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Wind Turbine Operation & Maintenance based on Condition Monitoring

WT-Ω

Final report

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Acknowledgement

This report is part of the project entitled WT_Ω (WT_OMEGA = *Wind Turbine Operation and Maintenance based on Condition Monitoring*) which has been carried out in co-operation with Lagerwey the WindMaster, Siemens Nederland, and SKF.

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SUMMARY

In 1999, ECN has taken the initiative to investigate the further application of condition monitoring for wind turbines. With financial support from NOVEM, ECN has carried out the project WT-Ω.

The project included three parts, being:
1. A literature study on available condition monitoring techniques, also including a selection of techniques which has added value for wind turbines.
2. Instrumentation of a turbine and demonstration of some of the selected condition monitoring techniques.
3. Identification of new areas for further development such as new sensors, algorithms and system integration.

This document contains a summary of the literature survey and an overview of the work that has been carried out to instrument the Lagerwey LW50/750 and the Enron 1.5S turbines.

The literature study has been carried out and gives insight in the application of condition monitoring techniques and the possibilities, economically as well as technically. The most interesting areas have been identified, taking into account the state of the art of the monitoring techniques.

For the second part of the project, a prototype of the Lagerwey the Windmaster LW 50/750 was selected. Great advantage of this turbine was that instrumentation for load measurements was already available for certification. So for the condition monitoring project only additional measurements with respect to process parameters had to be added. Critical subsystems, where added value of condition monitoring can be expected are the pitch system and the main bearing.

Important disadvantage of this type of turbine is the absence of a gearbox, which is normally considered as a critical component where important costs reduction can be achieved when faults are detected in an early stage. Also the main bearing is not representative for common wind turbine designs.

For a development project on condition monitoring, steady state operation for a long period is necessary in order to be able to recognise trend in characteristic signals. The prototype of the Lagerwey was prone to frequent replacement of components and control software. Because steady state operation could not be assured, the measurement program has been cancelled.

In order to carry out the second phase of the project, another turbine was selected to perform measurements. The ENRON 1,5s turbine, owned by Siemens and located in Zoetermeer, appeared to be suitable for the project because the main objective is electricity production and the design can be considered as representative. The drive train is conventional, including a gearbox, it operates with variable speed and it has three independent electrical pitch systems. Besides that, Siemens was also very interested in the project from the point of view of maintenance for off shore wind application.

Unfortunately, the time delay in the project caused by the non-availability of the Lagerwey turbine, the time needed for instrumentation and consultation for the Lagerwey turbine as well as for the Enron turbine appeared to be so time consuming that the third part could not be carried out. The measurement system for the Enron turbine has been implemented and will be used in a successive project.

Important spin-off of the project is the development of fibre optic measurement technology. This techniques offers large potential with respect to blade condition monitoring and load reduction. A first measurement system has been installed in the DOWEC turbine for load

measurements. Further development should result in off-the-shelf sensors and instrumentation, which can easily be integrated in the wind turbine control system.

From the experience gained during the project it can be concluded that:

- There is a rapid growing interest for condition monitoring for wind turbines.
- Systems, based on vibration analysis, developed for other branches of industry, are available.
- The effectiveness of standard condition monitoring systems for wind turbines is not yet demonstrated and not yet evident.
- Besides the standard condition monitoring techniques, there are also opportunities for more specialised provisions which can be implemented in the wind turbine control system.
- The activities for adaptation and verification of standard monitoring techniques for wind turbines as well as development of specialised functions require will require a long term.
- A measurement facility, which is available for a long period and which is provided with flexible communication provisions is essential for development and improvement of condition monitoring systems.

1. INTRODUCTION

1.1 Background

The operational costs of offshore wind turbines that are presently commercially available, seem too high to make offshore wind projects economically viable. For offshore wind, the costs for O&M (Operation and Maintenance) are estimated in the order of 30 to 35 % of the Costs of Electricity. Rough 25 to 35% is related to preventive maintenance and 65 to 75% to corrective maintenance (note that onshore this ratio is approximately 1:1). The revenue losses for offshore wind turbines are estimated in the same order as the direct costs for repair whereas for onshore projects the revenue losses are negligible [7], [8], [9].

One of the approaches to reduce the cost for corrective maintenance is the application of condition monitoring for early failure detection. If failures can be detected at an early stage, the consequence damage can be less so the repair will be less expensive. Offshore wind turbines however, will benefit the most from the fact that with early failure detection, repairs can be better planned. This will lead to shorter downtimes and less revenue losses.

The application of condition monitoring has grown considerably in the last decade in several branches of industry. The interest from the wind turbine industry and operators is also increasing for the reasons mentioned above. Because of small financial margins in the wind turbine branch, the relatively small production losses, the minor effects on the electricity network (a wind turbine is operating stand-alone), and the easy access, the application remained limited to some experimental projects. Additionally, most components have been designed for the lifetime of the turbine, which implies that degradation leading to replacement, is expected not to occur.

At present, with the increasing installed power of the wind turbines, the application of off shore wind turbines and major problems with gearboxes, the necessity of condition monitoring cannot be neglected any longer. Some components, although designed for the turbine lifetime, fail earlier than expected. This is emphasised by the approach of insurance companies in Germany, which simply require application of monitoring provisions. Otherwise, expensive preventive replacements or inspections should be carried out periodically. Also the development of special purpose instrumentation for wind turbines result in more or less off the shelf systems for a reasonable price.

1.2 Objectives

In 1999, ECN has taken initiatives to further investigate the applicability of condition monitoring for wind turbines. With financial support from NOVEM, ECN has carried out the project WT_Ω (WT_OMEGA = *Wind Turbine Operation and Maintenance based on Condition Monitoring*) from 2000 to 2003. The objectives of the project were threefold:

1. making an inventory of the available condition monitoring techniques and selecting a set which has added value for wind turbines;
2. to instrument a wind turbine and demonstrate some of the selected condition monitoring techniques;
3. identifying areas for further development, e.g. new sensors, algorithms for data analysis ,or integration of the systems in the turbine and wind farm controller.

For **objective 1**, a literature survey has been carried out and reported in [1]. A summary of this study can be found in Chapter 2. It gives insight in the application of condition monitoring techniques and the possibilities, economically as well as technically. A trade off has been performed to identify the most interesting application areas, taking into account the state of the art of the monitoring techniques. Some techniques seem very promising on a long term, which requires a separate development with related risks. Fibre optics measurement technology is such a technique. (Note that the development of fibre optic measurement techniques is outside the scope of this project and will not be discussed further on. Details can be read in [2].) The condition monitoring systems and techniques that seem promising for optimising the maintenance procedures of wind farms have been summarised in Chapter 3.

For **objective 2,** a prototype of the Lagerwey the WindMaster LW 50/750 turbine was selected. The LW 50/750 is a direct drive turbine with a rated power of 750 kW, independent electro-mechanical blade pitch mechanisms, and variable speed. Based on the literature study, a measurement and instrumentation plan were made, with the aim to obtain measurement data for further signal analysis. This turbine was selected because Lagerwey the Windmaster was already a partner in the project, and this turbine was already instrumented for load measurements. Only additional instrumentation had to be added at relatively low costs.

After the turbine was fully instrumented, it appeared that the consequences of applying condition monitoring systems to a prototype were underestimated. The blades were replaced several times during the project, the parameter settings changed regularly and the back-to-back converter was subject of continuous development. For condition monitoring experiments, a stable configuration for a longer period is very important. The start of the measurement campaign was postponed several times, waiting for a configuration that remained unchanged for a period of at least 3 months. Unfortunately, the required stable configuration could not be assured by Lagerwey the Windmaster. After waiting for almost 1 year, but without obtaining valuable measured data, the project team decided to cancel the measurements. The measurement and instrumentation plan and the experiences with the LW 50/750 turbine are described in Chapter 4 and Annex A.

After consultation with Novem, the project team decided to continue with the condition monitoring experiments, however it was realised that within the constraints of the project (mainly limited time and budget) the initial project objectives could not be fully met. First of all, another project partner and another turbine had to be found. Secondly, the new turbine had to be instrumented again, and finally a measurement period of at least 3 to 6 months was necessary. Within the constraints of the project, only the instrumentation of a new turbine was feasible. Finalising the measurements and collecting relevant data was not possible. To make sure that the condition monitoring experiments could be finished satisfactorily, a new project was defined. It was decided to initiate a new European project on condition monitoring for offshore wind farms (CONMOW) [6]. This new project should be regarded as the “successor” of WT_ Ω.

The new project partner was Siemens Nederland N.V.. Siemens has shown their interest in the project for some time, and offered the possibility to use the Enron 1.5S turbine in Zoetermeer for condition monitoring measurements. The Enron 1.5 S turbine is more suited for condition monitoring experiments since it is equipped with a gearbox, and a high speed generator. The Enron turbine is more representative for the first generation offshore turbines than the LW 50/750 turbine. Due to technical and contractual matters among the partners and General Electric (formerly Enron Wind), it took about a year before the instrumentation of this turbine started. By the end of the project, the Enron 1.5 S turbine was instrumented to a large extent and ready for executing the CONMOW project. The instrumentation is very flexible, and incorporates the possibility to install different condition monitoring techniques for development and evaluation. This is described in Chapter 5.

Unfortunately, the **objective 3** could not be met, mainly due to the problems with the LW 15/750 turbine. The remaining time and budget appeared to be too limited to collect and analyse measured data and to draw robust conclusions on how to incorporate condition monitoring in the O&M procedures of an offshore wind farm. However, the positive result is that the project ended with an instrumented turbine with which it is possible to continue the condition monitoring experiments over a longer period of time. This is necessary because trends in characteristic signals will manifest very slowly and that it might take years in stead of months to detect significant changes. So, the CONMOW project, which is the successor of WT_ Ω, has better prospects to meet the original WT_ Ω objectives, The WT_ Ω plan was clearly too ambitious.

2. LITERATURE STUDY (SUMMARY)

A literature study [1] has been carried out which includes a broad overview of available condition monitoring techniques. Next to this inventory of condition monitoring systems, techniques and methods for data processing, the literature study also contains possible application areas within wind energy. This was done for typical sub systems in wind turbines.

The literature study also includes a chapter covering the economical aspects of condition monitoring systems. However data are very limited, depending on the design and also changing rapidly due to development of specific systems.

2.1 Condition Monitoring Techniques

The following techniques, available from different applications, which are possibly applicable for wind turbines, have been identified:

1. Vibration analysis
2. Oil analysis
3. Thermography
4. Physical condition of materials
5. Strain measurement
6. Acoustic measurements
7. Electrical effects
8. Process parameters
9. Visual inspection
10. Performance monitoring
11. Self diagnostic sensors

2.1.1 Vibration Analysis

Vibration analysis is the most known technology applied for condition monitoring, especially for rotating equipment. The type of sensors used depend more or less on the frequency range, relevant for the monitoring:

- Position transducers for the low frequency range
- Velocity sensors in the middle frequency area
- Accelerometers in the high frequency range
- And SEE sensors (Spectral Emitted Energy) for very high frequencies (acoustic vibrations)

Examples can be found for safeguarding of:

1. Shafts
2. Bearings
3. Gearboxes
4. Compressors
5. Motors
6. Turbines (gas and steam)
7. Pumps

For wind turbines this type of monitoring is applicable for monitoring the wheels and bearings of the gearbox, bearings of the generator and the main bearing.

Signal analysis requires specialised knowledge. Suppliers of the system offer mostly complete systems which includes signal analysis and diagnostics. The monitoring itself is also often executed by specialised suppliers who also perform the maintenance of the components. The costs are compensated by reduction of production losses.

Application of vibration monitoring techniques and working methods for wind turbines differ from other applications with respect to:

- The dynamic load characteristics and low rotational speeds
  In other applications, loads and speed are often constant during longer periods, which simplifies the signal analysis. For more dynamic applications, like wind turbines, the experience is very limited.
- The high investment costs in relation to costs of production losses.
  The investments in conditions monitoring equipment is normally covered by reduced production losses. For wind turbines, especially for land applications, the production losses are relatively low. So the investment costs should for a important part be paid back by reduction of maintenance cost and reduced costs of increased damage.

2.1.2 Oil analysis

Oil analysis may have two purposes:

- Safeguarding the oil quality (contamination by parts, moist)
- Safeguarding the components involved (characterisation of parts)

Oil analysis is mostly executed off line, by taking samples. However for safeguarding the oil quality, application of on-line sensors is increasing. Sensors are nowadays available, at an acceptable price level for part counting and moist. Besides this, safeguarding the state of the oil filter (pressure loss over the filter) is mostly applied nowadays for hydraulic as well as for lubrication oil.

Characterisation of parts is often only performed in case of abnormalities. In case of excessive filter pollution, oil contamination or change in component characteristic, characterisation of parts can give an indication of components with excessive wear.

2.1.3 Thermography

Thermograhy is often applied for monitoring and failure identification of electronic and electric components. Hot spots, due to degeneration of components or bad contact can be identified in a simple and fast manner. The technique is only applied for of line usage and interpretation of the results is always visual. At this moment the technique is not interesting for on line condition monitoring. However cameras and diagnostic software are entering the market which are suitable for on-line process monitoring. On the longer term, this might be interesting for the generator and power electronics.

2.1.4 Physical condition of materials

This type of monitoring is mainly focussed on crack detection and growth. Methods are normally off line and not suitable for on line condition monitoring of wind turbines. Exception might be the usage of optical fuses in the blades and acoustic monitoring of structures.

2.1.5 Strain measurement

Strain measurement by strain gauges is a common technique, however not often applied for condition monitoring. Strain gauges are not robust on a long term. Especially for wind turbines, strain measurement can be very useful for life time prediction and safeguarding of the stress level, especially for the blades. More robust sensors might open an interesting application area. Optical fibre sensors are promising, however still too expensive and not yet state-of-the-art. Availability of cost effective systems, based on fibre optics can be expected within some years. Strain measurement as condition monitoring input will than be of growing importance.

2.1.6 Acoustic monitoring

Acoustic monitoring has a strong relationship with vibration monitoring. However there is also a principle difference. While vibration sensors are rigid mounted on the component involved, and register the local motion, the acoustic sensors "listen" to the component. They are attached to the component by flexible glue with low attenuation. These sensors are successfully applied for monitoring bearing and gearboxes.

There are two types of acoustic monitoring. One method is the passive type, where the excitation is performed by the component itself. In the second type, the excitation is externally applied.

2.1.7 Electrical effects

For monitoring electrical machines MCSA (Machine Current Analysis) is used to detect unusual phenomena. For accumulators the impedance can be measured to establish the condition and capacity.

For medium and high voltage grids, a number of techniques are available:

- Discharge measurements
- Velocity measurements for switches
- Contact force measurements for switches
- Oil analysis for transformers

For cabling isolation faults can be detected. These types of inspection measurements do not directly influence the operation of the wind turbines.

2.1.8 Process parameters

For wind turbines, safeguarding based on process parameters is of course common practice. The control systems become more sophisticated and the diagnostic capabilities improve. However safeguarding is still largely based on level detection or comparison of signals, which directly result in an alarm when the signals become beyond predefined limit values. At present, more intelligent usage of the signals based on parameter estimation and trending is not common practice in wind turbines.

2.1.9 Performance monitoring

The performance of the wind turbine is often used implicitly in a primitive form. For safeguarding purposes, the relationship between power, wind velocity, rotor speed and blade angle can be used and in case of large deviations, an alarm is generated. The detection margins are large in order to prevent for false alarms. Similar to estimation of process parameter, more sophisticated methods, including trending, are not often used.

2.2 Possibilities of application in wind turbines

In the previous chapter, the available techniques have been identified. The next step is to establish the applicability and desirability for wind turbines. The decision w.r.t. investments for condition monitoring provisions is based on the economical factors. The rate of return of the provisions is determined by the investment costs, the relevant failure characteristics, the cost savings of maintenance and damage and the reduction of production loss. For off shore wind application, the cost savings due to reduction of corrective maintenance will be the most important factor. When extra visit can be avoided or postponed to a regular visit, or when more damage can be prevented, considerable amounts of money can be saved.

2.2.1 Rotor

Blades

Strain monitoring can be used for life time prediction. Methods are not yet "well developed" but there certainly is interest and potential for condition monitoring based on strain measurement. The measurement techniques and the necessary rotating interfaces, which push up the investments, are reasons that this type of monitoring is not often used. Techniques based on optical fibres are in development and will be suitable for commercial application within some years. Several parties work on this subject (Smart Fibres, FOS, Risoe, ECN, and some manufacturers.).

Vibration monitoring and acoustic emission are also interesting for condition monitoring of the blades. Acoustic emission can be used to detect failures in the blade.

2.2.1.2 Pitch mechanism

Large turbines often have independent pitch control. Safeguarding is often realised by current measurement / time measurement and pitch angle differences. Trend analysis based on parameter estimation is not applied up to now, but might be an interesting possibility for condition monitoring.

2.2.2 Nacelle

Gearbox and main bearing

Gearboxes are widely applied components in many branches of industry. Condition monitoring is more or less common practice. Despite all design effort, wind turbines often had en still have problems with gearboxes. So condition monitoring is of growing interest, because the costs of replacement are very high.

Condition monitoring techniques for gearboxes are:
1. Vibration analysis based on different sensors
2. Acoustic emission
3. Oil analysis

For vibration analysis, different types of sensors can be used. Most commonly used are acceleration sensors. Also displacement sensors can be used, which might be of interest for bearing operating at a low speed (main bearing).

Acoustic emission is another technique, based on higher frequencies. For vibration analysis the frequencies related to the rotational speeds of the components are of interest. For acoustic emission higher frequencies are considered, which give an indication of starting defects. The effects normally attenuate after short period.

Oil analysis is especially of interest when defects are identified, based on one of the previous techniques and is of use for further diagnostics. Based on characterisation of parts and component data, diagnosis can be approved. This simplifies the repair action.

Lubrication of oil itself can also be a source for increasing wear. There exist a strong relationship between the size and amount of parts and the component life time. Also moist has a strong reducing effect on the lubrication properties. Safeguarding of the filters and on line part counting and moist detection can help to keep the oil in an optimal condition. Costs resulting from oil replacement as well as from wear of the components can be reduced by an optimal oil management.

2.2.2.2 Generator

The generator bearing can also be monitored by vibration analysis techniques, similar to the gearbox. Apart from this, the condition of the rotor and stator windings can also be monitored by the temperatures. Due to the changing loads, trend analysis based on parameter estimation techniques will be necessary for early detection of failures.

2.2.2.3 Hydraulic system

The hydraulic system for pitch adjustment is the most critical. However this is not relevant for the GE-turbines (electrical pitch adjustment). Condition monitoring of hydraulic systems is very similar to other applications because intermittent usage is common practice.

2.2.2.4 Yaw system

Although the yaw system is rather failure prone, condition monitoring is difficult because of the intermittent usage. The system is only operating during a longer period during start-up and re-twisting. However the operational conditions during these actions are certainly not representative. The loads are relatively low, because the turbine is not in operation in this situation. Apart from this, the lubrication conditions are not constant.

2.3 Economical Aspects

Because financial margins are very small for wind turbines, economic aspects play a very important role. The installed power per wind turbine is relatively small. Wind turbines are available in the order of 1 MW, while other power generation units are in the range of 10 up to several hundreds of MW's. So the production loss due to failures are very small for wind turbines, compared with other units. On the other side, due to the low installed power per wind turbine, the investment level for condition monitoring system is relatively high. So from economical point of view, the margins for investments are very small for on shore application.

For offshore application, the situation is quite different. Due to the restricted accessibility of wind turbines for maintenance, the waiting and repair periods, following a failure will be considerably longer, which implies increasing production losses and repair costs. Together with decreasing prices of condition monitoring systems, the economical break even will decrease significantly.

A condition monitoring systems, based on vibration analysis is in the range of €10000 to €15000. Although the robustness with respect to failure detection/forecasting is certainly not yet demonstrated, the level of investment makes application feasible.

On line oil analysis is still very expensive. However these kind of sensors are relatively new, which implies that reduction of prices is likely over the coming years. Similar to vibration monitoring oil analysis is also focussed on one of the most critical wind turbine components, being the gearbox.

Apart from the condition monitoring systems, based on vibration analysis and existing applications, there are also techniques which can specially developed for wind turbines. One of the techniques, based on general (available) measurement signal, require specific algorithm development and verification. However, it is expected that these kind of algorithms can be implemented in the control system of the turbine, which implies that no extra hardware investment is involved.

Condition monitoring of the blades is rather new, and very expensive at this moment. The measurement techniques are based on optical fibres. The sensors are very expensive, however large series and automation of the production process can cause a dramatic decrease of production costs. Also at the side of the instrumentation, developments are necessary with respect to cost reduction and improvement of robustness. Developments are still necessary for algorithms as well as for the instrumentation and sensors.

2.4 Conclusions

Before condition monitoring can be applied successfully for wind energy, at least the following items should be solved

Improvement of safeguarding functions
Wind turbine control systems incorporate an increasing functionality. Some of the functions come very close to Condition monitoring. With relatively low costs, some more intelligence can be added, which makes early fault detection based on trend analysis possible. (Pitch mechanism, brake, yaw system, generator).

Development of global techniques
Apart from safeguarding, trending of wind turbine main parameters (power, pitch angle, rotational speed, wind velocity, yaw angle) can give global insight in the operation in the turbine. It may be possible to detect that "something might be wrong". Dirt on the blades has a strong reducing effect on the power production, which can also be detected by trend analysis.

Adaptation of existing systems
In other industries, condition monitoring provisions are normally separate systems, apart from the machine control and safe guarding functions. The monitoring is often focussed on a very limited number of aspects. For wind turbines however, the system to be monitored is rather complex and the margins for investments are small. The number of systems is very high. So when existing systems are used, the adaptation should not only be focussed on the dynamic load behaviour, but also on streamlining the system and integration.

Information mapping
Offshore wind turbines normally operate in a park, which is remote controlled from a central control room. Because a great number of turbines is controlled from the central facility,

information should be processed and filtered before being reported to the operator and maintenance planning.

When applying condition monitoring techniques in wind turbines, the following two pitfalls should be considered.

Application of existing techniques
Only adaptation of existing systems is often not sufficient to make them suitable for wind turbines. Although the systems will "function" of course, the effectiveness can only be determined on the long term.

Robustness of secondary systems
Manufacturers often have an aversion to a large amount of sensors. Failure of condition monitoring functions may never result in turbine stop. Operational decisions are made by the control system or by the operator.

From the literature study, the following overall developments in condition monitoring have been recognised.

Oil filtering and monitoring
There is an increasing interest for oil filtering and diagnosis. There is no doubt about the importance of adequate filtering and the price of sensors is decreasing. Troubles with gearboxes and pressure from the side of insurance companies have enlarging effects.

Blade monitoring
There is an increasing interest in blade monitoring. However, blade instrumentation is still very expensive. However there are several developments going on at this moment, in which developers in instrumentation as well as wind turbine manufacturers and blade manufacturers are involved.

Standardisation of interfaces / control system versus CM-instrumentation
Condition monitoring is a specialism, which requires knowledge and experience. Signal processing and interpretation are often outsourced by firms, who are also involved in the maintenance. These firms need access to the systems involved. Standardisation in the field of communication and interfacing is of increasing importance in order to accommodate these systems.

3. SELECTED SUB-SYSTEMS, COMPONENTS AND CM-TECHNIQUES

3.1 Global condition monitoring techniques

Apart from the applied condition monitoring techniques on sub system level (gearbox, pitch mechanism, e.s.o.) there is already a lot of information available in the wind turbine. Normally this information is only used at the level of safeguarding. Exceeding of the alarm levels often simply results in a wind turbine shut down and waiting for remote restart or repair. By application of more advanced methods of signal analysis, focussed on trends of representative signals or combination of signals, significant changes in turbine behaviour can be detected at an early stage. Because the approach is based on general turbine parameters, the information will also be of a global nature, so specific diagnostics cannot be expected.

Application of this approach does not require additional investments in hardware. Only development costs are involved. Although it cannot be expected, that the results will be very specific, information which give an indication that something might be wrong can already be very valuable. In literature, some references have been found however, concrete results are not available. This means that long term development will be necessary.

In this chapter, also the application of “model based condition monitoring” will be discussed. Model based condition monitoring is suitable for non-stationary operation. It will be explained later on.

3.2 Pitch mechanism

The pitch mechanism is one of the most vulnerable systems in a wind turbine. Following the development of larger wind turbines, the importance of the pitch mechanism will increase because:

1. The pitch mechanism is part of the safety system for large wind turbines
2. Pitch adjustment is of increasing importance for power control and load reduction provisions

Nowadays condition monitoring of this system is restricted to the individual performance of the servo motors themselves at the level of detection of maximum current. However model based condition monitoring of all three servo-systems is a promising possibility in this situation. Model based condition monitoring is suitable for non-stationary operation. The process I/O signals are used for diagnosis of the system, see Fig. 3.1.

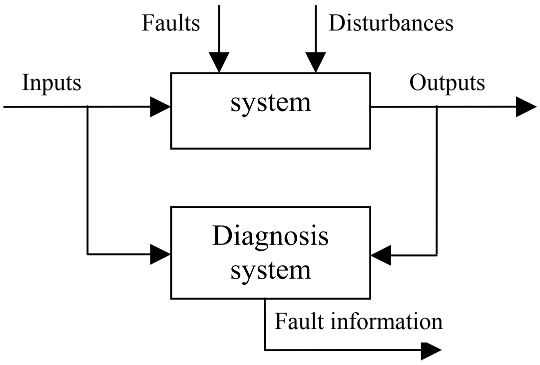


Fig 3.1: *Principle of model based fault detection*

The diagnosis can be based on the residual of the process and estimator output signals (see Fig. 3.2). In this situation, a constant model is used. The difference between the output of the system and the output of the model can be monitoring. Trend analysis of this residu can be used to detect changing characteristics of the system.

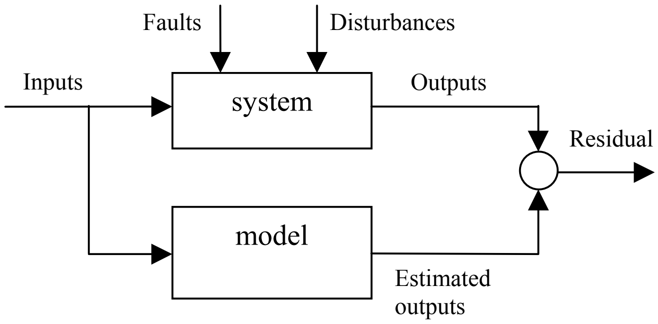


Fig. 3.2: *Fault estimation based in residual*

Another possibility of model based fault detection is continuous estimation of the model parameters, based on the measured I/O values and to monitor the trends in the paramaters (see figure 3.3). The performance strongly depends on the accuracy of the estimation procedure. The number of I/O signals and the measurement accuracy of these signals are of importance to be able to detect changes in trends in an early stage.

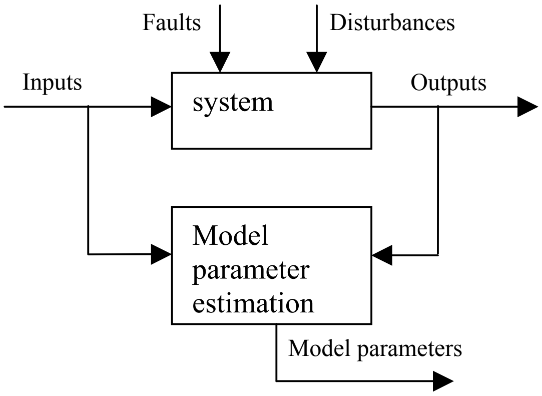
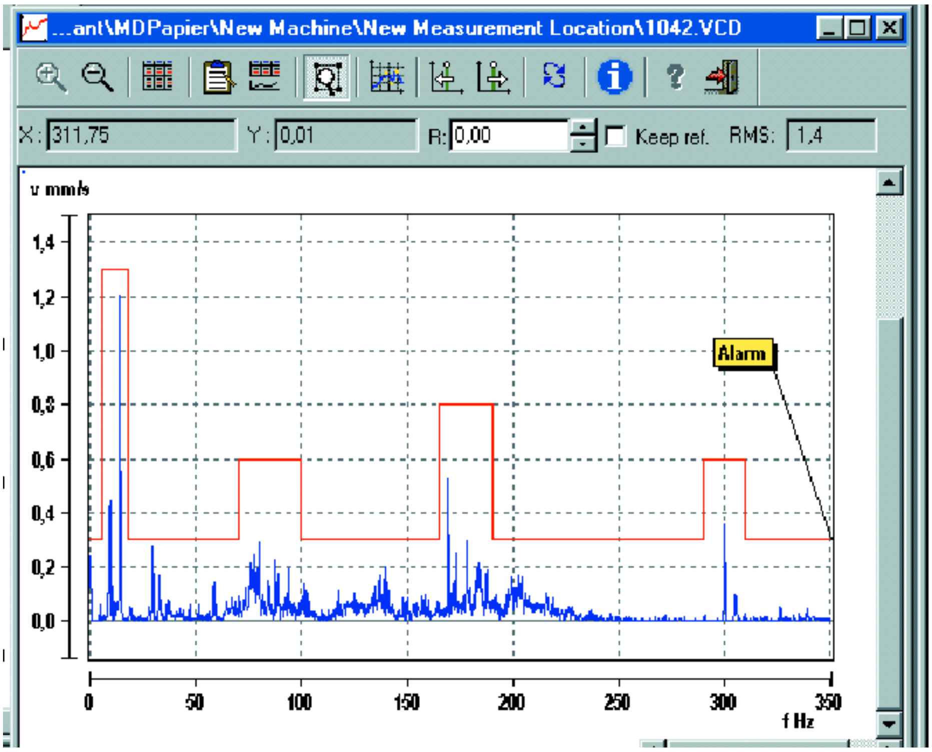


Fig. 3.3: *Fault estimation based on model parameters*

Because the application of this technique is very specific for this application, the algorithms should be developed. This requires specific knowledge of the system, the control and model development. On the other side the application of the technique in a real wind turbine does not or hardly require addition hardware and sensors.

3.3 Gear box

The importance of monitoring the condition of the gearbox is obvious by now. Because there already exists a lot of experience in this field. Also for wind energy, specialised companies supply special systems adapted for wind turbines (SKF, Pruftechnik, Gramm&Juhl, Schenck).


...ant\MDPapier\New Machine\New Measurement Location\1042.VCD

X: 311,75 Y: 0,01 R: 0,00 ☐ Keep ref. RMS: 1,4

Fig. 3.4: *Example of fault detection based on FFT (source: Prueftechnik)*

The fault detection is often based on frequency analysis and level detection for certain frequency bands. Based on the level of amplitudes, status signals can often be defined and generated. Diagnosis is often done by the supplier of the system or of the gearbox, because specialised knowledge is required for signal interpretation.

The effectiveness of these systems is yet not evident. Due to the non-stationary operation, it appears to be difficult to develop effective algorithms for early fault detection, especially for variable speed operation. Practical experience builds up very slowly, because component degeneration is fortunately a slow process, and additional information about turbine loads and operational conditions are only fragmentarily available.

3.4 Main bearing

The situation with the main bearing is identical to the gearbox. Along with condition monitoring of the gearbox, most of the systems also monitor the main bearing and the generator bearings.

3.5 Sound registration

During the project, it was decided to cancel the condition monitoring based of sound/noise. From the manufacturer point of view it appeared difficult to define a development target for this item. In practical situation, maintenance personnel can often well observe what is wrong. This is based on long experience, and it will be very difficult to extract this information from noise signals. Furthermore, the sound is heavily disturbed by the background and also strongly dependent on the operational conditions of the turbine.

3.6 Blade monitoring

There are already some practical examples of blade monitoring. LM for instance has a system available, which operates completely, stand-alone and which is focussed on detectiing excessive vibration levels and sending messages to the company. The system uses acceleration sensors. The system has mainly been used for prototyping but was intended to be widely applied for stall regulated turbines in the 600 kW range.

NGUp has a sensor available, which was developed by blade manufacturer Aerpac. This sensor is based on a proportional proximity sensor, in combination with a bar mechanism. This system was developed for the same purpose as the LM sensor.

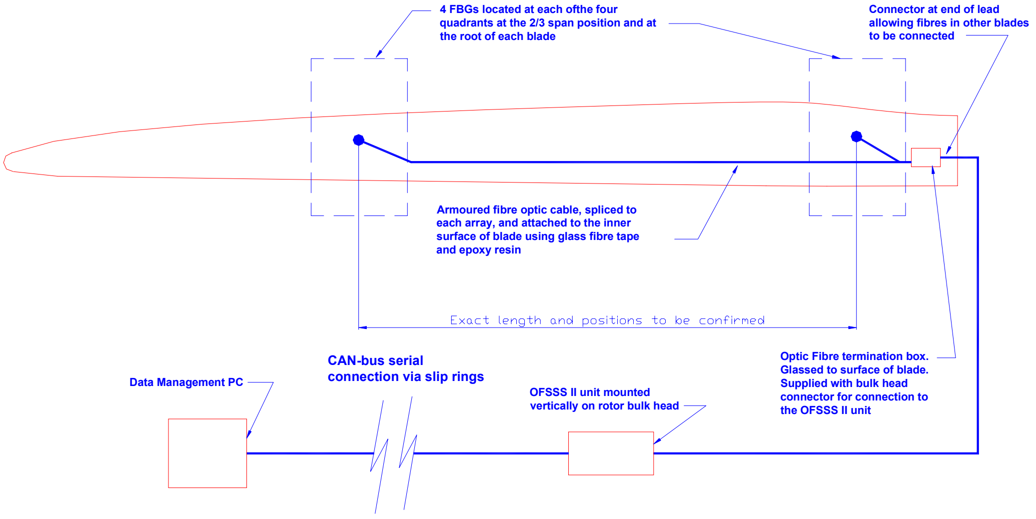


Fig. 3.5: *Principle of fibre optic blade monitoring*

Although the LM system as well as the Aerpac sensor already have a track record, application of fibre optic measurement techniques are foreseen as the most promising.

4. INSTRUMENTATION OF THE LAGERWEY 50/750

Initially, the prototype of the Lagerwey 50/750 (see Fig. 4.1)was chosen for the execution of the measurement programme. Important advantage of this turbine at that time was the fact that this turbine was already instrumented to carry out load measurements.. At the beginning of the project, the turbine was a prototype and it was expected that after one year of operation, the configuration should remain stable, and that the turbine should stay in operation as a production turbine. Initially, the fact that the turbine was a prototype, only seemed to have advantages. There was a close collaboration with the manufacturer, which makes the instrumentation easier, the design data was accessible, and the turbine could be adjusted very easily without too many consequences for the revenue losses.

Fig. 4.1: *Lagerwey LW 50/750 turbine*

An important disadvantage of the choice of this turbine design with respect to a general condition monitoring project was the specific design. For condition monitoring the gearbox is probably the most vulnerable component, while the Lagerwey turbine is a direct drive machine. Also the main bearing is specific for this design. So for this turbine the condition monitoring aspect were mainly focussed on the pitch mechanism, the main bearing and general detection mechanisms. The disadvantages were recognised in the beginning of the project but they seemed minor as compared to the advantages mentioned above.

The main bearing is a critical component for this design. This bearing is not a normal roller bearing, but a 4 point ring bearing with a large diameter. Rothe Erde, the supplier of the bearing has also delivered a vibration sensor which was also incorporated in the measurement system. Besides the vibration, also the bearing temperature was monitored.

For the execution of the measurement program, a measurement and instrumentation plan [5] has been prepared. This plan includes long term stationary measurement without faulty conditions in order to define the reference values for all normal conditions (wind speed, wind direction, start-up and stop procedures, etc.). Besides the stationary measurements, the plan also included measurements under faulty conditions (e.g. oblique inflow, pitch errors, etc.). It was expected that within one year measurements, significant degradation of main components would not occur. Therefore, the measurement campaign intended to focus on the assessment of the various condition monitoring techniques and the data collection and analysis. A summary of the instrumentation plan is given in Annex A.

The condition monitoring systems were installed in the turbine and the entire measurement system was functioning by the end of 2000. The measurement program should start as soon as the configuration was stable. This situation was expected in the beginning of 2001 but at that time, Lagerwey announced that the blades would be changed very soon, probably in May 2001. In January 2002, Lagerwey was still carrying out major changes to the turbine (blades and frequency converter) and Lagerwey could not guarantee that the configuration would remain unchanged for a period of 3 months.

Although some data was collected in 2001, it was insufficient to draw robust conclusions. In the beginning of 2002, it was decided to stop the measurement campaign and to continue the project with another partner and another turbine. The fact that the turbine was a prototype seemed advantages in the beginning of the project but in the end it turned out that this was the main cause for not successfully finalising the project.

At that time it was realised that within the constraints of the project (mainly limited time and budget) the initial project objectives could not be fully met. First of all, another project partner and another turbine had to be found. Secondly, the new turbine had to be instrumented again, and finally a measurement period of at least 3 to 6 months was necessary. Within the constraints of the project, only the instrumentation of a new turbine was feasible. Finalising the measurements and collecting relevant data was not possible. The new partner with which the project could be continued was Siemens Nederland N.V.. Siemens has shown their interest in the project for some time, and offered the possibility to use the Enron 1.5S turbine in Zoetermeer for condition monitoring measurements. (see Chapter 5).

5. INSTRUMENTATION OF THE ENRON 1,5 S

A second possibility for execution of measurements was the ENRON 1.5S-turbine of Siemens in Zoetermeer, see Fig. 5.1. This turbine has representative features for large wind turbines for offshore applications:

1. Conventional drive train with gearbox and main bearing
2. Individual electrical pitch mechanism
3. Double fed asynchronuous generator
4. Variable speed operation
5. Operation focussed on production

Fig. 5.1: *Enron 1.5s turbine of Siemens in Zoetermeer*

However, with respect to the experiments that had to be carried out in the WT_Ω project, the choice of the turbine had some disadvantages:

1. Design information of the turbine was not available for the project team
2. the turbine manufacturer was indirectly involved which slowed down the instrumentation process.
3. Load measurements were not available, so the load measurements had to be applied again.

From the beginning on, Siemens had the intention to support the project. However, the efforts before the actual instrumentation started took more time than originally planned, mainly due to contractual matters, insurance and arrangements with respect to liability.

It was evident to involve this specialised company in the project. SKF was interested in participating in the project with a condition monitoring system (WindCon), especially designed for wind turbines. The latter partner was invited because of the presence of a gearbox and the conventional main bearing.

At the end of 2002, all instrumentation was available and tested at ECN and brought over to Zoetermeer. The instrumentation of the rotor sensors has been carried out, the interface with the wind turbine control system has been installed, as well as the connection between the trafo station and the tower base. The schematics of the instrumentation plan are given in Fig. 5.2.

At the time the data acquisition system was about to be installed, the successor of the WT_Ω project CONMOW *(Condition Monitoring for Offshore Wind Turbines)* was approved by both the EU and Novem. It was decided to postpone the installation of the measurement system since new parties were involved and the measurement system had to meet other specifications. The schematics of the CONMOW measurement system are given in Fig. 5.3. The major difference between the two measurement systems is that the CONMOW version is more open for all parties to exchange data through the Internet. This has a strong preference for experiments on the longer term.

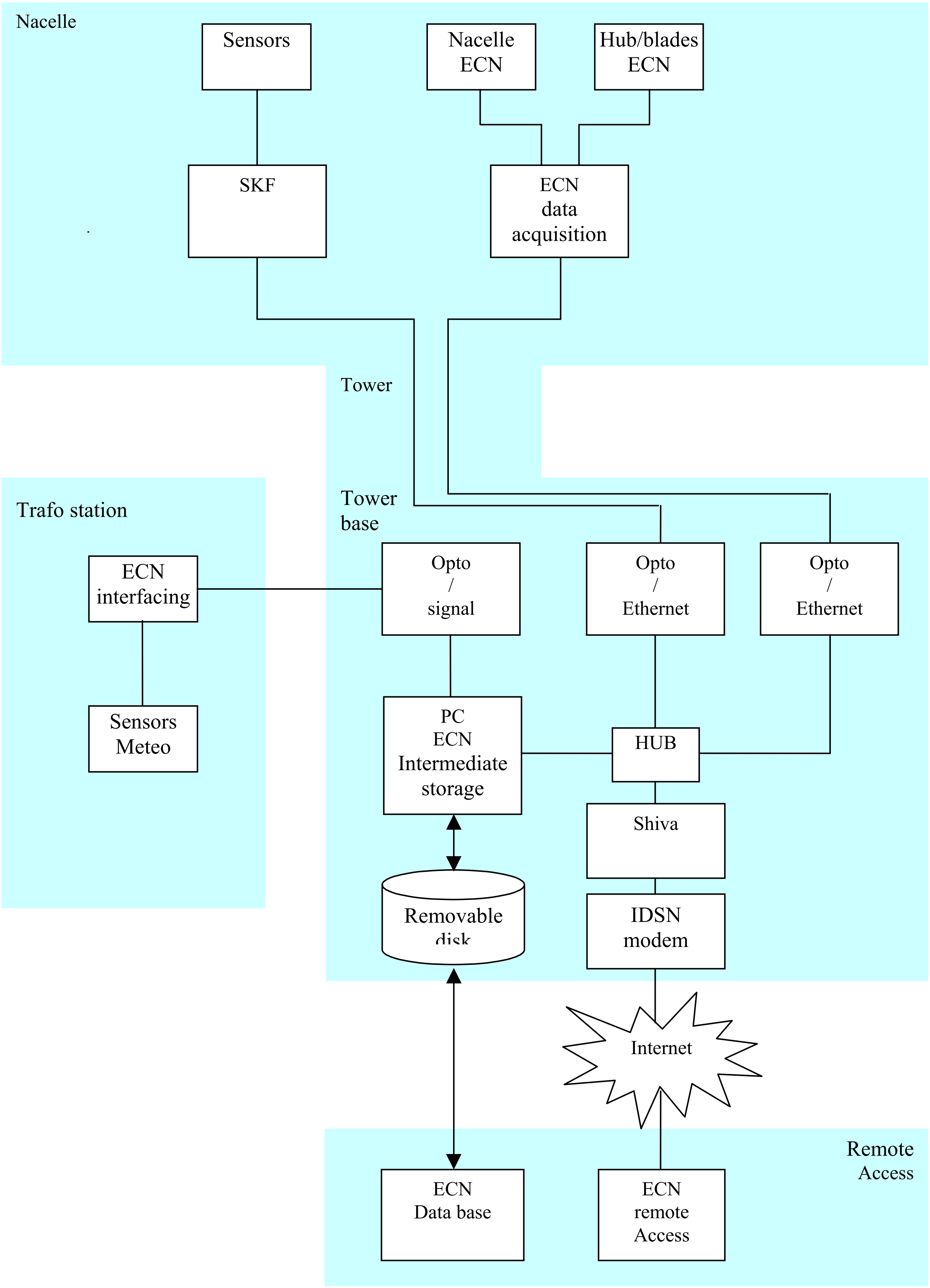


Fig. 5.2: *Outline of the measurement system for the WT_Ω project*

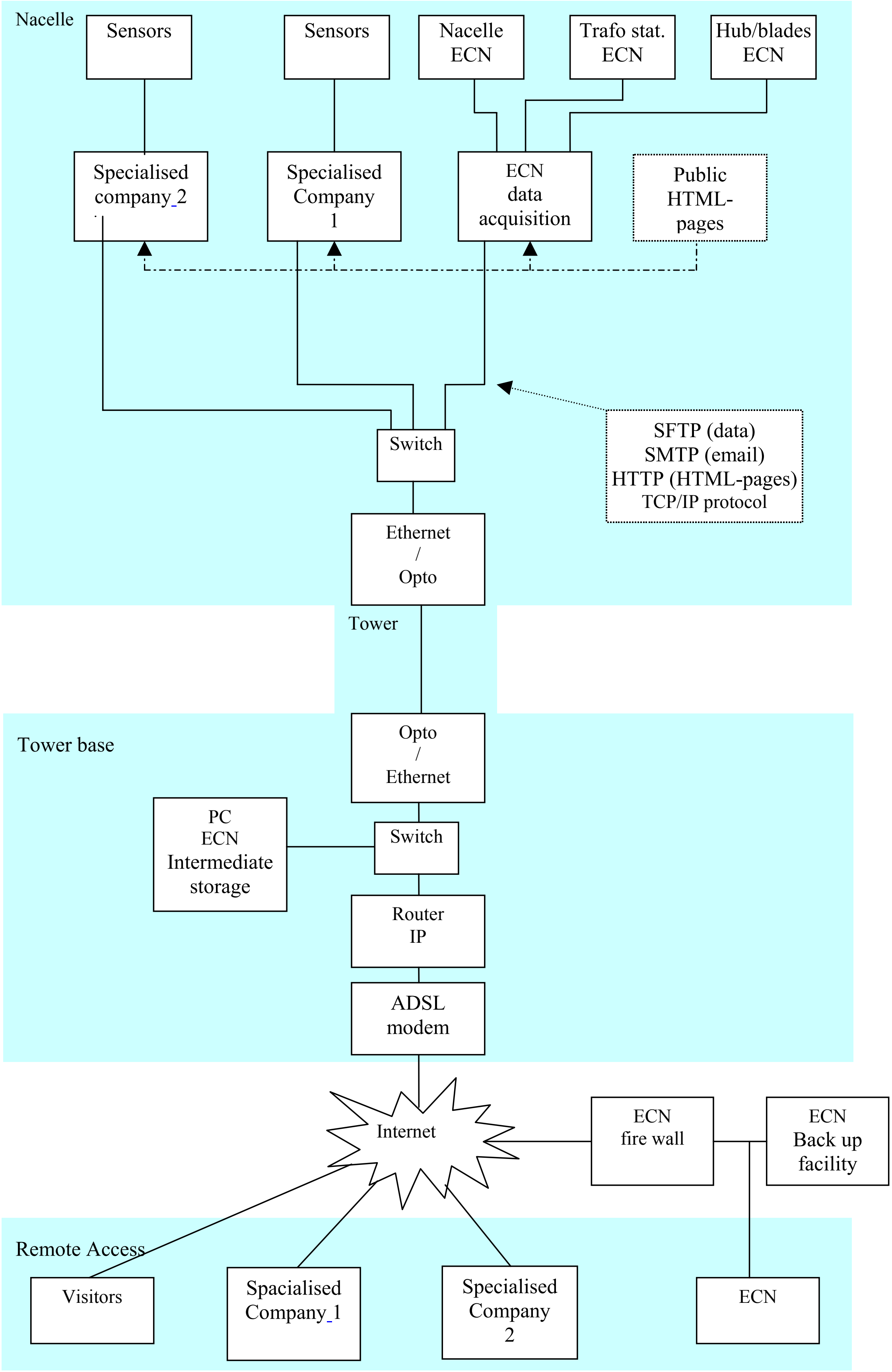


Fig. 5.3: *Outline of the measurement system for the CONMOW project*

6. CONCLUSIONS

ECN has carried out the project WT_Ω (WT_OMEGA = *Wind Turbine Operation and Maintenance based on Condition Monitoring*) from 2000 to 2003 with financial support from NOVEM. The objectives of the project were threefold:

1. making an inventory of the available condition monitoring techniques and selecting a set which has added value for wind turbines;
2. to instrument a wind turbine and demonstrate some of the selected condition monitoring techniques;
3. identifying areas for further development, e.g. new sensors, algorithms for data analysis ,or integration of the systems in the turbine and wind farm controller.

The first objective has resulted in a literature study, published in [1]. The second objective resulted in two instrumented turbines, the LW 15/750 and the Enron 1.5s turbine of Siemens in Zoetermeer. Unfortunately, both turbines did not run under stable conditions for a longer period of time during the project, so a relevant set of measured data to draw conclusions from is missing. The final third objective could thus not be met.

The positive result however is that the project ended with an instrumented turbine with which it is possible to continue the condition monitoring experiments over a longer period of time. This is necessary because trends in characteristic signals will manifest very slowly and that it might take years in stead of months to detect significant changes. So, the CONMOW project (*Condition Monitoring of Offshore Wind Turbines*), which is the successor of WT_ Ω, has better prospects to meet the original WT_ Ω objectives, The WT_ Ω plan was clearly too ambitious.

From the experiences gained up to now, the following conclusions were drawn.

- There is a growing interest in the application of condition monitoring techniques for wind turbines. The reasons for this increasing interest are:
    1. The increasing installed power per wind turbine and the related higher investments
    2. High costs for corrective maintenance at a too early stage, and need for reducing them
    3. Future off-shore applications with limited access for corrective maintenance
    4. Requirements from insurance companies in Germany to regularly replace and repair drive train parts.
    5. Growing interest of specialised companies which supply condition monitoring systems
- Some issues may hamper the introduction of condition monitoring in wind energy. However, there are still some important points which limits the success on a longer term:
    1. Effectiveness of condition monitoring systems is difficult to demonstrate due to the long measurement periods that are required.
    2. Further development of algorithms for early failure prediction requires long time periods and additional measurement data.
    3. Interpretation of results still requires specialised knowledge.
- The number of available systems based on vibration analysis, developed for other branches of industry and adapted for wind turbines, is increasing and available for reasonable prices.
- The ability of failure forecasting of the available system is not yet evident. Algorithms should be adapted and verified for non-stationary application in wind turbines.
- Specialised involvement will be of growing importance with respect to condition monitoring for the bearings, gearboxes and generator bearings. Condition monitoring functions are embedded in special hardware, integrated in the system top be monitored and

separated from the wind turbine control system. The supplier of the monitored system will often also perform interpretation of signals.

- General condition monitoring techniques, which can be interpreted as extension and refinement of current safeguarding techniques should be developed for this application based on known algorithms and methods, like model reference methods.
- General condition monitoring techniques can be integrated in the wind turbine control system, which means that only development costs are involved, however often customised for each wind turbine type.
- Development and verification of condition monitoring techniques requires long term measurements in a production environment. Normally such a facility is not available. The wind turbine in Zoetermeer gives the opportunity to create an environment facilitating this development. The instrumentation scheme, as implemented for WT-Ohm has been modified for the CONMOW project It has been extended and based on Internet technology in order to be able to incorporate the equipment (and knwoledge) of more specialised companies, and to realise automated interchange and transport of data.

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APPENDIX A: MEASUREMENT AND INSTRUMENTATION PLAN OF THE LAGERWEY 50/750

The measurement plan of the Lagerwey 50/750 was focussed on the following main items:

1. Measuring the performace of the pitch system
2. General measurements of the wind turbine
3. Measurements on the main bearing

ad 1: Measuring the performance of the pitch system.

The blade angles are normally adjusted by individual servo motors. Each blade has an independent control loop, based on position control. The systems have a common position set point signal. Power is supplied via a slip ring set. The servo motors are directly coupled with a reduction box.

For emergency situations, the blades are moved to the vane position by DC-motors directly connected with accumulators. The DC-motors are coupled with the same reduction box as the servo-motors via an electromechanical coupling.

In order to monitor the performance of the pitch system, the following signals are measured:

1 Pitch angle (3)

2 Current to servomotor (3)

3 Pitch angle velocity (3)

4 Pitch angle set point (1)

5 Servo speed set point (3)

6 Temperature reduction box (3)

7 Temperature servo motor (3)

8 Status signal servo brake

9 Status emergency

10 Accumulator current

ad 2: General measurements of the turbine

The general measurements are used to support signal analysis for the pitch system as well as for the main bearing, together with results from load measurements. On the other side, this measurments can be used stand alone in order to monitor the wind turbine performance in general terms. The signals to be measured are:

1 Rotor speed

2 Azimuth angle

3 Electrical power

4 Wind speed met mast

5 Wind speed wind turbine

6 Wind direction met mast

7 Yaw misalignment

8 Air temperature

9 Air pressure

10 Rain detection

ad 3: Measurements on the main bearing

From the main bearing, the following signals will be measured:

1 Bearing temperature

2 Vibration

In figure A1 an overview of all measurements (excluding the load measurements) is given.

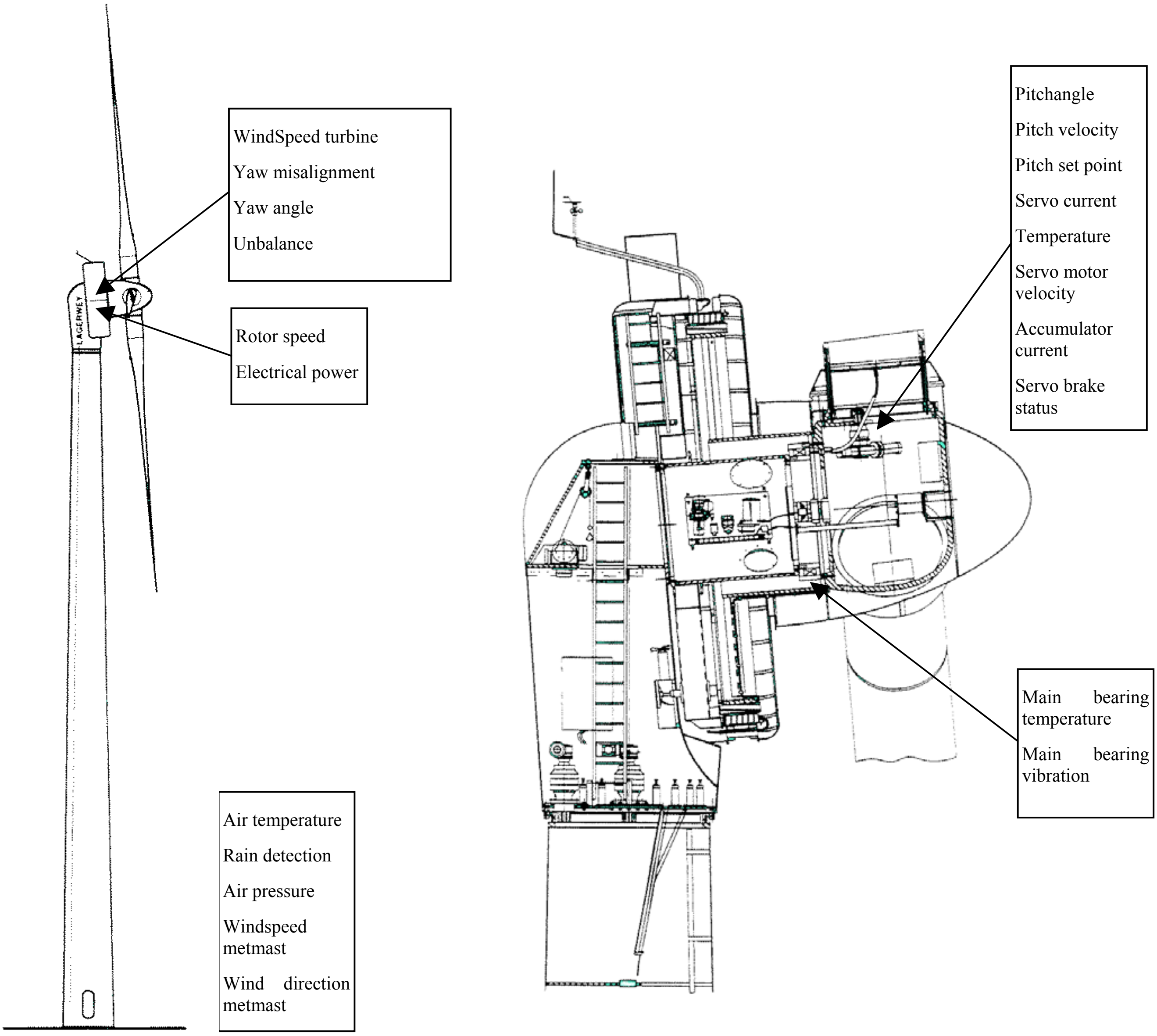

Figure A1: Instrumentation scheme of the Lagerwey 50/750

All measurements will be executed continuously in 10-minute periods. Data storage will be done following a capture matrix based on statistical values (mean and standard deviation of the wind speed).

Additional to the continous measurments during normal turbine operation, special measurment campaigns are foreseen. These campaigns are focussed on simulated faults in the pitchsystem.

APPENDIX B: MEASUREMENT AND INSTRUMENTATION PLAN OF THE ENRON 1,5S TURBINE

The measurement programme for the Siemens Enron turbine is focussed on the following items:

1. Measurement of pitch system variables
2. Measurements of main bearing parameters
3. Measurement of gearbox and generator parameters
4. General wind turbine parameters.

ad 1: Measurement of pitch system variables

The ENRON turbine also has independent pitch control for all three blades. It is equipped with DC-servo-motors, which are used for normal as well as for emergency pitch adjustment. Because the ENRON-turbine is a production turbine, the control signals are not all measurable. The following signals are available after additional provisions from GE-side:

1 Pitch angle (3)

2 Desired pitch angle (1)

3 Temperature reduction box / servo motor (3)

4 Motor current (3)

ad 2: Measurements of main bearing parameters

The measurement signals of the main bearing are used by SKF and used for their own system. The following signals are used:

1 Acceleration main bearing (transversal)

2 Acceleration main bearing (radial)

3 Main bearing temperature

ad 3: Measurement of gearbox and generator parameters

The measurement signals for the gearbox and generator are also used by SKF for their own system. These signals are:

1 Acceleration gearbox (transversal)

2 Acceleration gearbox (radial)

3 Acceleration generator (radial)

ad 4: General wind turbine parameters

The general wind turbine parameters are used for signals analysis of condition monitoring techniques on subsystem level (pitch system, main bearing, gearbox and generator) as well as for safeguarding on a general level. Additional to the common process parameters, also the main shaft torque as well as the load on the blades will be measured:

1 Wind speed
2 Rotor speed
3 Azimuth angle
4 Electrical power
5 Unbalance
6 Yaw angle
7 Yaw misalignment
8 Main shaft torque
9 Lead lag moment blade root
10 Flap moment blade root
11 Air temperature
12 Air pressure
13 Rain detection

All measurements will be executed continuously in 10 minute periods and stored on a removable hard disk in the tower base PC. It was decided not to use a capture matrix because of several reasons. For this turbine no measurement mast was available. For the wind speed measurements the anemometer on the nacelle was used so that the measurements are disrupted by blade passage. For a capture matrix, the wind speed and variance are normally used for classification. On the other hand, the storage capacity on a removable hard disk was large enough to store data for about a month, so from this point of view there was not really a need for using a capture matrix.

Additional to the continuous measurements, short campaigns with simulated faults were also foreseen. For the pitch system faults can be introduced without the risk for permanent turbine damage. For the main bearing, gearbox and generator it is much more difficult to simulate faulty situations without risk for permanent damage.

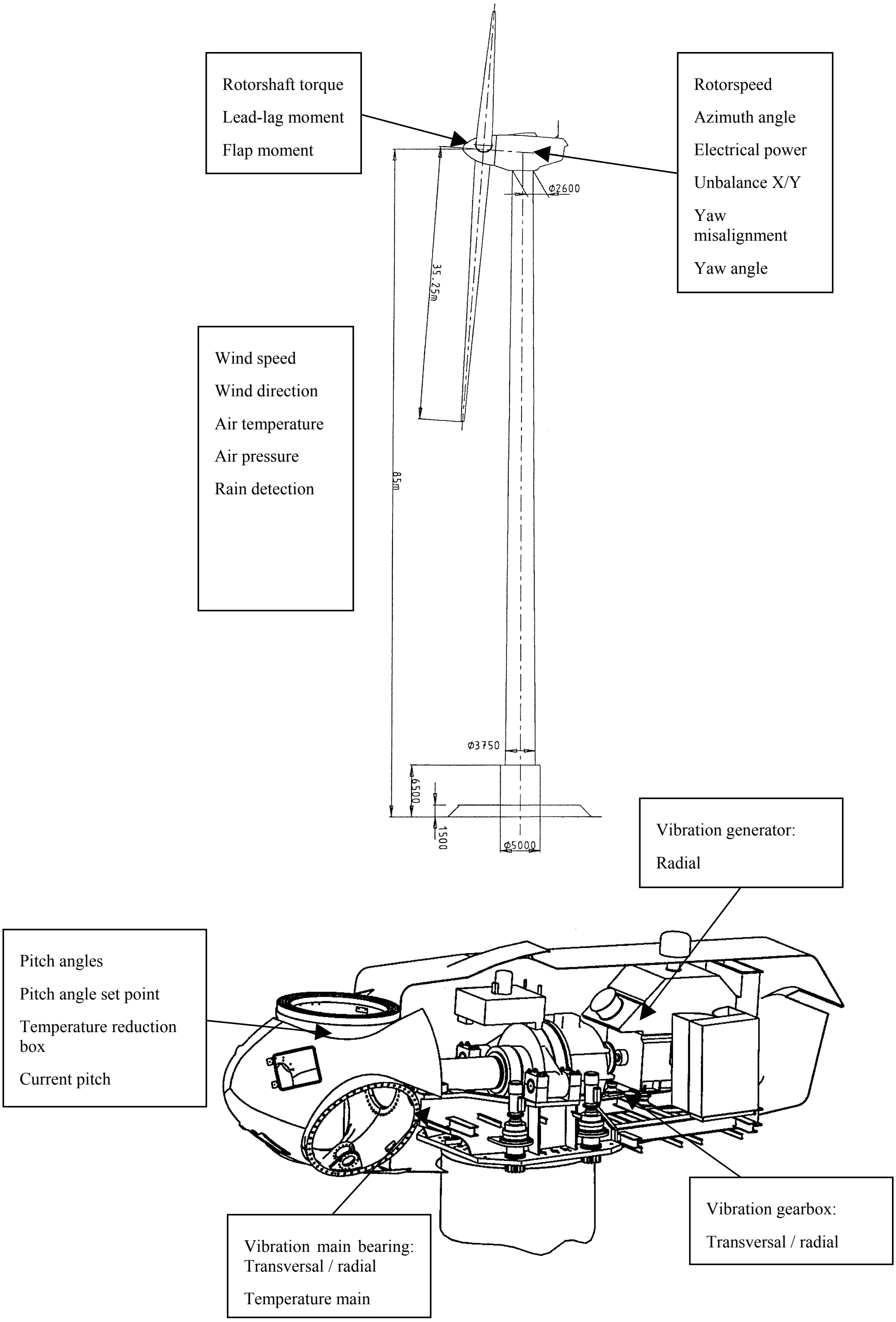

Figure B1: Overview of Siemens wind turbine measurement system