intelligence;
- Time series analysis using regression techniques;
- Using a weather monitoring station (future development).

The hardware is based on commercial equipment from manufactures as National Company [12], also designed especially for SMIT software. In general, the signal condition follows the diagram shown in Fig 4.

The whole fault detection system is built around MATLAB Software routines for spectral analysis of current and vibration to extract essential information from the sampled time domain data, time series regression and artificial intelligent classification.

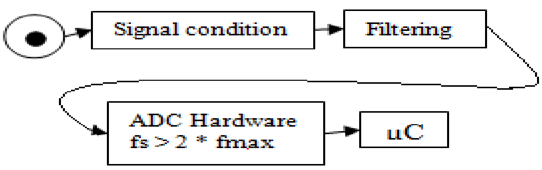

Fig. 4 – Generic electrical signal processing for data acquisition

Fig. 5 – Up: Example with motors. Down: the motor working as generator

3.2 New algorithms

1. The first algorithm uses an accelerometer to monitor vibrations on the gearbox and in the generator where the line currents are also monitored. To identify faults, two assays were performed. The first, an induction motor was used as motor and the second one as generator. In the first test, four induction motors were used, one healthy and three motors with some kind of damage provoked, like broken bars. The motors were tested with full load, half load and without any load (Fig. 5, up side). The same test was performed using the motor as generator, and introducing loads (Fig. 5, down side). The acquisition was performed with a National Company USB 2.0 – Model 6251, the accelerometer Monitron MTN/1100CQ, a MTN/1100C and current sensors SEFRAM, model "SP 261". Fig 6, 7 and 8 show vibration signals.

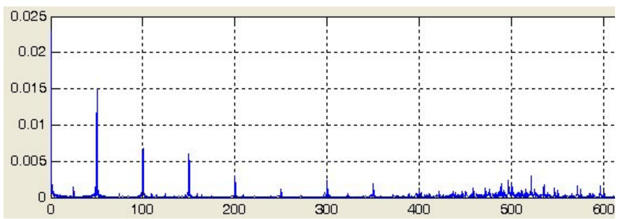

Fig. 6 – Vibration analysis using an FFT with 6000 points, fs= 2Khz. Healthy Motor, no load

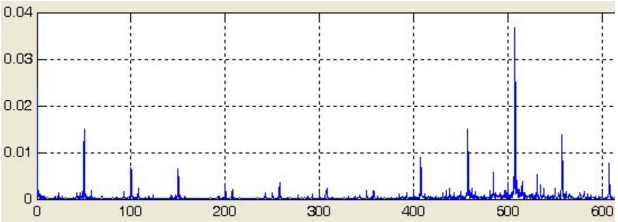

Fig. 7 – Healthy motor with full load

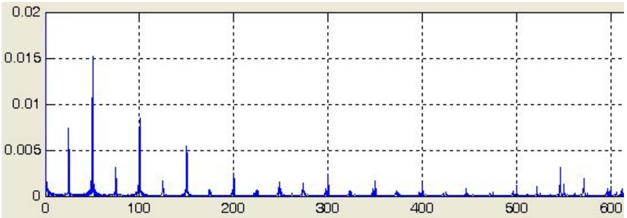

Fig. 8 – Motor with fault and with no load

2. The second step in this study was to monitor the wind speed. To accomplish this task a WMT50 from Vaisala [13] was used. This sensor uses ultrasonic technology to measure the wind speed and direction (Fig. 9, left side) and can be used for precise measurements, and for geographic signature of normal wind behavior. An RS232 interface communication permits to send and receive data. However, for a large scale implementation, the WMT50 is very expensive and in this case an analogue anemometer is recommended (costs about 50 Euro, Fig.9, right side). The maintenance system only needs the wind speed. In this case, they were performed tests with an analogue cups anemometer. The number of revolutions per minute is registered electronically after some electronics.

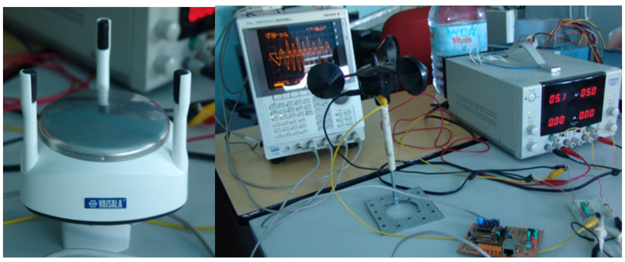

Fig. 9 –Left: WMT50 from Vaisala. Right: analogue cups anemometer

3. From wind and power measurement it is possible to predict the power curve. The main idea is to relate the power curve with normal or faulty condition.

4. Weather forecast is done based on web sites information, and by using the measurements given by the anemometer. The combination of this information is performed by using time series analysis.

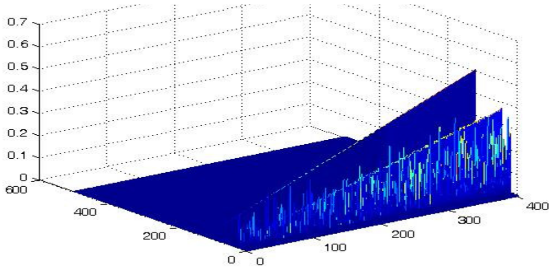

Fig. 10 – Simulated example as shown in Fig 11. FFT monitoring over time.

5. Classification using artificial intelligence is performed basically using Support Vector Machines (SVM) only for deciding between a good situation and a fault situation.
6. Time series analysis using regression techniques are used to track some frequencies (see [14],[11] for more information) along time. This will give a time series to monitor and to check when they will tend to a situation where some fault will occur in the future. The regression is made based on SVR, ARMA and ARIMA models [21], [28].

These algorithms are all implemented in MATLAB Software where the simulations are performed and regression algorithms based on time series are compared.

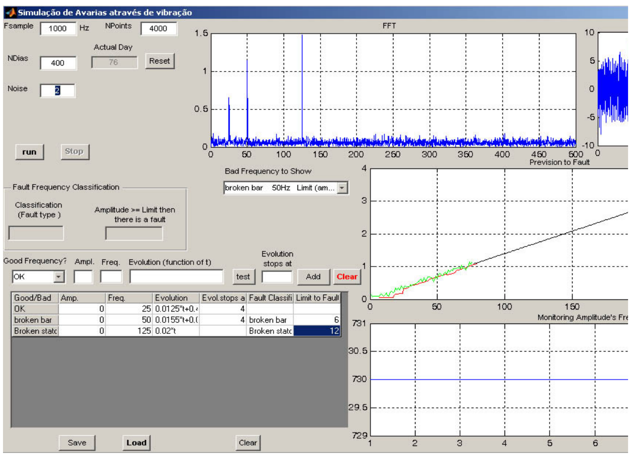

Fig. 11 – MATLAB program to monitor through time some key frequencies obtained from the vibration signal in the gearbox and generator

3.3 New SMIT on-condition module

To integrate the methodologies described in section 3.2, a special hardware is necessary. Fig 12 shows the hardware.

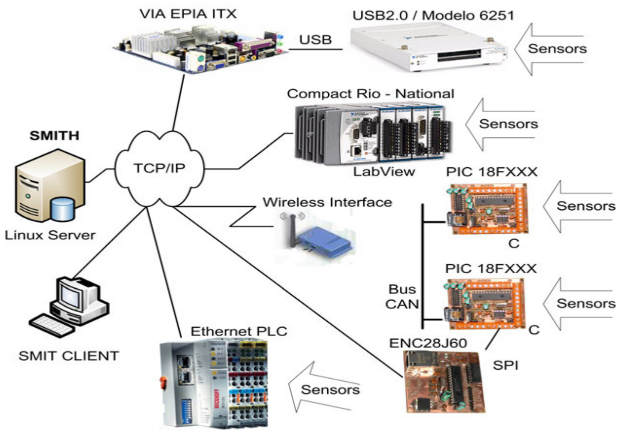

Fig. 12 – Maintenance Management System – SMIT and respective hardware for data acquisition

The system can incorporate commercial acquisition hardware. For low cost implementations a special hardware is used based on CAN 2.0B network and Ethernet Network. The designed hardware uses microchip technology, PIC18F2685 for Can and ENC28J60 for Ethernet connectivity (Pic 18J86G60). In the instrumentation a special board incorporates a low pass filter and amplifier / attenuator electronics with the cut-off and the gain set by software.

The SVM integration uses some measures in the corresponding vector (wind velocity, wind direction, low rotor velocity, high rotor velocity, active power and reactive power).

SVM can be seen in an easy way, as a mapping technique between measurement space and feature space (see Fig.13). More details can be seen in [20], [21], [22], [23] and [24]. To perform the mapping, kernel functions are used. The algorithm uses a training phase where measurements are classified. After training phase the algorithm can “tell” us the condition of new data.

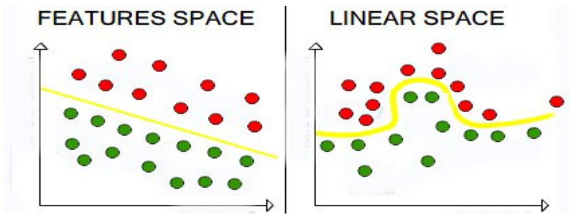

Fig. 13 –Transition between the Linear Space to Feature Space made through a kernel function

Figs. 14 shows examples of real data measured in a wind turbine installed in Denmark [27]. It is also possible to simulate it in MATLAB Software - all the wind turbine behavior including wind statistical distribution. More details can be seen in [25], [26] and [27].

Using the SVM with the quadratic optimization algorithm, a performance classification around 93% was achieved.

Using SVM with the least square optimization (called LS-SVM) method, a performance of 91% was achieved.

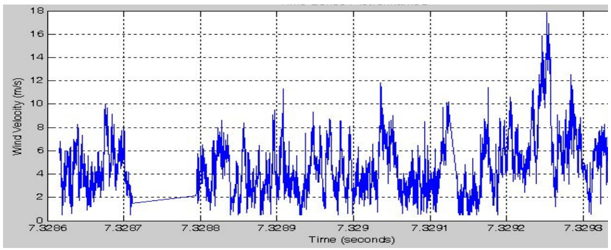

Fig. 14 – Wind velocity in the top located cup anemometer

4 Integration of Modules

4.1 Computing

Fig. 12 represents the SMIT system. The system has client/server architecture.

The server is based on Linux [16] and a Desktop/Laptop client for windows environment [15]. The Linux server incorporates the following functionalities: database PostgreSQL [17]; web [19], fax and email server [18]; a TCP/IP server for reception of data acquired from different acquisition points; SNTP/NTP Server; SNMP [29] and ftp server. To dialog with other applications, the system supports insert/update/delete using web services technology and also import/export in csv/xml format. The system is very portable; it can run on Windows/Unix/Linux/Mac OS, if and only if PostgreSQL and PHP are available.

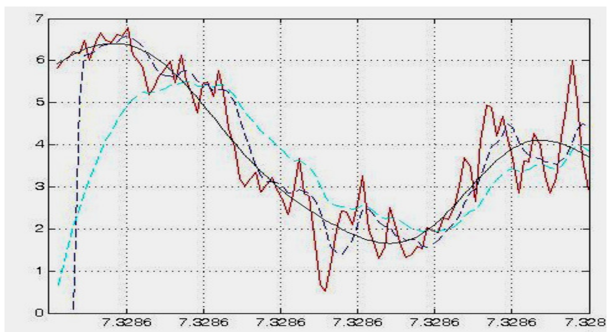

Fig. 15 – Example of time series forecasting (in this case, wind velocity). White, exponential smoothing, with alpha=0.4. Blue, moving average with N=5. Black color, SVR with RBF, 10.

4.2 Hardware/Firmware

For acquisition, SMIT can incorporate different hardware. The following hardware can work on SMIT:

1. **High Performance:**
   - LabView Software – acquisition boards with special hardware.
2. **Middle Performance:**
   - Ethernet PLCs – acquisition boards with special hardware.
3. **Low Cost:**
   - MicroControllers – Microchip ethernet and CAN solutions;
   - Adaptative Filtering, and signal condition - accepts 10 channels of 100 Khz max sampling.

Some comments about the three past approaches:

1. The first choice is highly recommend for very special conditions where performance is necessary.
2. The second is recommended for integration on industry, where standard environment like OPC and SCADA technology are necessary.
3. The third is the special hardware design, namely from the first author of this paper, for low cost acquisition system, maintaining a good performance. This hardware is developed using Microchip technology, although not to be top microcontrollers, they are sufficiently popular and cheap, keeping a good relation cost/performance. We consider that this development adds scientific value and has potential to be used day-to-day in a near future.

For accomplish the task, four boards had been tested (Fig. 16)

- PIC18F2685 + ENC28J60 (Ethernet and CAN);
- DSPIC18F4310 + ENC28J60 (Ethernet and CAN, for high sampling rate);
- PIC18F2620 + ENC28J60 (Ethernet only);
- PIC18F67J60 – Ethernet only.

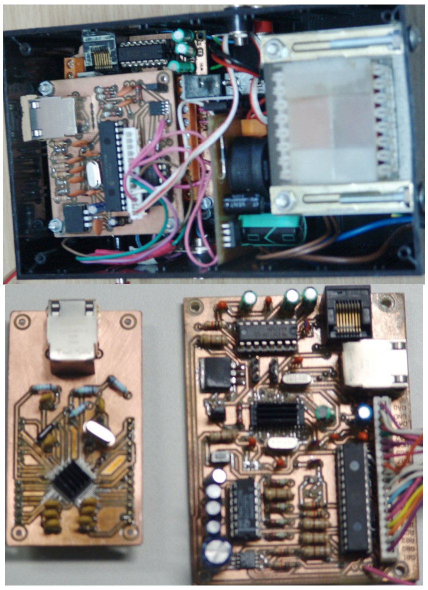

Fig. 16 – Top: PIC18F2685, down right: PIC18F2620, down left: PIC18F67J60

For Adaptative Filtering and signal condition, a board has been also assembled, allowing the user to setup the gain and the cut-off frequency of a low pass Butterworth filter (Fig 17).

The system accepts 5 channels of 100 KHz (shared) max sampling (PIC18), and 5 channels of 1 MHz (shared) max sampling (DSPIC).

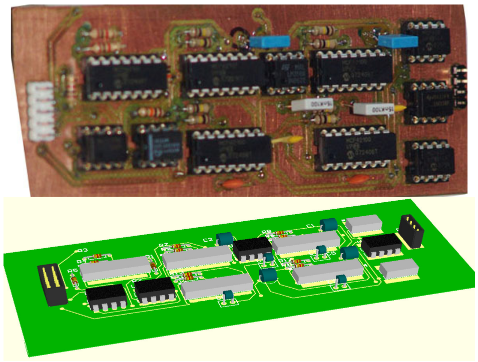

Fig. 17 – Filtering board (DIP version)

To upload the software (firmware) remotely from the SMIT Linux Server into the PICs, a special boot loader was programmed. The Client for upload the new firmware that can run under Windows or Linux.

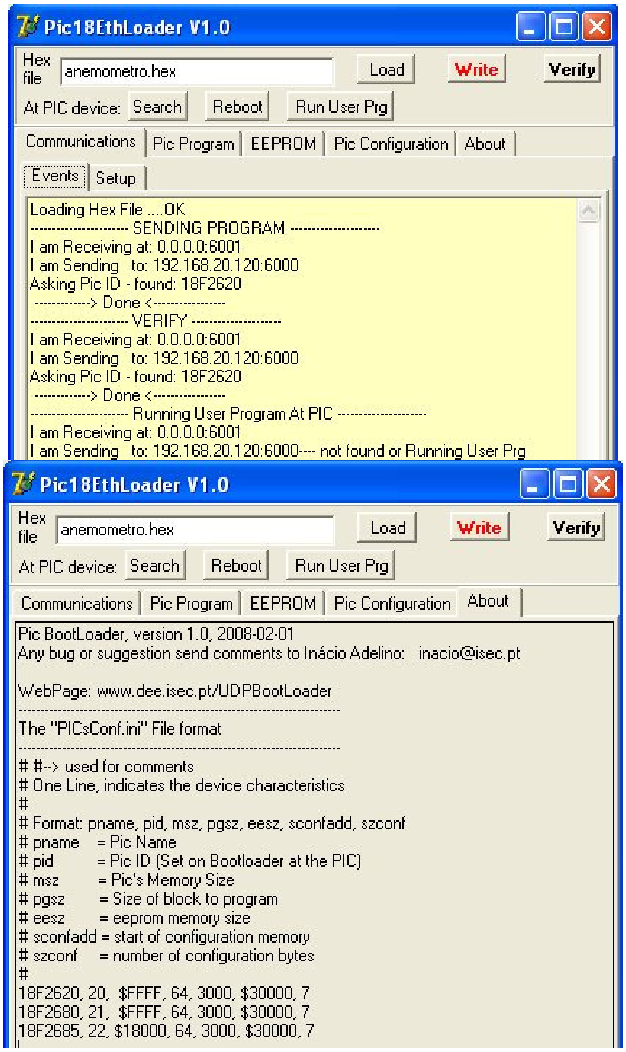

Fig. 18 – Bootloader Client (Windows Version)

The bootloader can download firmware to any node (including CAN and Ethernet), using an Ethernet node as gateway. The bootloader uses an encryption algorithm for transmission (based on a 87 bytes key). The main characteristics of this hardware are the low cost and the possibility for RTC (Real Time Clock) synchronization.

The RTC synchronization through IP network can be achieved using SNTP (Simple Network Time Protocol), NTP (Network Time Protocol), IEEE 1588 PTP (Precision Time Protocol) and SynUTC, among others.

To manage the RTC synchronization between 10ns intervals, special hardware is necessary for timestamp packets in the moment it is received. For this high demanding task, the timestamp is performed in hardware (the chip receiving Ethernet packets, should save the timestamp), and National Semiconductor released the DP83640 chip in the first months of 2008, supporting the 1588 PTP protocol. The IEEE 1588 can also be used only in software implementation, which can achieve good performance. In this implementation, the SNTP has been used to synchronize Ethernet boards and the other modules using the CAN network.

4.3 The local and national databases

In the earlier point the use of web services technology was focused. This is an enormous advantage to implement some solutions, for example:

- A national database for fault diagnosis;
- A national database for spare parts;
- Local database for work orders, technicians and so on, but working in connection with national databases.

Having a national and local database enables relevant information to be shared among different clients to give support in detecting the source of faults, and so on. However, specific data should not be shared, like costs, suppliers, working orders, and planning policy. Web services make this task very easy. About these subjects see also [2].

One example of this methodology is under the Wind Turbines Maintenance, where many relevant data can be inserted in a national database, like types of faults, the way to solve them, maintenance indicators, like MTBF, MTTR, and so on. This is important not only to share knowledge (considering any worry about company competitions), but also to plan the produced power and risks to fulfill expected wind production (by failure or no wind).

Another important situation where this approach is relevant is in hospital field because the importance of many equipment, namely the life support and others in general. The diversity of suppliers, the price of equipment and spare parts, the small number of some equipment, the location of some suppliers of maintenance services and many other singular situations, are reasons enough to consider the hospital equipment a case study for the approach behind referred.

```
<?php
require_once('libSOAP/nusoap.php');
$wsdl="http://smitserver.pt/smit/webservices/serverSOAP.php?wsdl";
$client=new soapclient($wsdl, 'wsdl');
if ($client->getError()) {
   echo 'Client Error: ' . $client->getError() ; die(0);}

$param=array(
  "database"=>"smit", "login"=>"adm", "passwd"=>"adm",
  "sql"=>"select * from insertom_p15('parameters');");

$lv_value=$client->call('runSQL', $param);
if ($client->fault) {
          echo 'Fault: '; print_r($lv_value); die(0); }

if ($client->getError()) {
  echo 'Error calling function: ' . $client->getError(); die(0);}
```

```
echo $lv_value . "<br>";
  // returns from SQL function insertom_p15:
  //    'OK' – update done,
  //    'OK-INS' – First insert
  // By default, the service returns the following values
  // --------------------------------------------------
  //    'ERROR: 1' – No permissions to run the SQL
  //    'ERROR: 2' – Database connection failure
  //    'ERROR: 3' – The user does not exist
  //    'ERROR: 4' - Error running SQL
print_r($lv_value);
?>
```

Fig. 19 – WebService example to run queries from third party software against SMIT database

To include new modules in SMIT is very easy; because the framework is developed in Delphi for windows client/server architecture and for web development Symphony PHP Web Framework. The database is documented in web pages (every table and field, expected values, etc). The module to receive data from field measurements is fully configured in the database (number of clients, sockets to receive data, acquisition method, etc).

Nowadays almost one hundred of on-condition techniques are known and many others could be developed. It is because of this that SMIT was developed with an architecture that can support new modules, namely for predictive maintenance. But this integration is not a sum of more modules but a real integration where each new on-condition component dialogues dynamically with the main modules, like planning and work orders, among others.

The new predictive modules can receive data through keyboard, PDA, specific tools, like thermographic cameras, noise meters, or on-line acquisition. This makes SMIT not only a maintenance management system but an asset management system and a system that makes this management available 24 hours a day, and an alert system for the complete accompanying of behavior of equipment and systems.

5 Further Developments

Based on this point of development, where the maintenance management system was enriched, namely the SMIT, there are also new opportunities to improve, namely:

- New on-condition modules;
- Renewal methodologies for wind equipment in an environmental approach;
- Withdrawal of equipment in an environmental approach;
- Improvements based on new approaches based on fuzzy theory;
- Integration of SMIT with other software tools for a general management in any organization;
- Risk analysis in the several areas of asset management.

6 Conclusion

When equipment is in pre-dysfunction state it sends out signals or symptoms that are not within the perception range of human senses. To search for an early detection of these signals, techniques that enable to model and predict environmental effects, like emissions, including noise effects, oil degradation and infrared thermography, are an evolution in the direction of ecological predictive maintenance.

Several of these techniques have their limitations. However, in certain applications they are the best choice.

In this article a maintenance strategy applied to a renewable energy was presented.

The developed software SMIT, summarily described in the paper, and that is totally stabilized at the present date, is a powerful tool for maintenance management and is used as the background for these new developments.

Because the tendency in the future is to use typical house/industrial equipment that includes a communication network like ZigBee (now with a great expansion in the area of wireless sensors), the inclusion of a new software module for on-condition monitoring based on on-line instrumentation is relevant. The paper points out a methodology that is under development.

Additionally, the equipment sends out signals or symptoms that are usually not within the perception range of human senses but can translate environmental dysfunctions. The accompanying and forecasting based on these signals, like noise, oil degradation and temperatures, aims to manage on-condition maintenance approach in an ecological way.

We think this is a way to contribute for a new world.

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