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Norwegian University of Science and Technology
Department of Marine Technology

M.Sc.THESIS

Title: Performance monitoring of compressors with electrical drive	**Delivered: 14.06.10**
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Abstract:

Compressors are widely used in the oil and gas industry, and have been so for many years. Previously, gas turbines where the standard driver for big offshore compressors, but as an ever increasing amount of attention is put on the emission of CO_2 and NO_X and the electric motor technology is developing this option is becoming more popular. This shift of drive technology introduces new possibilities for condition monitoring by the use of electrical signals from the motor. That is the background for this report.

The objective of this report was to describe state-of-the-art condition monitoring techniques using electrical signals and to suggest new approaches to condition monitoring made possible by these techniques. In addition monitoring approaches was to be demonstrated on example data from Statoil facilities.

This report starts with a brief introduction to the different maintenance techniques and the benefits gained by using condition based maintenance.
Then a short description of a generic compression system and the main components is given. The most frequent failure modes for each component are presented along with the condition monitoring approaches capable of detecting them.
Vibration analysis and performance analysis is shortly described before the condition monitoring techniques using electrical signals are presented.
The dominating method is named Electrical Signature Analysis. This is a non-intrusive method which analyses the current and voltage frequency spectra. Many failure modes will appear as specific frequencies in this spectra, thus failure detection and diagnostics are possible by this method. Some examples of failure frequencies are given. By the use of this method mechanically and electrically related problems can be detected, not only in the drive, but also in the gear and driven equipment. Some examples of available ESA tools are presented, including MCM and ALL-SAFE PRO.

A new approach for condition monitoring by the use of classical methods and ESA combined is proposed. At the end a tool named Early Fault and Disturbance Detection, developed by ABB, is presented and a short analysis of process data is performed.

Keyword:

Condtion monitoring, compressors, electric motor

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MASTER THESIS
for
M.Sc. student Magnus Starheim Waarli
Department of Marine Technology
Spring 2010

Performance monitoring of compressors with electrical drive

The MSc. thesis will be concerned with methods for condition monitoring of compressors driven by electrical motors. The focus will be on utilizing the opportunities introduced by reading data from the electrical machinery – in addition to classical instrumentation (vibrations etc.) and process data. Especially consider the use of variable speed drives with accompanying logic systems (such as "Drive Monitor" from ABB).

The main tasks in this thesis should be to:

1. Describe the state-of-the art of condition monitoring using electrical signals, and derived variables such as motor torque and speed. Compare with traditional instrumentation and discuss benefits and new opportunities.

2. Suggest new approaches to condition and performance monitoring.

3. Investigate and demonstrate monitoring approaches on example data from Statoil facilities and laboratory tests at NTNU.

During the period for this master thesis work the candidate need to have close cooperation with Statoil.

The thesis must be written like a research report, with an abstract, conclusions, contents list, reference list, etc.

During preparation of the thesis it is important that the candidate emphasizes easily understood and well written text. For ease of reading, the thesis should contain adequate references at appropriate places to related text, tables and figures. On evaluation, a lot of weight is put on thorough preparation of results, their clear presentation in the form of tables and/or graphs, and on comprehensive discussion.

Three copies of the thesis are required. One of these should the candidate deliver to Statoil.

Starting date: 18th January 2010
Completion date: 14th June 2010
Handed in

Trondheim 18th February 2010.

Tom Anders Thorstensen
Associated Professor II

Preface

This master thesis is written as a fulfillment of a two year master study at NTNU department of marine systems. The workload of the thesis is 30 study point, or equal to four regular courses. The thesis is written for Statoils Research centre at Rotvoll Trondheim. The thesis has been written in the period from the 18th of January 2010 to the 14thof June 2010 with guidance and supervision from Tom Anders Thorstensen and Erling Lunde from Statoil.

My direction of specialization is marine operational technology so the thesis main topic is within this field. The background for the thesis is that as environmental considerations and emissions become more important and electric motor technology develops an increasing number of compressors in the oil and gas industry is equipped with electric drive system. This introduces new possibilities for condition monitoring by using the electric signal. My task is to describe these possibilities and new approaches made possible by them.

I wish to thank Tom Anders Thorstensen and Erling Lunde for the help and guidance they have provided during my work with this thesis.

Magnus waarli

Trondheim 14.06.10

Summary

The oil industry is an industry with high cost, high incomes and complex equipment. The down time cost in the event of a failure is high, and the consequences of a failure could be catastrophic in terms of human safety and environment. Therefore a good maintenance strategy is wanted. By having a good maintenance strategy the downtime will be minimized, production maximized and the safety will be improved.

The systems encountered in the oil and gas industry are generally complex systems with many failure modes and different mean time between failure, hence to set an optimal maintenance interval can be very hard. Therefore condition monitoring and condition based maintenance is a well suited method for this industry.

Developments in electric motor technology and increased focus on emissions have introduced a change to compression systems the latest years. An increasing number of compressors are installed with electrical motors as their prime driver. This development has introduced new possibilities for condition monitoring by the use of electric signals such as current and voltage.

The most used method for this purpose is named Electrical Signature Analysis (ESA). This method was developed in the mid eighties at Oak Ridge National Laboratory for condition based maintenance and diagnostics purposes in electro-mechanical equipment. There is a wide variety of techniques included under the name of ESA. Common for them all is that the electric motor or generator is used as a transducer to detect faults, both electrical and mechanical, within a system. ESA is a non-intrusive method where current and voltage signals from the motor control center are used. Small changes in these signals generated by torque or air gap variations as a result of faults in the system are detected by the use of amplitude demodulation and Fast Fourier Transform or other similar techniques to perform spectral analysis. The fact that different failure modes show up at different frequencies in the current spectrum makes it possible to find the root cause. The method can also provide values of motor speed, torque and power. Since its development ESA technology has proven its capability to detect a variety of faults, both of electrical and mechanical origin. Examples of such are detection of motor bearing faults, stator and rotor problems, gear failures and compressor rotating stall.

It has been proposed that a combination between the traditional condition monitoring techniques for compressors, vibration analysis, temperature monitoring and performance monitoring is combined with ESA to monitor a compression system with electric drive and gear. By doing this it is believed that the diagnosis capabilities are improved compared to the traditional approaches, as high resolution frequency spectra can be provided by ESA.

At the end of the report a partial analysis of data from a compressor system as the one mentioned above is performed in a new condition monitoring tool named Early Fault and Disturbance Detection. The tool is developed by ABB in cooperation with Statoil and is a tool developed to monitor entire process plants or platforms by the use of data driven methods and algorithms. The idea is to detect faults without the need of complex process models and detailed system knowledge. The tool is found to be well suited for compressor fault detection, however this has not been verified and further work should include this.

Contents

Figure list

Abbreviations

CM	Condition Monitoring
CBM	Condition Based Maintenance
PM	Predictive Maintenance
AC	Alternating Current
DC	Direct Current
VSD	Variable Speed Drive
VFD	Variable Frequency Drive
PWM	Pulse Width Modulation
MCSA	Motor Current Signature Analysis
ESA	Electrical Signature Analysis
CSA	Current Signature Analysis
MCA	Motor Circuit Analysis
BDF	Bearing Defect Frequencies
BPOR	Ball Pass Outer Race
BPIR	Ball Pass Inner Race
FFT	Fast Fourier Transform
GMF	Gear Meshing Frequency
ORNL	Oak Ridge National Laboratory
MOV	Motor Operate Valve
CF	Center Frequency
LF	Line Frequency
RS	Running Speed
EMI	Electromagnetic Interference
DM	DriveMonitor
MCM	Motor Condition Monitor
EFDD	Early Fault and Disturbance Detection
EFD	Early Fault Detection
PDA	Plant-Wide Disturbance Detection
PCA	Principal Component Analysis

1 Introduction

The industry in general and the oil industry especially are under constant pressure to reduce costs and increase production rates. In addition health, safety and environmental factors are also a focus area these days. A way of addressing all these issues is by implementing a good maintenance strategy. By doing this sudden and expensive shutdowns can be avoided and high cost rush actions avoided. In addition a good maintenance strategy will ensure that the equipments operating condition is at its best giving higher production rates.

The systems encountered in the oil and gas industry are generally complex systems with many failure modes and different mean time between failure, hence to set an optimal maintenance interval can be very hard. Therefore condition monitoring is a well suited maintenance technique for this industry.

Compression systems are widely used on oil and gas production platforms, processing plants and for natural gas transportation. A trend for these systems is that an increasing number of them are fitted with electric motor drive. The electric motor control center contains a lot of information concerning motor current and voltage which can be accessed and analyzed without expensive sensor technology. This introduces new possibilities for condition monitoring by the use of methods such as electrical signature analysis and motor current signature analysis.

Another reason to review the possibilities for condition monitoring of compressors is the fact that subsea compression with electric drive is a new technology being evaluated and considered by oil and gas companies. Compression systems placed subsea will be hard to access for maintenance actions and hard to monitor. So as new applications of compressors are introduced and new drives make more information available new approaches to condition monitoring should be considered and their applicability for compression systems evaluated.

This was the background for this thesis. The original problem formulation is shown at the first pages of this report. The questions I have tried to answer in this report are:

- What are the different approaches for condition monitoring by the use of electrical signals and what kind of information can they provide?
- Are the methods capable of being applied to a compressor system?
- Can condition monitoring by the use of electrical signals replace any of the traditional monitoring techniques and lead to a new approach for compression system condition monitoring?

In addition some test data from a compressor driven by electrical motor is imported into a new condition monitoring tool developed by ABB, named Early fault and Disturbance Detection for analysis.

The field of condition monitoring is large, with many approaches, thus a whole lot of theory is available. Due to this and the fact that I have limited knowledge concerning electrical systems the methodology of each approach is not presented in detail. The focus of the presentation is rather put on what capabilities each method has. Some theory concerning the traditional fields of compressor condition monitoring is also presented in order to compare the different methods and possibly combine them.

1.1 Report structure

The second chapter of this report gives a brief introduction to the different maintenance strategies, how to choose amongst them and the benefits of choosing condition based maintenance and thereby introduce the need for a condition monitoring system. It also describes the core of condition monitoring and outlines the most important monitoring methods.

The third chapter gives an introduction to compressors driven by electrical motors. The main assets in such a system, the compressor, motor and gear, are described shortly and failure modes and condition monitoring approaches for each are presented.

Chapter four and five gives a brief overview of the traditional condition monitoring techniques vibration analysis and performance analysis. Some theory on how they can be performed and what they can provide of results are presented.

Chapter six presents Electric Signature Analysis and Motor Current Signature Analysis. This is two methods for condition monitoring where the electrical are being used. The background and basics of the methods are described. Theory on how different failures can be identified is also presented along with some relevant examples. Finally some comments on how this approach is suited for a system such as the one in chapter three is made.

Chapter seven presents some existing tools that utilize the methods presented in chapter six for condition monitoring of entire systems.

In chapter eight I propose a new approach for condition monitoring of the entire system based on the theory presented earlier in the report.

Chapter nine gives a description of the Early Fault and Disturbance tool. Some of the underlying theory is presented as well as a description of the possibilities of the tool. The data and work flow is also described.

In chapter ten an actual system similar to that described earlier in the report is described. The process parameters available for analysis are listed. A partial analysis in EFDD is performed and some thoughts on how this could be completed are given.

2 Condition monitoring

Condition monitoring (CM) is the process of monitoring one or more parameter of condition for an item or system to detect deviations that might be the result of an initiating failure. By detecting a failure at an early stage, maintenance can be planned and scheduled and CM is hence an important part of preventive maintenance and predictive maintenance as shown in the figure below. The end result of condition monitoring will as shown in the figure below be condition based maintenance. CM does not predict failure; it only helps predicting the time to failure. Nevertheless, a deviation from a reference value (e.g. temperature or vibration behavior) must occur to identify impeding failures. These limits will either come from quantitative or qualitative methods, data-driven methods or experience alone. This will be further discussed later on.

Before I go deeper into condition monitoring, the theory and methods, I will give a brief overview of maintenance in general to show where and why CM is appropriate.

2.1 Maintenance

All systems will, during operation, be subjected to wear and the condition will eventually be degraded to a condition where a maintenance action is needed to continue safe and economical operation. Several strategies for maintenance planning and execution exist today. Figure 2.1 shows the main strategies. By implementing the right maintenance strategy large economical savings can be made.

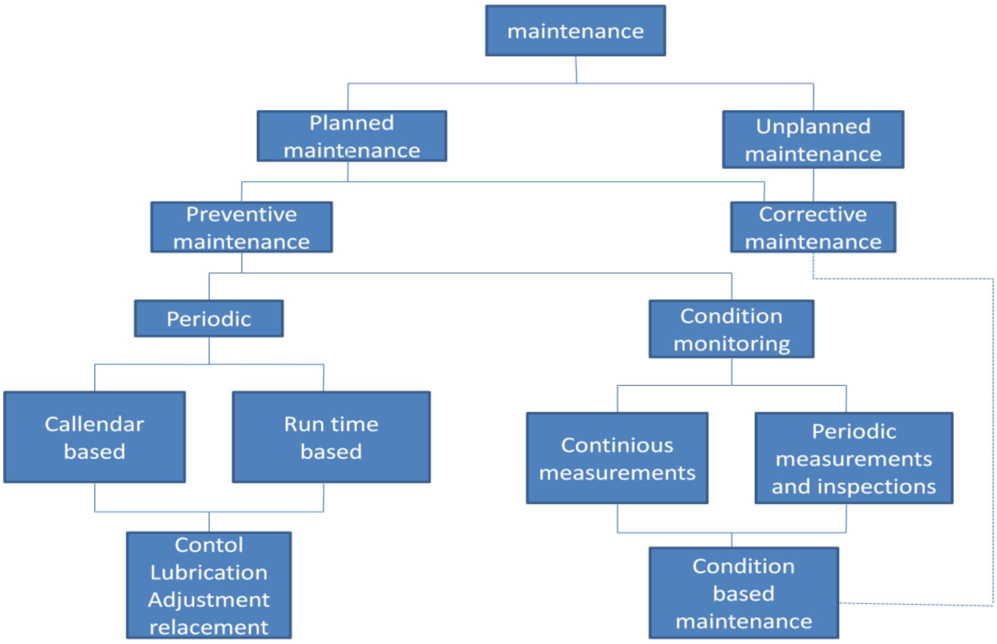

Figure 2.1: Maintenance types (1).

2.1.1 Maintenance techniques

Corrective maintenance

This policy simply implies to let an item run until it fails, then replace or repair it. This policy is suited for items where failure is non critical in terms of safety, economy and availability. Since it can be planned to let an item run until it fails this maintenance policy is classified as planned maintenance.

Preventive maintenance

This policy is, as the name implies, aimed at detecting deteriorating faulty conditions before a failure actually occurs, thereby preventing failure of the item. This policy should be used when a failure is critical with respect to safety, availability or economy. There are two main ways of performing preventive maintenance. Either by periodic maintenance or by condition monitoring and condition based maintenance (CBM). The former method implies overhaul or replacement of item with planned time intervals between each action. The latter is based on overhauls or replacement depending on the items technical condition. While it might seem easier to plan and execute maintenance with periodic intervals this technique could lead to a situation where items in good technical condition are replaced. This is illustrated in the report written by Finn are Michelsen (2).He mentions an example where 600 valves were taken out for periodic maintenance. Of these only 180 actually needed repair, while the remaining 420 where ok. This shows the weakness off the method, and the potential savings, both in terms of time and money, by implementing CM and CBM.

2.1.2 Deciding maintenance strategy

Which one of the strategies in figure 1 to choose depends on several factors such as safety, availability and economy as described above. A simple diagram for decision making is shown in figure 2.2.

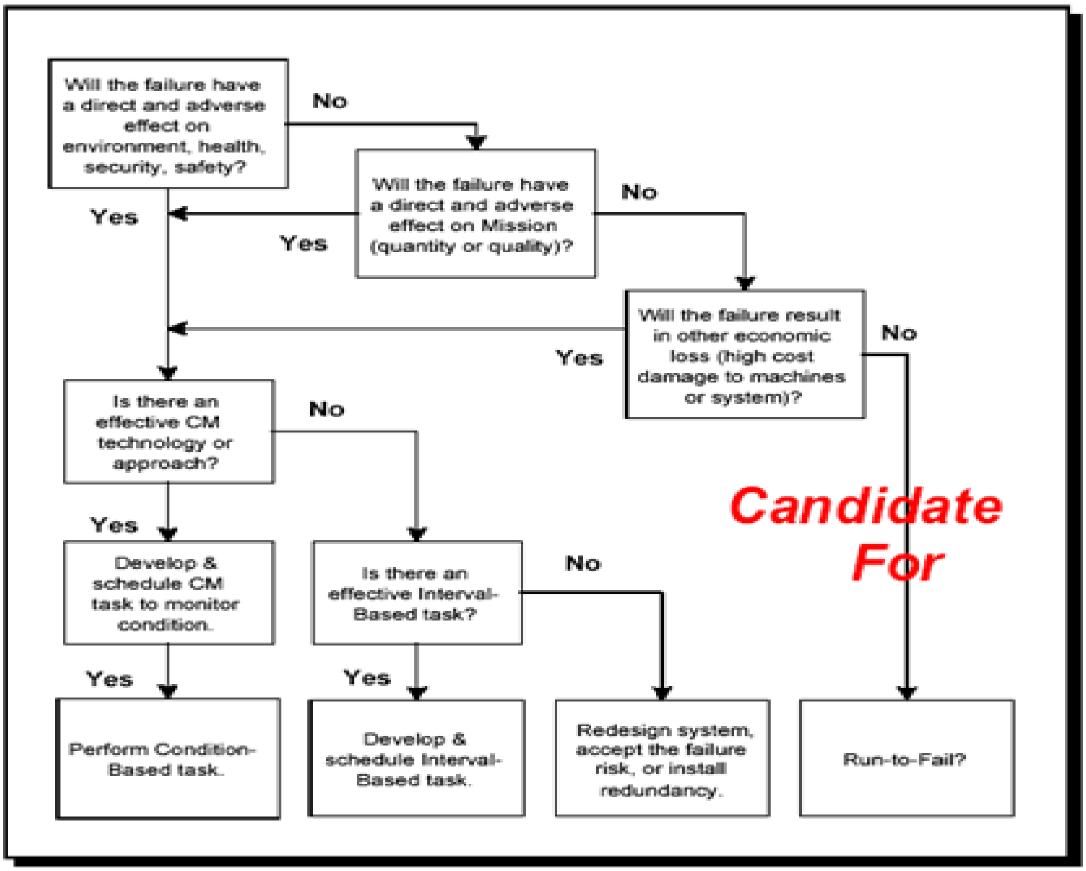

Figure 2.2: RCM logic tree (3).

2.2 Basic demands for CM to be applicable

As indicated in figure2.2, and explained earlier, the failure should be critical in terms of safety, availability or economy before preventive maintenance should be applied. When one of these three factors is fulfilled the next choice is between CM and periodic maintenance. To decide this, the question is whether CM has any effect. This question depends upon the failure distribution and if the failure is detectable or not.

2.2.1 Failure distribution

If the distribution is as curve 2 on the figure below, with aging of a component and failure occurring at a mean value with small deviations, periodic maintenance intervals could easily be determined, and this method would be cheaper and therefore better suited.

If periodic maintenance is applied to a failure distribution there are three basic approaches as shown to the left in figure 2.3:

- Short period. This will lead to few failures, but many maintenance actions and thereby high maintenance costs and downtime.
- Long period. This will lead to many failures and the costs and downtime connected to this.
- A compromise between the two before mentioned. This will not be optimal in any way.

Normally CM is preferable for components which have an unclear failure distribution, hence, an optimal interval for maintenance is difficult to achieve. This is illustrated in figure 2.3, where the long, lower curve, marked 2, is the failure distribution best suited for CM.

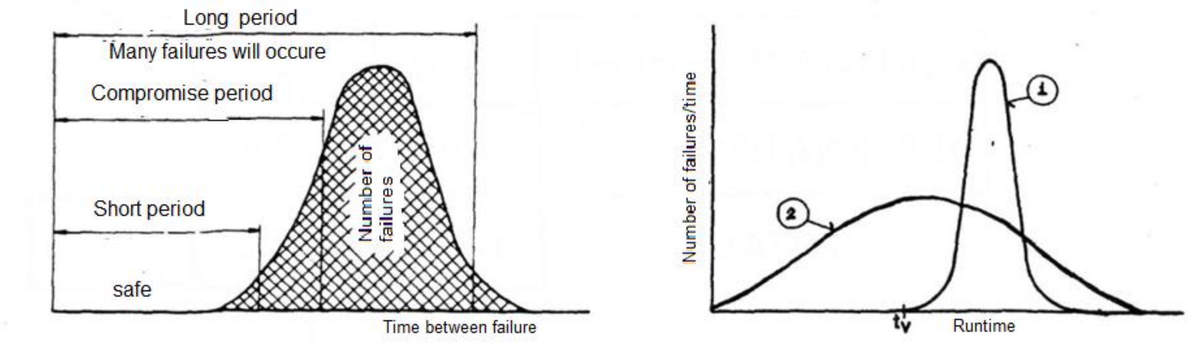

Figure 2.3 Failure function and maintenance period (1).

2.2.2 Failure detectability

If the failure distribution is suited for CM there are still two basic factors which that to be present:

- The failure evolves slow enough to be able to do a maintenance action/intervention[1] before breakdown.
- There exists a adequate control method

If a failure suddenly occurs without any warning, no monitoring scheme will be of any help for failure prediction. There has to be some kind of measurable parameter which shows a change prior to failure. This indication also has to come at a sufficiently early stage and develop slowly enough, so that countermeasures can be taken.

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[1] Intervention includes system going in ”safe-mode”/”shut down”.

2.3 The core of CM

The CM process consists of three core processes, observation, analyzing, and decision-making.

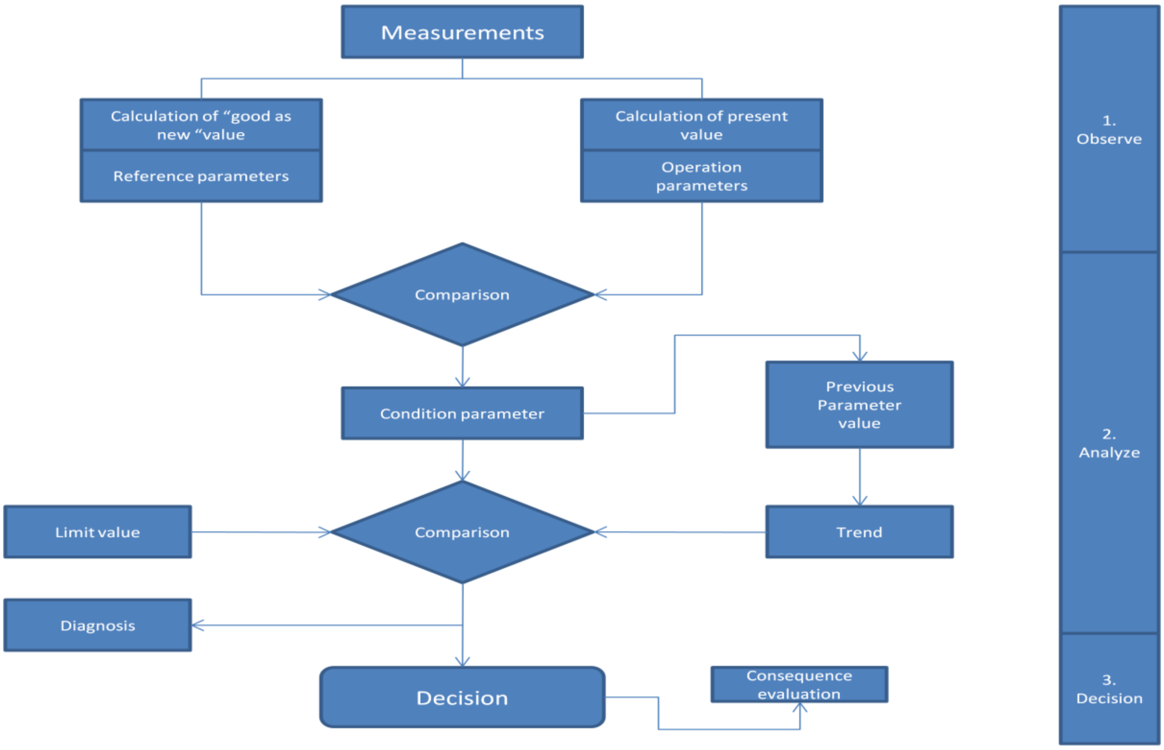


Figure 2.4: Flow diagram for CM (1).

2.3.1 Observation

Observation can be performed in several ways, both manually and automatically, online and offline. Every method gives some kind of indication of condition. However, there are considerable differences between the methods. The main difference is the time from detection to failure. There tends to be a connection between complexity of the observation and analysis and warning time. This is shown in figure 2.5, where time from observed deviation until failure of equipment is named T_S (warning time). It is observed from this that by using subjective methods, which is based on human senses such as hearing, smelling or seeing a failure the warning time becomes short. If one applies continuous measurements the warning time is significantly longer.

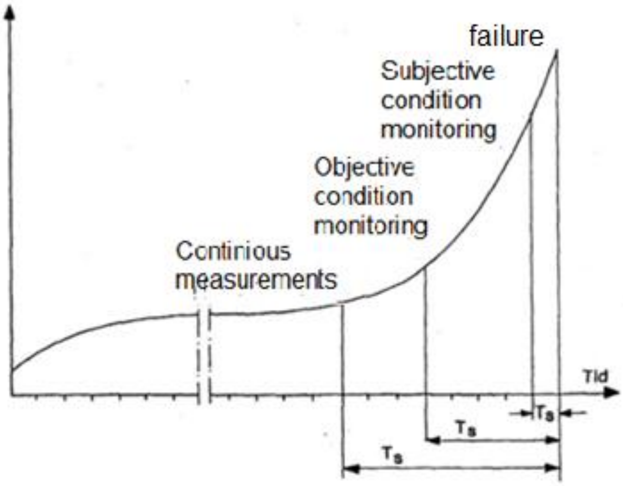


Figure 2.5: Monitoring method vs. warning time (1).

The process industry is in general widely monitored, but only a small or no particular warning is given before failure. This may be due to the complexity of the data monitored. A systematic use of these data could give us the desired warning. As stated in (1) there is a blurred transition between monitoring itself and condition monitoring.

When it comes to how often measures of condition should be done, the main parameter will be the rate in which a failure develops. A slowly developing failure will require longer sampling intervals than a rapid developing failure. Another factor that will influence is the capacity of the method in terms of data transferring and calculations.

2.3.2 Analyzing

When the observation is made the results needs to be analyzed. This is typically done by the use of a condition parameter. This parameter is meant to give an indication of how the technical condition has changed since the item was new and in perfect shape. Rasmussen (1) proposes a parameter as shown below, where the reference parameter is from operation of the system when it is in perfect condition, and the operational parameter is the one measured at a time of operation.

$$Condition\ paramenter = \frac{reference\ parameter - operational\ parameter}{reference\ parameter} \cdot 100\%$$

This condition parameter can then be compared to a pre determined limit. If it is over this the condition is unacceptable and maintenance should be planned. This is a simple example, and in real life the situation is most often more complex. The condition parameter can change with operational conditions and this should be taken into consideration.

One could also use the condition parameter for trending purposes to detect deteriorating conditions and predict further development. By doing this the time for maintenance planning would be longer than the one achieved by using instant values and a fixed limit.

2.3.3 Decision making

The final step is decision making. By analyzing the condition parameter, diagnosing what is wrong and evaluating the consequences a decision on what to do and when to do it is made. Ideally one should be able to wait until an opportunity for maintenance is present and then fix the problem. By proper trending and the use of experience this could be achieved.

2.4 Methods for condition monitoring

Roughly CM can be divided into the following areas of use, shown below, from Rasmussen (1):

- Thermodynamic CM
    - Control of efficiency, coating, temperatures etc.
- Vibration control
    - Controlling the changes in vibration signals which develops over time and say something about the condition of the vibrating system(e.g. machinery)
- Oil analysis
    - Look for wear particles and pollution in hydraulic- and lubricating oils. Size and composition of the particles are important information about the condition.
- Acoustic issue
    - A very high frequent vibration appears when a crack or a corrosion crack is starting to grow.
- Corrosion measuring
    - Measure the level of corrosion with special corrosion-feelers and the voltage level etc.
- Special inspection aids
    - X-ray, ultrasound, magnetic powder e.g. for crack detection
    - Fiber optics
    - Thermography
    - Ultrasound microphone for leak detection

In addition to the abovementioned methods there is another approach worth mentioning. This is electrical signal analysis. This method is developed for electrical motor condition monitoring. Further theory concerning the relevant methods for this project work is presented later on in the report.

2.5 Benefits of CM

There are several benefits achieved by applying condition monitoring to a process or system, both economical, environmental and health and safety matters are influenced in a positive direction. All of these benefits come from the possibility to detect deviations in the process at an early stage before they escalade and major failures occurs.

The detection of a problem before an actual fault is fully developed allows for more efficient maintenance planning. This introduces the possibility to perform planned maintenance actions, which is typically more cost efficient than the unscheduled maintenance needed when equipment is allowed to run until it fails. Spare parts could be ordered and delivered in a normal manner rather than rushing to get it after the original part is broken. This “warning” at an early stage will also help prevent unscheduled shutdowns which are extremely costly for most modern systems these days, especially in the oil industry.

The possibility to act before the equipment brakes down will also help prevent accidents and spills which can lead to environmental catastrophes and human injuries, both of which are costly and bad for the company’s reputation.

As a result of these factors the system can, with efficient condition monitoring, diagnosing and preventive maintenance achieve better operational stability, better production rates and higher profits.

3 The Compression system

Compressors can be found everywhere around us, in a wide variety of applications, thus there are also large variations in size and design. The application areas of compressors vary from small units in refrigeration units, through bigger ones used as turbochargers in combustion motors, to enormous ones for natural gas pipeline transport. In the oil and gas industry centrifugal compressors are popular due to several factors. The three mentioned below is especially important for offshore applications, where weight and size are critical parameters.

- They have a high ratio of horsepower per unit of weight
- They can deliver higher airflows than reciprocating compressors of the same size and higher pressure ratios than axial compressors with the same amount of stages.
- They have high reliability.

There are three main types of drives that are used for centrifugal compressors. These are listed below with traditional application areas. Deciding which one of these that are best suited for operation of a compressor depends on a variety of factors, such as compressor size, location of the unit and the process it is to be used in. In many applications a combination of the three are used. The examples of applications mentioned below are given by P. Boyce (4).

1) Electric motor. This type of drive is often used for smaller flows. Electric drives are also used in combination with the others, especially for startup purposes. This type of drive is often combined with a speed increasing gear.
2) Steam turbine. These are often found in chemical plants where generation of steam often is either a result of the process or needed in order to execute the process. By steam turbine drive these plants can utilize the excess energy, hence increase the overall efficiency.
3) Gas turbine. These are preferred for remote locations due to their low need for maintenance. In addition they are light. This makes them especially favorable for offshore purposes. Centrifugal compressors are well suited for direct connection with the turbine.

For export compressors, gas turbine drive has previously been the default solution. This is now changing. As electric motor technology has developed and emission of CO_2 and NO_X has gained more attention, the number of compressors driven by electric motors has increased. Often variable speed drives are selected. These do, according to ABB, have several advantages. Some of these are:

- High reliability and availability.
- High uptime.
- Low maintenance need, thus low maintenance costs.
- Good speed control, thus possibility to operate the compressor at optimal speed/power range.
- Low noise.
- No CO_2 and NO_X emission.
- High efficiency.
- Short starting time.

3.1 The electro mechanical system

A compression system driven by an electric motor consists of many units, each containing several components. All of these units have several failure modes and many approaches for condition monitoring. The figure below, given by (5), shows the six distinct sections of a system containing an electrically driven compressor. The sections are:

- The facility power distribution system which includes wiring and transformers.
- The motor control, which may include starters, soft starts, variable frequency drives and other starting systems.
- The electric motor.
- The mechanical coupling, which may be direct, gearbox, belts or another coupling method. In this report the focus will be on gears and direct coupling as this seems to be preferred for compressor drives.
- The load, which is the driven equipment. This might be a pump, fan compressor or other driven equipment. This report will focus on compressors.
- The process, such as gas boosting.

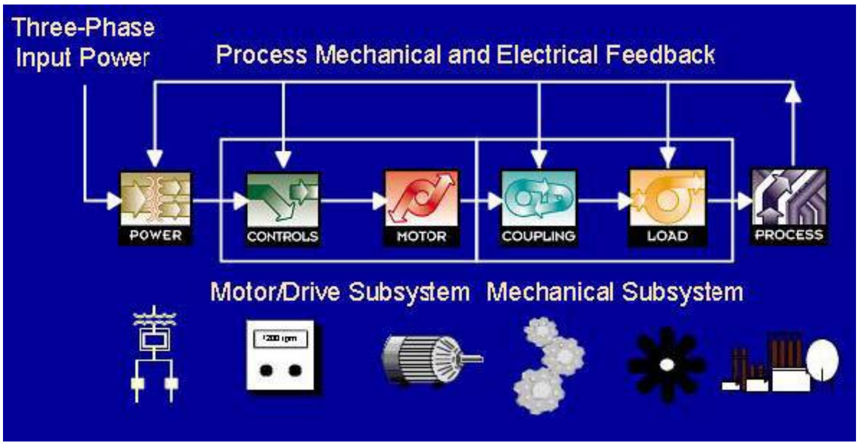


Figure 3.1: Components of compression system (5).

This is a complex system with many components or units, thus many variables to monitor. The traditional way to perform CM has been to monitor sections separately. Meaning that the electric motor makes the use of another tool than the driven equipment and coupling. Due to the limited scope of this project and the complexity of monitoring the entire system, the rest of the work presented in this report will be focusing on three of the sections. These three are the electrical motor, the coupling and the compressor.

It can be mentioned that in the system described above, and for the rest of the report, the gas compression system is simplified. What is meant with this is that in order for the gas to be compressed it is normally not sufficient with only the compressor itself. The gas typically passes through scrubbers and filters and the compressor has auxiliary systems for lubrication of bearings and for supply of seal gas. It is also important that these functions are monitored and in good condition to ensure optimal system performance and avoid failures.

In the following section the different components will be described, and the most common failure modes and monitoring techniques for each will be presented.

3.2 The electric motor

The electric motor is basically a converter of electric energy to mechanical torque. This is done by two main components in every type of electric motor, the stator and the rotor. As the names implies the stator is a stationary component, while the rotor is a rotating component. The two are separated by a small air-gap.

The categorization of electric motors is shown in figure 3.2. There are two main classes, based on the type of power supplied to the motor. These are alternating current (AC) and direct current (DC) drives.

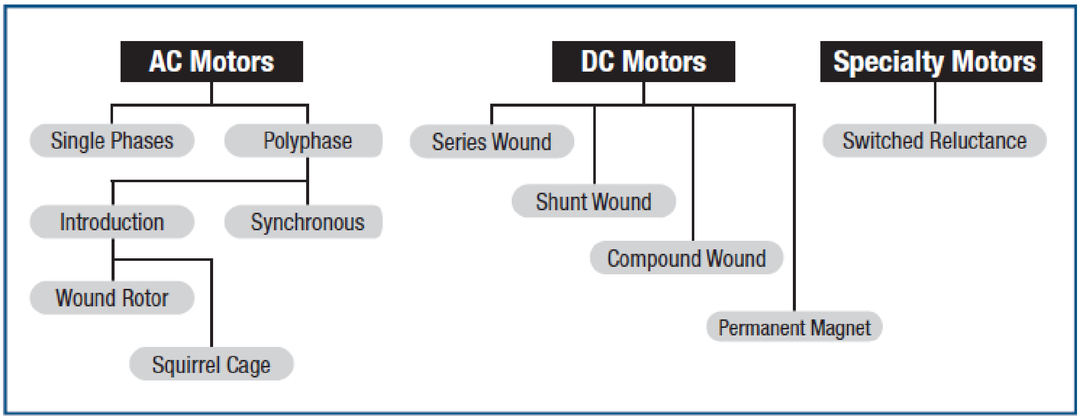


Figure 3.2: Categorization of Electric motors (6).

The two motor types found most relevant for this report are induction and synchronous motor, both polyphase AC types, since these are the ones most frequently used in the natural gas industry. The induction motor is the most used type for industrial purposes in general.

3.2.1 Basics of electrical motors

In this section a brief presentation of the main components in a generic electric motor is given and the basic of motor operation is explained. Figure 3.3 shows an exploded view of an AC motor.

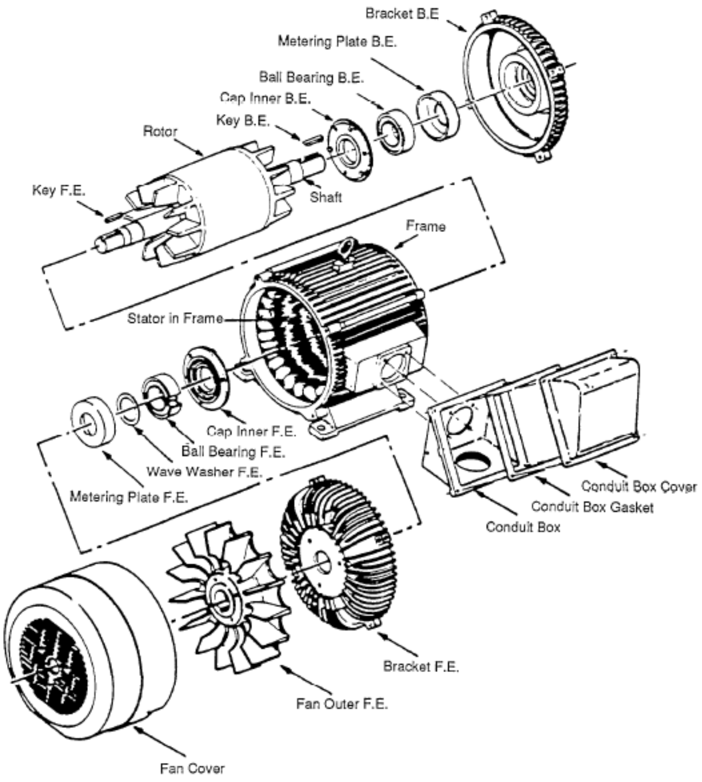


Figure 3.3: Exploded view of AC induction motor (7).

Stator: This part can, as mentioned earlier, be found in every kind of electric motor. It is a stationary part and one of the two main electrical components. It consists of a group of individual electro-magnets arranged so that they form a hollow cylinder. One pole from each magnet is facing towards the center of the group. The electro-magnets are made out of windings who are arranged so that when they receive the applied voltage they produce a rotating magnetic field (8). The applied voltage is supplied by a power source.

In both synchronous and asynchronous motors the stators electric field rotates at a speed called the synchronous speed. The synchronous speed is determined by the number of poles and the electrical supply frequency. The formula is shown below.

$$Synchronous\ speed = \frac{120 \cdot Frequency(Hz)}{number\ of\ poles}$$

While the synchronous motor operates at the synchronous speed the induction motor operates at a slightly lower speed. This difference between operational speed and synchronous speed is known as slip. The slip increases with increasing motor load.

Rotor: This is the other main electrical component which can be found in any type of motor. It is located inside the stator, and the two parts are separated by a small air gap. The rotor also consists of a group of electro-magnets, but these are arranged around a cylinder. The poles are facing towards the stator poles. The rotor is mounted onto the shaft. The electric field in the rotor is supplied differently in induction and synchronous motors.

Induction motors are also known as asynchronous motors. Common for all induction motors (except wound type) is that the rotors not are physically connected to any external circuits. The rotor current is induced by a magnetic field.

Synchronous motors, on the other hand, have current supplied to the rotor. This could be done by the means of brushes, slip rings or brushless excitation.

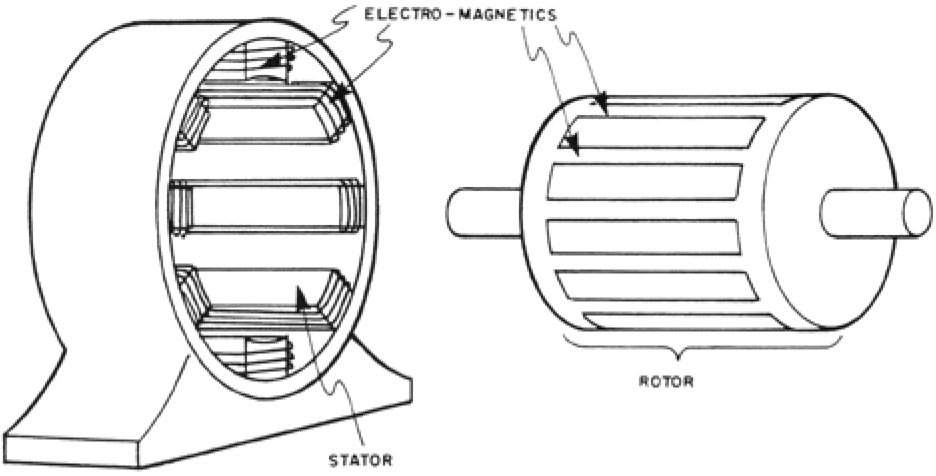


Figure 3.4: Main electrical components of AC motor (8).

Bearings: Electric motor bearings are most often standard bearings, meaning they are not specially designed for motor applications. The only differences are according to SKF (9) that they have higher noise standard and possible electric insulation to prevent electric current to pass through the bearing. Bearing theory including failure modes and condition monitoring is presented in a sub chapter later on.

Variable speed drives

Many processes can be performed more efficiently by the use of variable speed drives (VSD). This can for example be due to variations in the need for the product delivered by the process. In such a situation variable speed drives will be more efficient than the use of e.g. throttling valves, bypass valves or variable inlet vanes, which are some of the alternatives for compressor process control. In fact, using VSD is both the most common and the most efficient type of process control for electrically driven centrifugal compressors (10).

For a centrifugal compressor the use of a variable speed drive will introduce flexible operating conditions and make it capable of delivering constant capacity at variable pressure, variable capacity at constant pressure or a combination of variable capacity and variable pressure (11).

To control the speed of the electrical motor power electronics equipment like frequency converters are used. As shown in the formula for the synchronous speed, the frequency of the supply voltage determines the stator electrical field speed, thus the rotor speed. The most common method to accomplish variable speed is today by using pulse-width modulation (PWM) inverters to vary the frequency of the voltage waveforms (12). The output voltage will be sharp edged as shown on the figure below.

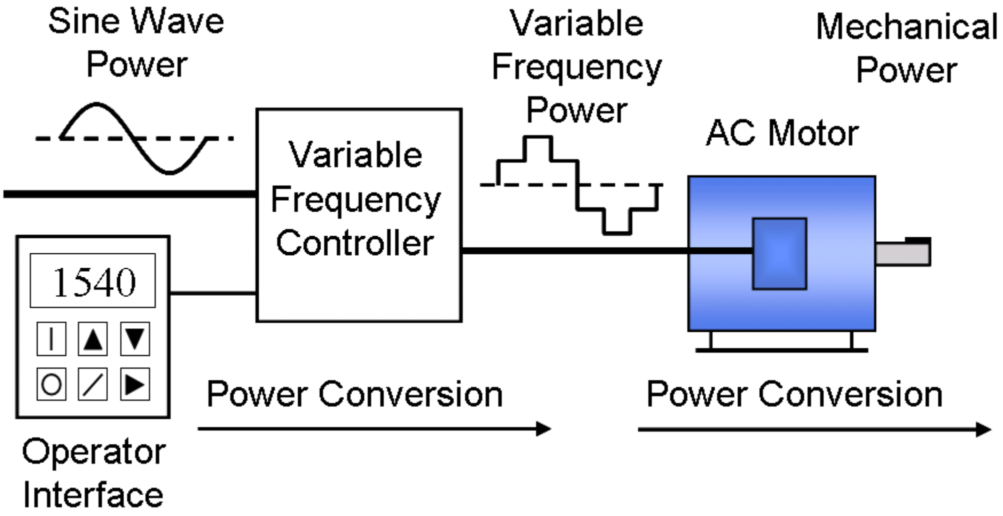


Figure 3.5: Frequency waveforms from VFD (13).

Due to the varying speed of the motor, the bearings are continuously strained during acceleration and deceleration. This variation increases the stress on the bearings compared to constant speed operating motors, thus bearing problems are more frequent in this type of drive (12). Bearing failures are described in detail later on in this report.

3.2.2 Motor Predictive maintenance

The electric motor is as shown above made up of several components, transferring both electric and mechanical loads, thus to monitor a motor can be done by many different approaches. In the following a brief presentation of some of the approaches is given. Those found relevant for this project will be further explained later on in the report

- Vibration analysis: Mechanical vibrations are measured through a transducer. The different methods and aspects of vibration analysis are described later on in the report. This method is generally best for detection of mechanically related problems, but can detect some problems with electrical origin in induction motors according to Hudson and Mellor (14). Examples of such problems are rotor bar issues, uneven air gaps and loose stator windings. If high resolution spectra are unavailable it is possible to distinguish between electrical and mechanical faults by measuring vibrations as the motor is switched off. The mechanically driven vibrations will reduce gradually to the point where the motor comes to rest, while the electrically influenced vibrations will reduce instantaneously at the point of isolation of the supply. This difference can be seen in figure 3.6 below. This might be a problem in compressor systems since a shutdown is an unwanted event and could be complex. Often, routines are made for shutting down and starting up compressors.

Figure 3
Coast Down - Electrical Faults

Figure 4
Coast Down - Mechanical Faults

Figure 3.6: Vibration spectra for coast down of motor (14).

- Thermography: Termographic surveys can detect abnormal temperature distribution in the motor. This can be a result of electrical or cooling problems. Is performed by using special imaging equipment capable of capturing infrared radiation. General trending of motor temperature can also provide useful information on the condition. Can detect bearing problems, but the lead time or warning time will generally be shorter than the ones achieved by vibration monitoring.

- Temperature monitoring: Basically the same possibilities and limitations as thermography, but due to the fact that temperature transducers has to be placed at different locations it will not give as good overview of the temperature distribution as this method.

- Oil analysis: For motors with oil lubricated bearings, oil monitoring can provide information on bearing health. This information could for example be if any wear components are present in the oil.

- Motor current signature analysis (MCSA): This method uses the electric motor as a transducer and is capable of detecting both electrical and mechanical faults throughout the system. The line current, at least for induction motors, can be analyzed in the same way as vibration signals. Specific failures cause specific current frequencies. Problems detectable include broken or cracked rotor bars, air gap variations and electrical imbalance, as well as mechanical conditions causing load variations. This method is described later in the report. In general electrically related problems are detected earlier with this method than with other techniques, while mechanical problems according to (5) generally are detected at a later stage than by vibration analysis.
- Electrical signature analysis (ESA): As MCSA it uses the electric motor as a transducer, but ESA also makes use of the voltage signal. Trending is possible, and ESA can, according to (15), detect winding and mechanical faults, through a larger part of the system, at an earlier stage than MCSA.
- Motor Circuit Analysis (MCA): This is a de-energized technique suited for evaluation of for instance control, cables, connections, stator and air gap issues. This is also described later in the report.

3.2.3 Typical electric motor failures

The electric motor consists of both electrical and mechanical components. Statistical data from the Electric Power Research Institute show that 47% of the motor failures are due to electrical faults. The remaining 53% are due to mechanical failures (16). A survey performed by IEEE, found in (17), in the period 1983-1985 supports these findings. The distribution of faults found by the IEEE survey for the different components is shown in figure 3.7 below.

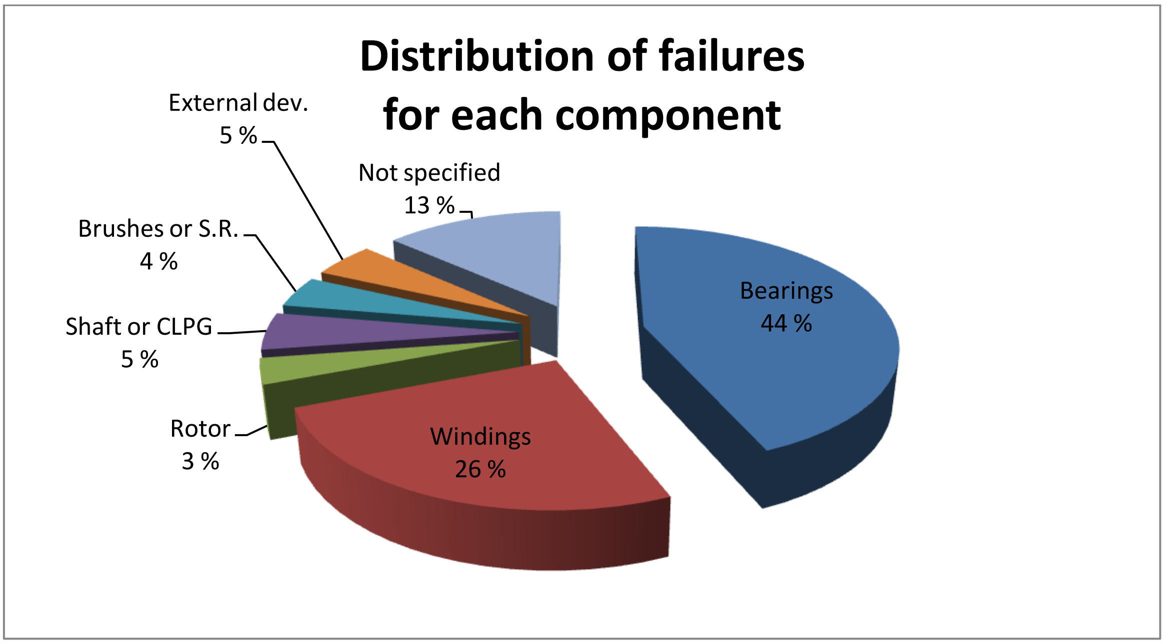


Figure 3.7: Failure statistics for electric motor components.

The problems related to electrical components are:

- Winding shorts between conductors or coils.
- Winding contamination.
- Insulation to ground faults.
- Air gap faults, including eccentric rotors.
- Rotor faults including casting voids and broken rotor bars.

These problems can be detected at an early stage by the use of MCA. ESA can detect early stage rotor faults and late stage stator faults. Vibration analysis can detect some of the failures at a late stage as many of the failure modes will induce vibrations.

The problems related to mechanical components are:

- Bearings, general wear, misapplication, loading or contamination
- Bad or worn shaft or bearing housings
- General unbalance and resonance

Most mechanically induced failures will at some point appear as bearing problems (14), so these can be detected with vibration analysis at an early stage. ESA can according to the same article detect the mechanical problems at a late stage. However, other articles claim that ESA has the ability to detect mechanical failures at an early stage (examples of this will be presented later on with references). I believe the reason for this could be the fact that Hudson`s article is older, from 1999, and that developments in the years after this has made the ESA technique better suited for detection of these problems.

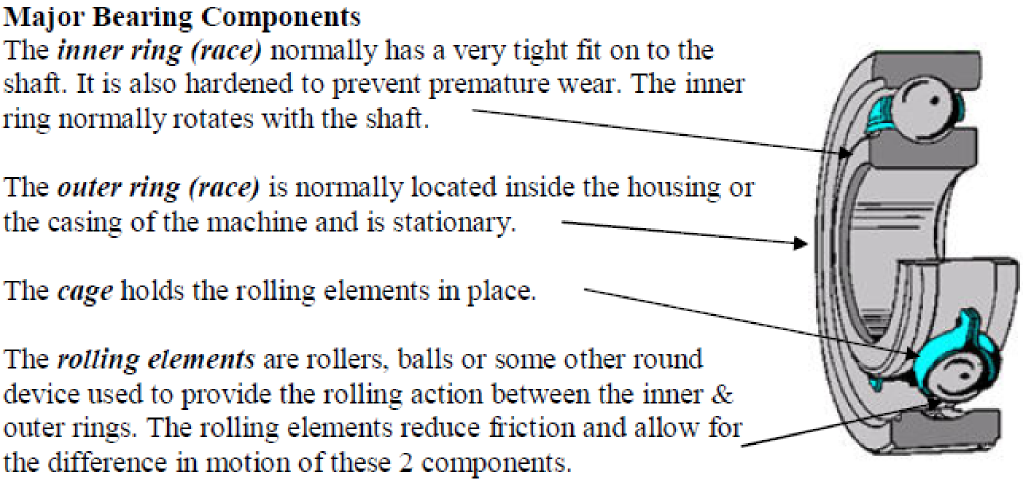
The theory presented above is summed up in the table below. The X indicates that the detection method is well suited and detects faults at an early stage, while L indicates that is possible to use, but not ideal and the condition will be identified at a later stage. The table is based on theory presented previously in the report as well as theory from chapter 6 and (15).

Failure mode / **Detection method**	**Electrical problems**				**Mechanical problems**		
	Stator	Rotor	Air gap	Insulation to ground	Bearings	Alignment	Load related
Vibration analysis	L	L	L		X	X	X
ESA	X	X	X		X	X	X
MCSA	L	X	X		L	L	L
MCA	X	X	X	X			
Temperature/Termography	L				L	L	L
Oil analysis					L		

3.2.4 Roller bearings

Since bearing failures are the reason for such a large percentage of electric motor failures it will be explained a bit more thorough in this section.

Roller bearings are present in a large majority of rotating equipment due to their low cost and high reliability. They separate the non-rotating components from the rotating, carry the shaft loads and position the shaft internally. In figure 3.8 below, given by Kruger (18), a roller bearing is shown with a brief description of the main components. Bearings are, as shown in the failure statistics for electric motors, the reason for a large part of electric motor failures. This shows how important condition monitoring of bearings are. Another fact that makes detection of bearing failures important is that bearings rarely fail on its own accord. This is stated by Howieson (19), who mentions possible reasons such as machine running unbalanced, misaligned or at a critical speed. So if a bearing failure does occur, the root cause should be found. Traditionally CM of bearings is done by the use of vibration analysis. Other techniques include acoustic emission, ultrasonic measurements, shock-pulse monitoring, measurement of the signal kurtosis and ESA. In this report only vibration analysis and ESA will be discussed.



Major Bearing Components

The ***inner ring (race)*** normally has a very tight fit on to the shaft. It is also hardened to prevent premature wear. The inner ring normally rotates with the shaft.

The ***outer ring (race)*** is normally located inside the housing or the casing of the machine and is stationary.

The ***cage*** holds the rolling elements in place.

The ***rolling elements*** are rollers, balls or some other round device used to provide the rolling action between the inner & outer rings. The rolling elements reduce friction and allow for the difference in motion of these 2 components.

Figure 3.8: Bearing components (18).

The same article tells that a bearing failure generally goes through 4 distinct phases. These are presented below with comments concerning fault detection in each stage.

stage 1: The failure normally occurs 0.1 to 0.125 mm below the surface of the raceway. When the failure occurs it is estimated that there is 10 to 20 % remaining bearing life. The cracking creates very low amplitude stress waves which can be detected with specialized sensors and signal processing techniques. This is however expensive.

stage 2: The fault progresses and microscopic pits occur on the surface of the component. At this stage it is estimated that 5 to 10 % of the bearing life remains. The pits cause the bearing components to vibrate at their natural frequencies. According to Kruger (18) ESA usually identifies bearing failures at this stage, and might even identify the fault at an earlier stage than some mechanical techniques.

stage 3: In this stage internal flaking, cracking and/or spalling occur. 1 to 5 % of bearing life remains. The faults present in this stage makes the signal strong enough to generate signals in the vibration spectrum at what are commonly referred to as bearing defect frequencies.

These frequencies are described on the next page. The same frequencies can be found in the ESA spectrum before they are present in the mechanical spectrum.

stage 4: When multiple cracks, excessive flaking or spalling occur, the fourth stage is reached. The rolling elements start to deform and the cage might disintegrate or break. 1% to 1 revolution of the bearing life remains.

It is normal to replace the bearing at stage 3. In this stage the fault is confined to the bearing itself and visually apparent. In stage 1 the fault is almost impossible to detect due to the fact that is below the surface. In stage 2 the defects are visible with the use of a magnifying device, thus hard to detect.

Once the bearing defect frequencies (BDF’s) are present in the spectrum a bearing fault is present for sure, and stage 3 failure has developed. The four BDF’s are listed below with a brief explanation. These values are dependent on the bearing geometry and expected values are given by the manufacturers. The values given are not exact. They will vary, and the actual observed frequencies are typically found within 5 to 10 % of the calculated.

- Ball Pass Outer Race (BPOR) is the frequency at which a fault in the outer race will show up.
- Ball Pass Inner Race (BPIR) is the frequency at which a fault in the inner race will show up.
- 2x Ball Spinn Frequency (2xBSF) is 2x the rolling element frequency.
- Cage Frequency (FTF) is the frequency the cage rotates at.

If vibration analysis is to be used, the results should according to (14) be trended. This goes for both overall levels and discrete frequencies relating to bearing frequencies. This is due to the fact that results can vary for apparently identical machines. For overall vibrations standards cover what is acceptable, but if enveloped/demodulated vibration spectra is to be used no such standards exists, thus trending would be useful.

3.3 Gear

In systems where centrifugal compressors are driven by electric motors gears are often used due to the simple fact that the electric motor speed typically is lower than the required compressor speed. Gears are a critical component in mechanical systems. They form a mechanical connection between the load and the drive, transmitting power, thus a gear failure will be critical causing down time and production stops. Therefore condition monitoring of gears are important, and it has according to (20) been an active research area within mechanical engineering for some time.

Due to the fact that a gear failures causes vibrations and the fact that vibration analysis is a well known and proven technology, this is the standard solution for CM of gears. Another approach to gear monitoring is the use of oil analysis, both on and off-line. The use of motors to detect gear failures has, according to (20), not gained much attention from the electrical engineering community. However, some papers describes that gear meshing frequencies can be observed in the current frequency spectrum. Rajagopalahn et al. (20) explains the frequency components by the fact that a fault such as a damaged tooth produces an abnormality in the load torque “seen” by the motor. This is then transferred to the motor current from the load. The same article also states that amplitude modulation is the most common mechanism of generation of the frequencies.

So to sum up the following CM methods can be used for gears:

- Acoustic emission
- Vibration analysis
- Electrical signature analysis: capability to monitor gears.
- Oil analysis

Typical gear failures include:

- Fatigue (tooth bending fatigue, contact fatigue, thermal fatigue)
- Surface Wear
- Stress rupture
- Spalling

To detect and diagnose gear failures the spectral pattern of the gear vibration is vital information (21). The most important component in the gear vibration spectra is the tooth meshing frequency and its harmonics (22). The meshing frequency can, as mentioned above, also be observed in the current spectrum. The gear meshing frequency is also known as the tooth mesh frequency and is simply the rate at which gear teeth mate together in the gearbox. The value can be calculated by multiplying the number of teeth on the gear with the rotational speed (in Hertz) of the gear or the rotational speed of the pinion wheel with the number of teeth on this wheel. There will always be vibration components present at this frequency.

A normal gear spectrum is given by Stevens (23). The spectrum is shown in figure 3.9. It shows peaks at 1 and 2 times RPM, along with gear mesh frequencies (GMF). Running speed sidebands are commonly present around the GMF. The peaks are of low amplitude. The GMF’s are sensitive to load changes, so that higher amplitudes can occur without the presence of a fault. Therefore, it is important to take measurements under the same load conditions if trending or comparing data is the purpose. If the GMF frequency increases without any speed or load changes, this is an indication of a developing problem. On the next pages some of the common gear failures are described along with their signatures in the vibration spectrum. The figures are from (23).

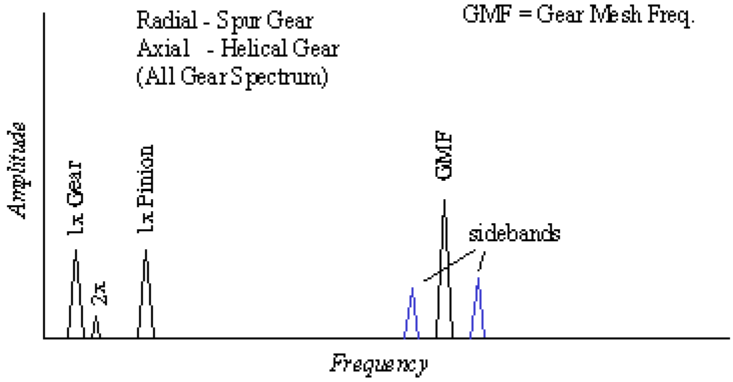


Figure 3.9: Typical gear vibration spectrum.

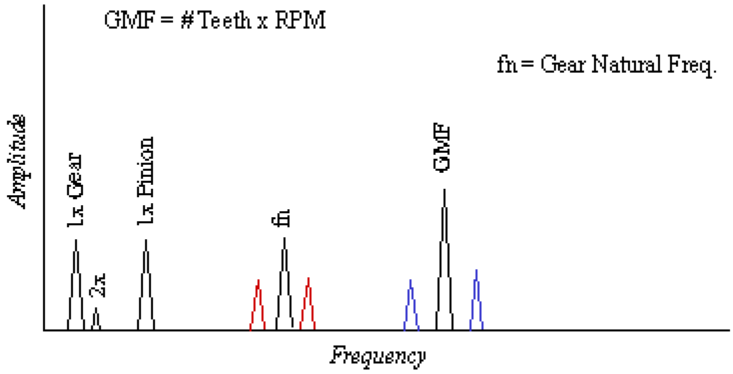


Figure 3.10: Gear tooth wear frequencies.

Gear tooth wear is indicated by excitation of the gears natural frequency and sidebands around it spaced at the running speed of the bad gear. The amplitude of the GMF might change, but a better indication might be that high amplitude sidebands surrounding GMF. This usually occurs when wear is noticeable.

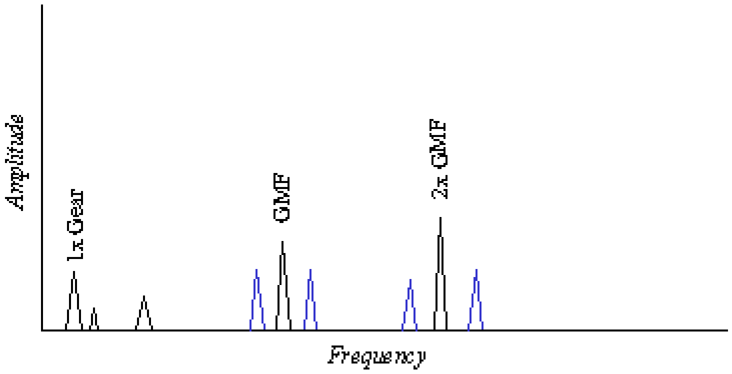


Figure 3.11: Gear misalignment frequencies.

If gear misalignment is present the second order of GMF or higher is excited. Sidebands at running speed will also be present. The first order GMF will often only show small amplitudes.

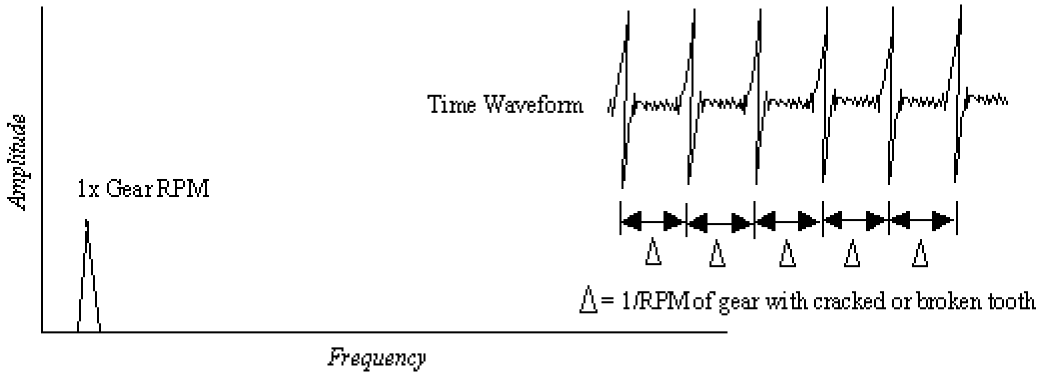


Figure 3.12: Cracked or broken tooth frequencies

If a tooth is cracked or broken a high amplitude signal at 1xRPM will be generated. In addition the gear natural frequency sidebands will be exited at its running speed. This situation could best be seen in the time waveform. Here a spike will occur every time the tooth with the problem meshes with the mating gear. The time between impact will be equal to one divided by the speed of the gear with the fault.

According to Victor (21), when using vibration analysis, it is usually sufficient to monitor the gear frequencies and watch their amplitudes grow due to normal wear. Based on previous historical data and experience one can predict at what value a failure will occur, and based on this a threshold value could be determined.

3.4 Compressor

A compressor increases the pressure of the gas and reduces its volume. How this pressure increase is achieved depends on what kind of compressor that is used. The different compressor types are shown in figure 3.13. For this report centrifugal compressors are considered, so the rest of the compressor theory presented will concern this type only.

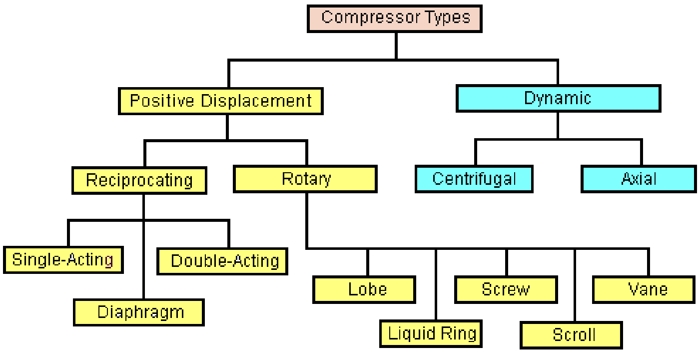


Figure 3.13: Compressor types.

Centrifugal compressors are dynamic machines and operate with a continuous flow. The operating speed of centrifugal compressors are higher than for other compressor types, especially for aircraft application, where the rpm can be in the range of 20 000 to 50 000. For commercial units the rpm is typically below 20 000. At such a high speed problems related to vibrations, lubrication of the bearings and unbalance are significant. However, centrifugal compressors have high reliability, and they can According to Boyce (4) operate for 2 to 3 years without shutdown. This is off course depending on operational factors but in the oil industry, with high shut down losses, the availability is of great importance.

3.4.1 Basics of centrifugal compressors

In this section the main components of a centrifugal compressor is presented along with a short description of how it works. A typical centrifugal compressor is made up of several stages to achieve the wanted compression ratio. Several stages mean that two or more impellers are mounted into the same casing.

Rotor: This is the only part of the compressor which is in motion during the compression process. It is basically a shaft with one or more impellers mounted onto it. A typically rotor assembly can be seen in figure 3.14 below. The components are described on the following page.

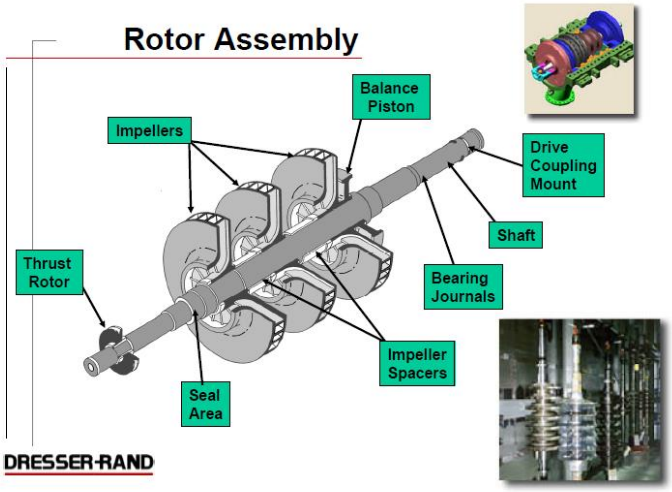


Figure 3.14: Rotor assembly (24)

Impeller: The impeller consists of two discs, referred to as disk and cover, or shroud, connected by blades. This is shown in figure 3.15. It is the impeller that transfers the mechanical shaft power to energy in the gas. The increase in gas energy, or enthalpy, is gained through higher pressure, temperature and velocity. As seen in the figure below gas enters the eye of the impeller in axial direction and is pushed outwards, being sent into the diffuser section with a flow in the radial direction. According to Boyce (4), it is normal practice to design the compressor in such a way that half the pressure rise takes place in the impeller and the rest in the diffuser.

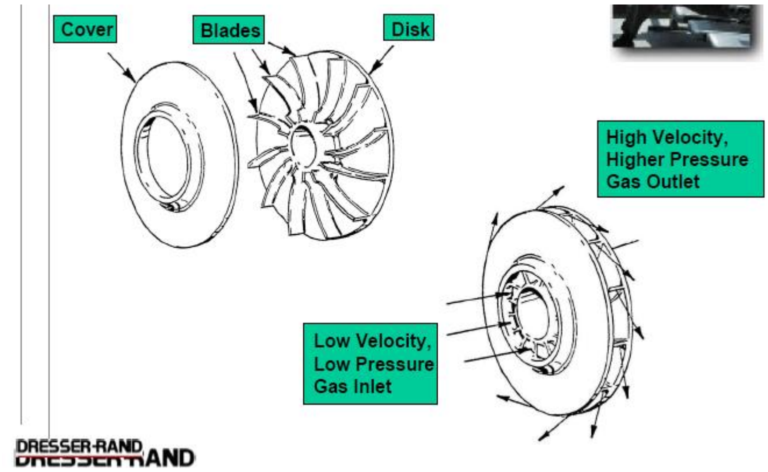


Figure 3.15: Impeller (24).

Diffuser: The diffuser is a circular chamber following a spiral path. In the diffuser the velocity of the gas decreases. This leads to an increase in the gas pressure. As mentioned above the pressure increase in this section is typically 50 % of the total pressure increase. In other words, the kinetic energy in the gas is converted into pressure energy. From the diffuser the gas goes into a return channel leading into the next impeller. A picture of a compressors impeller and diffuser can be seen in figure 3.16.

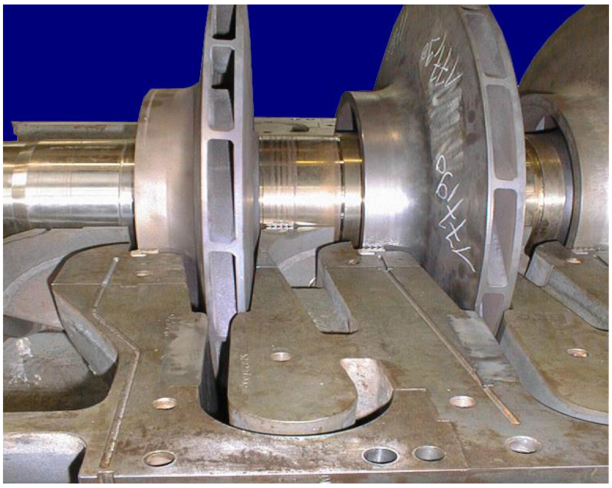


Figure 3.16: Cross section of a centrifugal compressor (24).

Return vane channel: Leads the gas towards the next impeller. The channels are fitted with blades to straighten the spiral gas flow and obtain axial inlet to the impeller.

Volute: The volute, also called discharge volute, is a circular chamber which collects the gas from the diffuser and conveys it to the discharge nozzle.

Thrust bearings: keeps the rotor in position axially.

Journal bearings: Keeps the rotor positioned radially.

Balance drum: The balance drum is mounted onto the shaft at the end, after the last impeller and its purpose is to balance the thrust produces by the impellers. The balance drum has compressor inlet pressure supplied to one side and delivery pressure supplied to the other.

3.4.2 Centrifugal compressor performance

A compressors performance is normally represented by a plot as shown in figure 3.17, given in Root cause and failure analysis (25). Here speed lines are plotted as a function of the flow and the pressure ratio. In this figure the speed lines are for constant aerodynamic speed, not mechanical speed. The corrections for actual flow rate and speed are done to reflect variations in inlet temperature and pressure. From the figure an operating margin can be defined as the flow margin between the choke point and the surge line at a constant speed line.

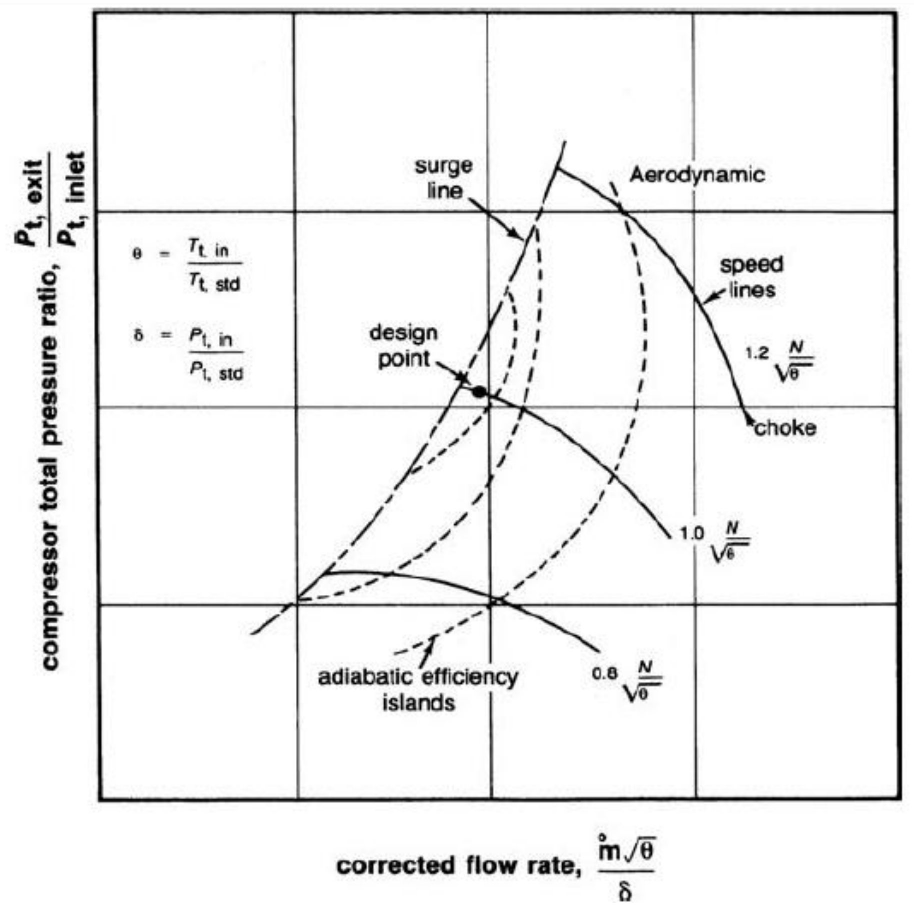


Figure 3.17: Typical performance plot for compressor

Surge is a phenomenon that occurs when the compressor does not have high enough flow to produce sufficient head. When this happens the main flow in the compressor reverses its direction for a small time interval. When this occur the exit pressure drops so that the flow regains its original direction again. Then the exit pressure rises again leading to another reversal of the flow. Normally there will be excessive vibrations and sound when surge occurs. Surge might cause serious damage to the compressor if not taken care of. Severe mechanical problems start to develop after only a few surge cycles. Due to this the operation line of a compressor usually is separated from the surge line by a safety margin.

Choke is a situation where the maximum mass flow rate at a given operating speed is reached. When this occurs the flow rate at the smallest area of the compressor is beyond mach one, thus it cannot be increased further. Another problem that might occur under these conditions is so called stone walling. This causes a rapid drop in the pressure ratio and efficiency.

Compressor work and power

The work done of the compressor on the gas can be estimated by the means of ideal thermodynamic processes. The process can be Isentropic, Polytropic or Isothermal according to (26). The Polytropic specific work (work/mass) is in the same book given as:

$$w_{pol,comp} = \frac{n \cdot R \cdot T_1}{n-1}\left[\left(\frac{P_1}{P_2}\right)^{(n-1)/n} - 1\right]$$

Where:

$w_{pol,comp}$ is the polytropic specific work with unit Kj/kg (Kilojoule/kg).

n is the polytropic exponent.

R is the gas constant. The value of the gas constant depends upon type of gas and weather it is one gas or a mixture of several. For one gas it can be found by dividing the universal gas constant by the molar mass. For mixtures it is a bit more complicated.

The unit of the work/mass is Kj/kg (Kilojoule/kg). To get the power of the compressor the mass flow, $\dot{m}$, has to be known. Then power is calculated as:

$$P = \dot{m} \cdot w_{pol,comp}$$

The power needed to be supplied the compressor to perform this work will be bigger as this is an ideal process and because mechanical losses will be present in the compressor. These losses can be accounted for by mechanical and thermodynamic efficiencies. However, this shows that in order to calculate the power consumed by a compressor, gas properties and flow rates should be known.

Compressor affinity laws

The affinity laws express the relationship between the head, capacity, speed and size of centrifugal blowers and compressors (27). The relationship between the different parameters and the speed with constant gas properties are:

Capacity (v) versus speed (RPM) $v_2 = v_1\left(\frac{RPM_2}{RPM_1}\right)$

Polytropic head (H) versus speed $H_2 = H_1\left(\frac{RPM_2}{RPM_1}\right)^2$

Theoretical horsepower versus speed $bhp_2 = bhp_1\left(\frac{RPM_2}{RPM_1}\right)^3$

Off course parameters such as gas temperature, molecular weight and density also makes an impact, but the equations above are shown to give an indication on how the different parameters are connected.

3.4.3 Compressor condition monitoring

The operation of a compressor with high rotational speed of the components, fluids flowing through, big forces being transmitted and high temperatures makes the amount of variables to monitor quite large. Thus there are many approaches to CM of centrifugal compressors. Below a few approaches are listed.

- Performance monitoring: determines if the equipment operates as expected by monitoring performance-indicating parameters. For compressors it is typical to calculate and monitor power consumption and efficiencies. Uses measured values of pressure, temperature, velocity, rotational speed, density etc. Is suited for detection of e.g. fouling and erosion.
- Vibration analysis: vibration transducers are typically mounted onto the bearings and most often it is the RMS value of the velocity or peak to peak displacement of the vibration that is measured. This is suited for detection of e.g. bearing failures, rotor failures, unbalance, looseness and rubbing.
- Temperature monitoring/Thermography: Temperature monitoring can be performed with temperature transmitters placed at different locations on the compressor. Typically at bearings. Thermography is done by the use of an IR-camera as explained earlier. All rotating machines create heat due to the friction, but lubrication and bearings minimize this. So under normal operating conditions the temperature created should be under a certain limit. If faulty conditions such as excessive wear, lack of lubrication, increased load, etc. occur the temperature of certain components can increase. This increase can be detected by these methods.
- Electric signature analysis: This method is suited to detect load related problems so in theory compressor failures could be detected. ORNL has designed and deployed computer-based ESA systems for continuous monitoring of compressors (28). However, what kind of faulty conditions this system has identified is not known. Some theory concerning this is presented later on in the chapter describing ESA.

3.4.4 Compressor failure

Centrifugal compressors are complex machineries, operating under though conditions, such as high speeds, high pressure ratios and temperatures. There are many components which may fail and in addition each component may suffer from different failure modes caused by a variety of factors. Depending on the application of the compressor, the design, operating environment and operating range, the dominating failure mode will change. In figure 3.18 the result of a industry survey of 500 olefin plant compressors are shown. The different failure modes and detection method are described below.

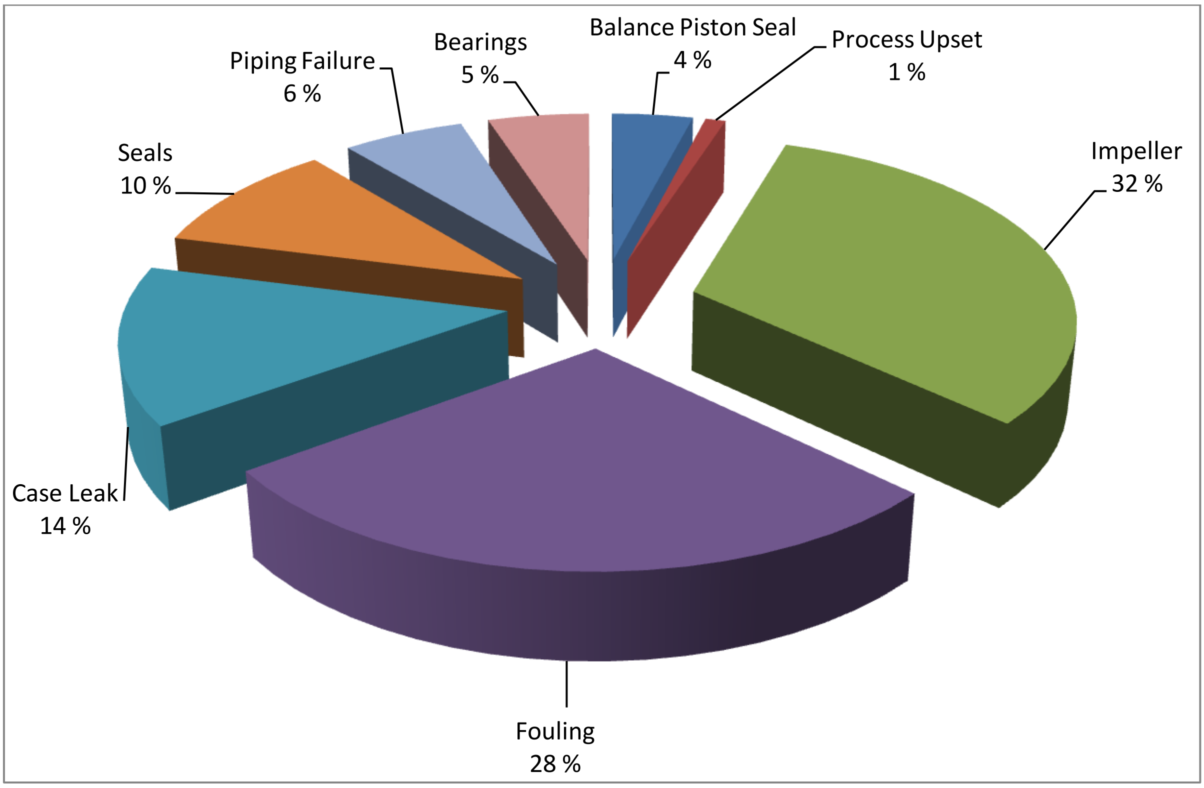


Figure 3.18: Contributing factors for compressor downtime (29).

- Thrust bearing failure: This can be catastrophic, leading to large compressor damage. It is rare as long as the machine operates under normal conditions. Failure of this component can be a result of several conditions. Examples of such are, given by Boyce (4), off design operation, dirt in the oil, fluid slugging and loss of oil pressure. Monitoring these bearings can be done by the use of a temperature transmitter. High rate of temperature change or high temperatures indicates a propagating failure. Axial proximity probes can also be used.

- Journal bearing failure: A failure in these bearings is not as serious as in thrust bearings. Some of the most frequent causes for failure are shaft or casing misalignment and rotor unbalance. Journal bearings can also fail due to excessive load, vibrations, lubrication failure, looseness (causes vibrations) and operation outside its temperature range. Detection of bearing degradation can be done by measuring vibrations. Another possible solution could be temperature monitoring.
- Impeller failure: The impeller is the component of a compressor with the highest stresses. The impeller rotates at a high speed, transmitting energy to the fast-flowing gas. Many different failures can occur at the impeller. Some of these are erosion, corrosion and fatigue failure. Impeller degradation can be detected by performance monitoring since the flow is affected and thereby the efficiency.
- Fouling: Fouling is by Boyce (4) described as the deposit and non-uniform accumulation of debris in the gas. The cause of this might be oil vapor, smoke, sea salt and vapor. Fouling is especially a problem encountered by centrifugal compressors in the process gas industry. Fouling disturbs the flow field and reduces the compressors mass flow. In some cases it might also reduce the pressure ratio. The change in these factors will cause the efficiency to decrease. Fouling is a temporary problem which can be solved by washing, but in a compressor intended to operate for long period without scheduled shutdowns a washing operation is not easily implemented. Fouling can, according to bkvibro (30), be detected by an increase in high frequency broad band vibrations, but changes in the efficiency will probably give an indication at an earlier stage.

The theory presented above is summed up in the table below. X indicates that the detection method is the best suited and detects faults at an early stage, while L indicates that is possible to use, but not ideal and the condition will probably be identified at a later stage.

Failure mode **Detection method**	**Thrust bearing failure**	**Journal bearing failure**	**Erosion/ corrosion**	**Seal failure**	**Rotor failure**	**Fouling**
Vibration analysis	L	X			X	L
Performance/efficiency			X	X*		X
Temperature	X	L				

*Based on an assumption.

4 Vibration analysis

Vibration is the oscillating motion mass about an equilibrium point. In rotating machinery such as a centrifugal compressor vibrations will always be present, even when the system is in perfect condition. This is according to Rasmussen (1) due to the fact that the force intended to run the process will influence the machinery itself, and since no machinery is completely stiff, this part of the force leads to vibrations. The vibrations will be a function of the machine dynamics such as the alignment and balance of rotating parts. Through time experience has shown that present to a system failure the vibrations increase. Rasmussen states that experience from the industry shows that the vibrations has shown an increase before failure in 90 % of the cases.

Measuring and analyzing vibrations is an effective way of monitoring the condition of rotating equipment such as gears, bearings, compressors and motors. It is a method which has proven its capability of detecting mechanical failures for many years. Due to this, vibration analysis as a condition monitoring method is widely used today. The list below shows some of the failures vibration analysis can detect in the different components of the compression system mentioned earlier on in this report. Although the method is capable of detecting all of these conditions it is not necessarily the best suited for the task, as discussed earlier in the report, e.g. in the section on electric motors.

Component:	**Condition:**
Electric motor	Broken or damaged rotor bars Air gap variations
Gear	Tooth meshing faults Misalignment Cracked teeth Eccentric gear
Rotors and shafts	Unbalance Bent shaft Eccentricity Misalignment Looseness Rotor rub Aerodynamic forces Blade resonance
Roller bearings	Pitting of race and ball/roller Spalling
Journal bearings	Oil whirl Journal/bearing rub

4.1 Principle of operation

According to Davies (31) CM utilizing vibration analysis is based on two basic facts:

- All common failure modes have distinct vibration frequency components that can be isolated and identified.
- The amplitude of each distinct vibration component will remain constant unless there is a change in the operating dynamics of the machine train.

The typical vibration analysis system consist of four basic parts (32):

1. Signal pickups, also called transducers
2. A signal analyzer
3. Analysis software
4. A computer for data analysis and storage

Davies also lists the different approaches to vibration analysis as:

- Overall monitoring: This is the most basic technique and also the most common vibration measurement in use. Measures over a broad band of frequencies and trends against time to indicate deteriorating conditions in the machinery. The typical values to measure are peak or root mean square (RMS) velocity. RMS is generally preferred.
- Spectral/frequency analysis: This is the most commonly used technique for CM in geared transmission systems. The method, as the name implies, analyzes the frequency domain representation of a signal. This gives a measure of the vibrations over a large number of discrete contiguous narrow frequency bands. All methods within this technique convert the time domain representation of the signal into the frequency domain. This could be done by the use of Discrete Fourier Transform (DFT). The most normal way of performing DFT is by using Fast Fourier Transform (FFT), which is an algorithm.
- Discrete frequency monitoring: I was not able to find any theory on this technique, but the name implies that it is something similar to demodulation or enveloping. Enveloping is a technique where specific frequencies are extracted from the overall vibration signal. This is the method best suited for frequency analysis of bearings and gears.
- Shock pulse monitoring: can be considered to be specialized application of characteristic frequency monitoring. It is based on the fact that when high-speed rolling element bearings fails energy is being emitted at ultrasonic frequencies. An accelerometer is mechanically and electrically tuned to a frequency of 32 kHz to detect these frequencies. This is a method widely used to monitor high speed bearings in the industry.
- Kurtosis: According to Gupta (33), a statistical parameter derived from the statistical moments of the probability density function of the vibration signal. The major advantage of this method is that the calculated value is independent of load and speed variations.
- Signal averaging: There are many types of averaging, but what seems to be common for them is that instead of using one section of time this method calculates an average by the use of multiple sections of the time waveform. By using the averaging approach the interpretation of complex and noisy signals are made easier, as the signal to noise ratio of the data is enhanced.

4.2 Comments

There are a lot of advanced and powerful methods within the field of vibration analysis, which if properly used can provide a whole lot of information concerning system condition and health. However, the use of these methods will demand expert personnel and specialized equipment, both software and hardware. Thus, the most normal way of performing CM by the use of vibration data is the overall method as mentioned earlier. If used, the more specialized techniques are probably performed at preset time intervals or if the overall signal indicates that something is wrong. And for such purposes handheld equipment is probably mounted on for the test and thereafter removed again. So for this report, when addressing vibration analysis, this will refer to the overall monitoring method.

5 Performance monitoring

Centrifugal compressor condition will, as with most other rotating machinery, slowly deteriorate from the “as-good-as-new” state during its lifetime. This deterioration is due to factors such as general wear, erosion, corrosion, leaks, etc., and will lead to poorer compressor performance. As a result, monitoring compressor performance for an indication of the compressors health has become an important part of predictive maintenance routines in the industry. Neal (34) states that performance monitoring by the use of thermodynamic models is the most used method for offshore compressors.

5.1 Principle

There are many specialized tools for compressor performance monitoring. Two examples of such tools are Turbowatch and Compass, both in use by Statoil at different installations. Common for the systems or tools are that they use measured values of many or all the following process parameters for the evaluation:

- Inlet and discharge pressure
- Inlet and discharge temperature
- Mass flow rate
- Gas composition
- Speed

The figure below shows the needed measuring devices and their placement in the system.

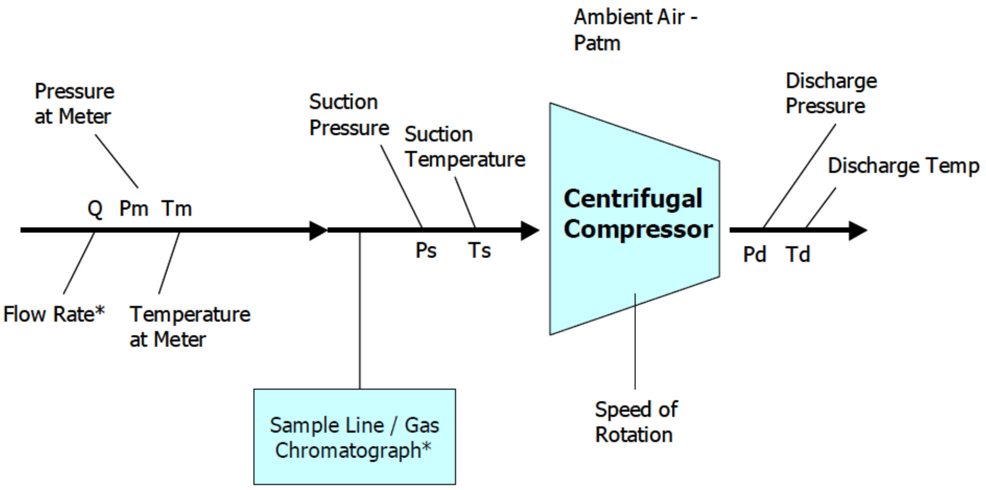


Figure 5.1: Location of performance test instrumentation for centrifugal compressor.

The output values or parameters from the evaluations, also called the condition parameters, are typically different kind of efficiencies. These are based on thermodynamic models of the compressor. There are several different compressor efficiencies. Below some of the most common ones are mentioned. The first two describes the thermodynamic efficiency of the compressor. Both are calculated in the same way, as the ratio between an ideal and a real process. The general formula for them is:

$$\eta = \frac{\dot{W}_{ideal\ process}}{\dot{W}_{actual\ process}}$$

- Isentropic efficiency: Based on isentropic process which assumes a reversible adiabatic process without losses, meaning no change in entropy.
- Polytropic efficiency: Based on polytropic process which is reversible but not adiabatic.

The efficiencies found are always less than one. This is due to the fact that the real process always has losses induced by such factors as friction and leaks.

In addition there are some other efficiencies describing the relationship between the energy supplied to the compression system from the drive and the energy increase of the gas. An example of such is the mechanical efficiency, which is the relationship between actual work performed by the compressor and the supplied shaft power.

It seems as the polytrophic efficiency is the most used of the ones listed above for centrifugal compressors. The calculations of these efficiencies are not explained any further in this report. This is due to the complexity of the calculations as the variables changes. However, it can be mentioned that the specialized tools for the purpose of thermodynamic calculations can handle the changes in parameters such as gas composition, and will provide output values such as efficiencies, the compressors power consumption, polytrophic head, etc.

Figure 5.2 shows a setup for performance monitoring of a compressor with electric motor drive with needed measurements and the derived variables.

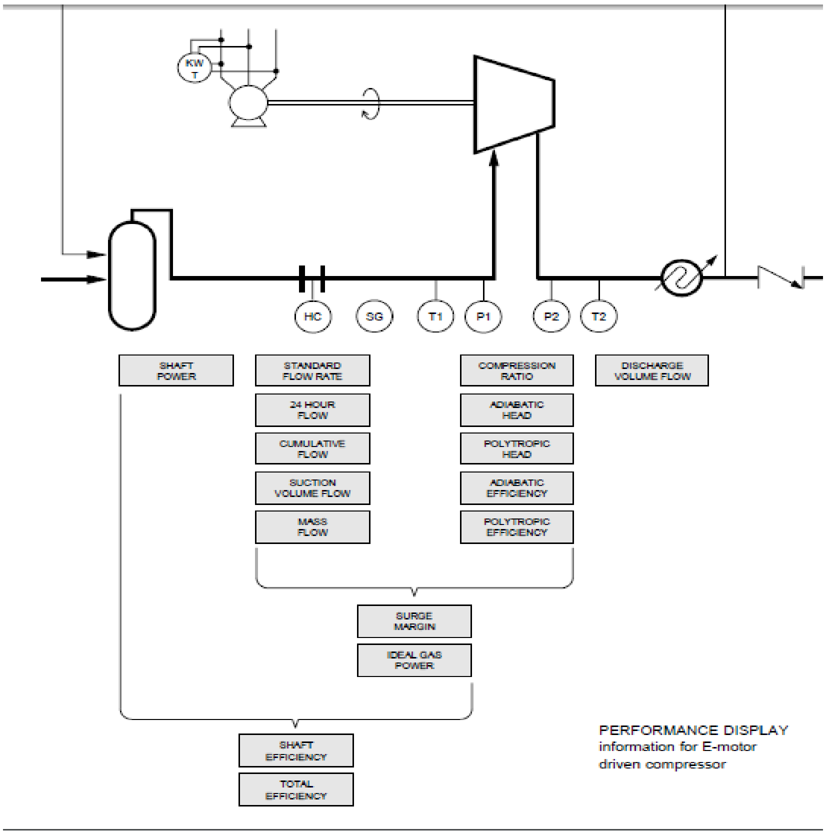


Figure 5.2: Performance monitoring setup of compressor with electric drive.

The performance parameters themselves to not necessarily tell much about the equipment condition so trending should be performed. By doing this degradation from the new condition can be monitored. A problem with this methodology is that the changes in operating conditions such as gas composition and compressor running speed can make it hard to compare results over time. To overcome this challenge a method of using similarity conditions can be used. This method is developed to adjust for differences in test conditions, and uses non-dimensional parameters for flow and head. By using these parameters, it is possible to directly compare data as long as machine mach number, isentropic exponent and volume flow ratio are similar. Further theory of this can be found in the Guideline For Field Testing of Gas Turbine and Centrifugal Compressor Performance (35).

To sum up, a general decrease in any of the efficiencies over time indicates that something is wrong even though operating conditions have changed as well.

5.2 Comments

To perform this type of monitoring a special tool such as those mentioned earlier is required. This is expensive, but I believe the benefits gained from knowing the performance of the system will be even greater. It might be possible to detect degradation by only analyzing data from the compressor without the thermodynamic models, but as more variables are introduced, this will become very time consuming and complicated. A possible solution to overcome this challenge might be an analysis tool such as Early Fault and Disturbance Detection. This tool and its possibilities will be described later on in the report.

6 Electrical Signature Analysis

Electrical Signature Analysis (ESA) is a relatively new approach to condition monitoring compared to such methods as vibration and temperature analysis. It was developed at Oak Ridge National Laboratory (ORNL) for diagnostics and CBM purposes of electro-mechanical equipment. There is a wide variety of techniques included under the name of ESA, as shown in figure 6.3. Common for them all is that the electric motor or generator is used as a transducer to detect faults, both electrical and mechanical, within a system. The ESA methodology is applicable to both AD and DC drives. It makes the use of current and voltage waveforms and can be used for online analysis. The basic idea behind the methods is that load and speed variations in electro-mechanical systems generally produce corresponding variations in motor current and voltage. These variations can be assigned to specific failure conditions.

The sensor setup can be seen on figure 6.1 below, for both motor and generator application. In both configurations it is a non-intrusive method where data from the motor control center or clamp on sensors mounted to electrical lines carrying input or output power is used rather than sensors mounted onto the equipment itself (36). A Fast Fourier Transform is in most cases used on the waveforms to be able to perform a spectral analysis. The output is similar to what a vibration analysis would have provided. This will be further described later on in the report.

Compared to vibration analysis the ESA methodology has several advantages. Some of these are according to ORNL that ESA:

- Do not require any additional sensors since the motor is the transducer.
- Is cheaper due to the fact that no additional sensors are required.
- Can monitor equipment remotely, so inaccessible equipment can be monitored.
- Gives a global indication of system performance while vibration sensors are sensitive to installation location.

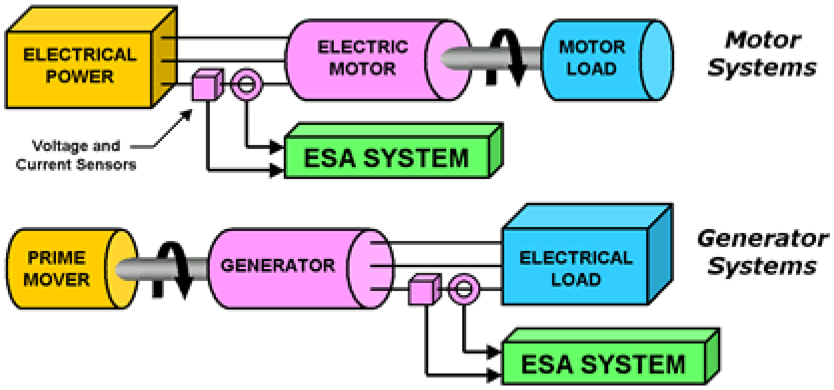
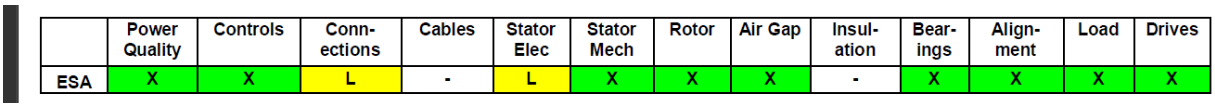


Figure 6.1: Sensor setup for ESA (36).

According to ALL-TEST PRO all ESA analysis systems require some motor nameplate information to perform the basic analysis. The necessary information is voltage, running speed, full load current and horsepower (or kW). Additional information can be entered for more detailed and accurate analysis. This additional information can be rotor bar and stator slot count, bearing numbers and information for the driven load such as gear tooth count and blade count for fans.

Since the ESA methodology was developed it has proven itself by diagnosing faults in a wide variety of equipment including generators, motors, fuel injectors, control valves, pumps, compressors, gearboxes, blowers and fans. Figure 6.2 given by ALL-TEST PRO (37) shows the capabilities of their ESA tool. Green indicates that a developing fault can be both detected and trended for CBM or PM purposes. Yellow indicates that a fault can be detected, but not at an early stage.



	Power Quality	Controls	Conn-ections	Cables	Stator Elec	Stator Mech	Rotor	Air Gap	Insul-ation	Bear-ings	Align-ment	Load	Drives
ESA	X	X	L	-	L	X	X	X	-	X	X	X	X

Figure 6.2: Capability of ESA (37).

6.1 Background

In 1985 Oak Ridge National Laboratory (ORNL) began a study, supported by the U.S. Nuclear Regulatory commission's Nuclear Plant Aging Research Program, where one of the main objectives was to identify condition monitoring methods for motor operated valves (MOVs). The study used data from sensors mounted on the valves, but ORNL in addition made efforts to extract data from the motor's current signature. The background for this effort was that the current signals could be acquired remotely and non-intrusively.

This research effort led to the development of several methods for signal analysis which are based on the electric motors ability to act as a transducer. These methods provided information about small time dependent load and speed variations in the MOVs. The signature of the variations could be connected with specific incipient failures or degradations, and could thus be used for condition monitoring and condition based maintenance. The methods which used only the motor current were named motor current signature analysis (MCSA), and have later shown the ability to be applied to a wide variety of motor driven equipment.

Later on several other techniques using the electric signal from the motor to detect failure has been developed at ORNL. These tools make the use of current, voltage and power monitoring and have been grouped under the name electrical signature analysis (ESA). The different techniques within ESA are shown in figure 6.3.

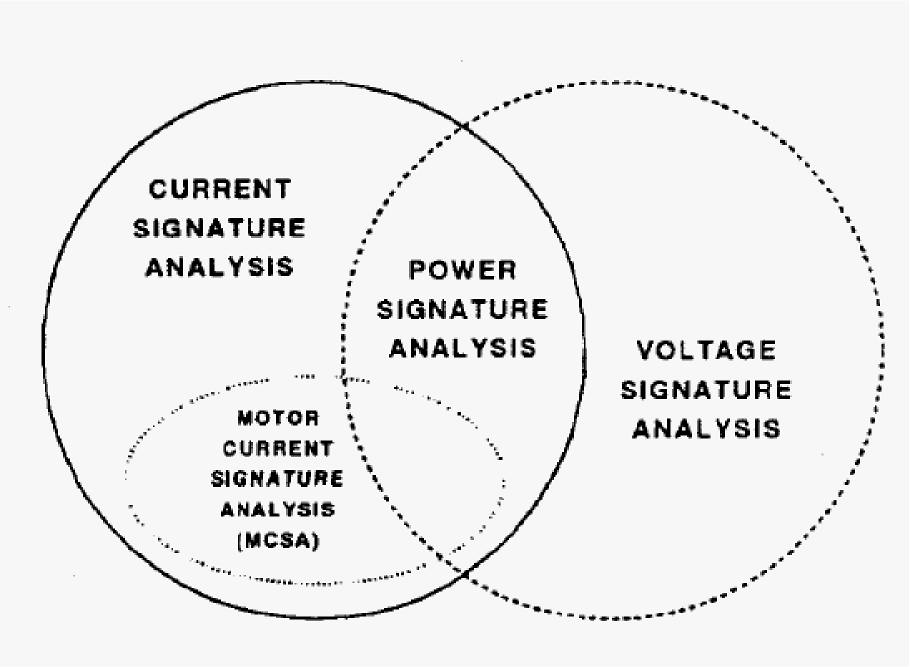


Figure 6.3: Techniques within ESA.

Since ORNL got their first patent on MCSA in 1990, 47 new patents with reference to the original from ORNL was registered in the U.S. by 2004. ORNL did by the end of 2004 have 15 patents on ESA. Figure 6.4 (36) shows this development in patent applications and gives an indication of the development of this field the latest years.

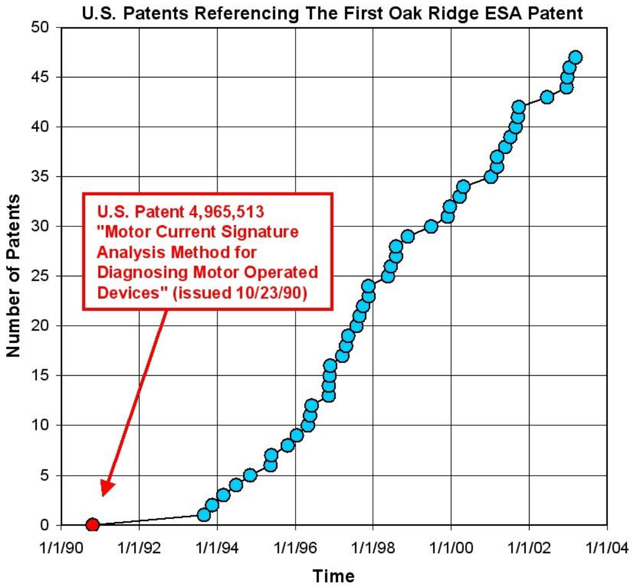


Figure 6.4: Patens applications with reference to MCSA.

6.2 MCSA theory

Motor Current Signature Analysis (MCSA) makes use of the current signal only. This is what separates it from ESA methods, which also makes the use of voltage signals. According to (37) MCSA methods will have more difficulties to distinguish incoming power related problems from motor and driven load problems. This is because, in general, if a peak is dominating in the voltage spectra then the source of the peak is incoming to the motor. If the peak is dominant in the current spectra then the source is related to the motor or load.

The method, briefly told, makes use of the fact that a system without defects will draw equal and balanced 3-phase current. If a fault occurs the wave shape of the current will be distorted. The reasons for these distortions are variations in load torque or radial forces within the stator air gap. Two examples of such are:

A bearing with a failure developing will have increased vibration levels as explained earlier in the report. The increase in vibrations will influence the current since it, according to (12), is a linear relationship between motor vibrations and motor current frequencies. As the rotor vibrates the result is air gap eccentricity. This again produces anomalies in the air gap flux density. The flux density changes affect the inductances in the machine which causes stator current distortion.

Another reason can be a load fluctuation in the system, which causes a change in speed. This will cause the per unit slip to change, which then causes changes in the sidebands across line frequency (38).

These mechanical changes are thus converted into electric current variations. The current variations are small compared to the average current drawn by the motor, but still detectable by the use of a suited analysis method. According to (39), most MCSA systems rely upon analysis of demodulated current. This involves removal of the fundamental frequency also known as the line frequency (LF). Frequencies found within the LF can then be used to identify faults. Figure 6.5 below shows the line frequency as it will appear when everything is in perfect condition. In figure 6.6 a second frequency has been introduced. Both figures are from (39).

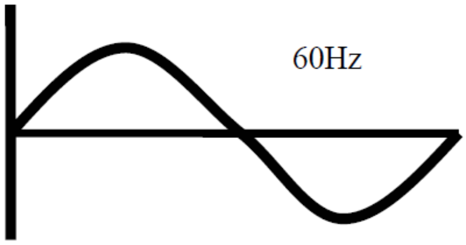


Figure 6.5: Perfect line frequency.

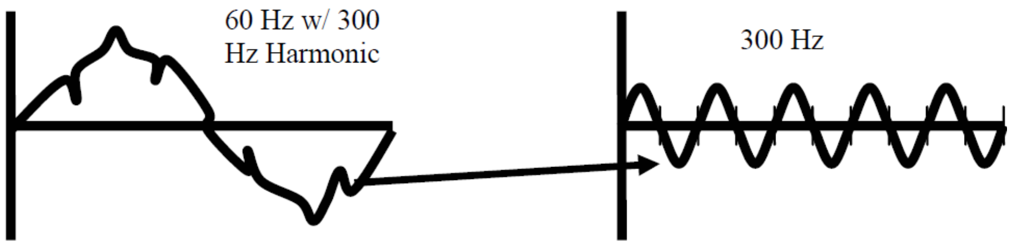


Figure 6.6: Line frequency with additional frequency.

To analyze this further a fast Fourier transform (FFT) is applied. The result of this is shown in figure 6.7. The sidebands found in the FFT spectrum indicate a faulty condition. What kind of problem it indicates depends on several factors such as number of sidebands, the intensity and separation. This is explained in the next section. Some guidelines for a "quick analysis", given by Penrose, are listed below.

Figure 6.7: FFT spectrum.

Penrose gives the following rules for quick analysis (These rules apply for motor failures, not for the driven load):

- PPF sidebands around LF demodulated current indicate rotor issues
- Mechanical faults are indicated by peaks in current but not in voltage.
- Electrical faults are indicated by peaks in both current and voltage.
- Bearing faults are indicated by peaks which are:
    - Not divisible by line frequency
    - Non-integer when divided by running speed
    - Peaks only in current

6.2.1 Failure signatures

As mentioned above different types of problems lead to different types of frequency components in the FFT spectrum. Below some of the common causes and their signatures will be presented. The theory and example figures shown in this section are from (39) if nothing else is stated, and is for a motor with the properties listed below:

- Running speed=1760 RPM
- Running speed frequency=1760/60=29.33 Hz
- Number of rotor bars=47
- Line frequency (LF)=60 Hz

6.2.1.1 Stator winding

Stator winding problems shows up as running speed sidebands around a center frequency (CF) found by multiplying the number of stator slots by the running speed.

With the motor properties given above the center frequency will be:

$$CF = 29.33 \cdot 42 = 1231.9$$

The sidebands will be located at both sides of this CF with a distance of 29.33 Hz, as shown in figure 6.8.

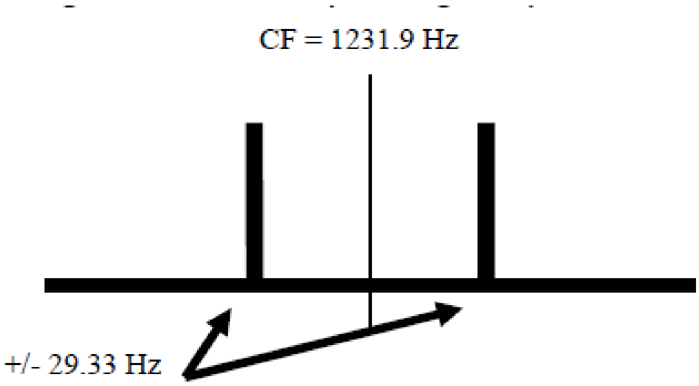


Figure 6.8: Stator winding failure frequencies.

Ball bearings

Ball bearing failure and its signatures in the frequency spectrum are explained earlier in the report, so the details of this are not included in this section. The BDF spectral peaks can be seen in the current spectrum at about the same time as in the vibration spectrum, when stage three failures have developed. However, failure frequencies can be seen as early as in stage 2 in the current spectrum. According to (40) ESA will usually identify failures at this stage. They will at this point appear as peaks in the range of 500 to 2000 Hz. This is because the systems natural frequencies are exited and these are typically in this range.

The frequencies at which the BDF's can be found in the stator current spectrum is calculated by the formula shown below, given by Benbouzid (41)

$$f_{bng} = |f_s + m \cdot f_{ch}|$$

Where f_s is the electrical supply frequency, m=1, 2, 3,…., and f_{ch} is one of the characteristic bearing frequencies.

This method for detection of bearing failures can be applied for the motor bearings. I have not been able to find theory concerning bearing failure detection in the driven equipment or coupling. However, some sources states that the failure has to be severe before ESA or MCSA is able to detect it. This might be bearings in one of these assets. Yet another reason for such a statement might be that it was said some years ago, and that the technology has developed since then.

Mechanical imbalance

This problem can be identified by determining the number of rotor bars (RB) times the running speed in Hz (RS) center frequency (CF). LF sidebands will be present around the CF, and then at a space four times the LF and 2 LF. A heightened running frequency peak can also be observed. Figure 6.9 shows an example of the failure frequencies mentioned.

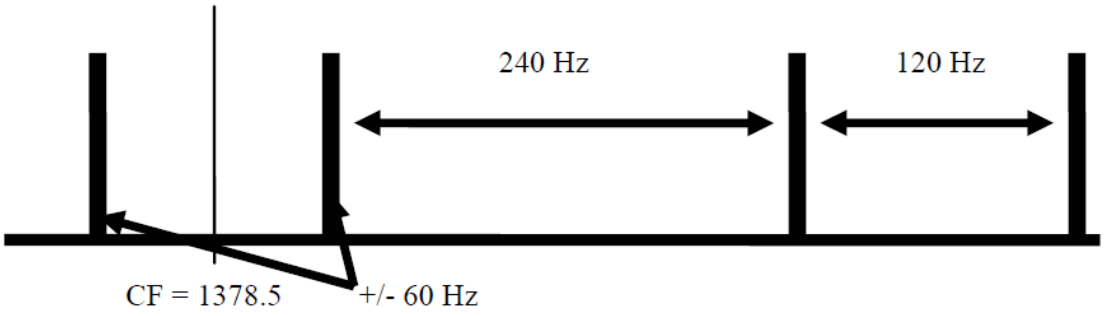


Figure 6.9: Fault frequencies for mechanical imbalance.

Gear mesh

The calculation of gear mesh frequency is described earlier in the report. Sidebands around this CF are an indication of gear mesh problems.

Blade pass frequency

It is also possible to find the blade passing frequency of rotors or impellors by simple relations. This is quite similar to the case with gear meshing frequencies, but in this case the frequency will be the driven shaft speed multiplied with the number of blades. It is stated in the same article that this frequency component will be present regardless of the number of broken blades or impellors. So peaks at this frequency with possible sidebands will indicate blade or impeller damage.

6.2.2 Variable speed drives

MCSA was originally developed for constant speed applications, so applying the method to variable speed drives introduces some challenges. In variable frequency drives the speed is changed by varying the operating frequency, and as this frequency is changed so are the sidebands in the frequency spectrum indicating faults. According to Ye (42) the operating frequencies can vary in the range of almost 0 to 60 Hz, thus the sideband components can vary within in the same area. He also states that to get the amplitude of these sidebands for fault detection accurate measurements of both frequency and slip speed is needed.

As mentioned earlier in the report the frequency is often changed by using PWM inverters. The output voltage from the PWM inverters is sharp edged as shown previously. Due to this the method introduces a significant number of harmonics to the input voltage of the motor, and when these are modulated by the mechanical bearing frequencies even more harmonics are introduced (12). In addition to these frequencies EMI[2] noise level is increased by the ASD, so that the detection of specific frequency components is even more complicated.

Yet another challenge is that FFT, which normally is used, requires stationary signals to be effective, and cannot be used during speed and frequency transients. To overcome these challenges other techniques such as time-frequency analysis can be used. Examples of such are the Wigner Distribution and instantaneous frequency estimation (43). These methods represent the signal energy with respect to time and frequency as the name implies. Yet another approach to analyze the frequency spectrum of non-stationary signals are wavelet packet decomposition (WPD), which according to Murat (44) provides finer frequency resolution compared to other techniques. It also posses better immunity to noise and transients and have less reliance on the accurate measurement of the speed (42).

In a study performed by Rosero et al. (45) , different joint time frequency analysis techniques are compared, and their capability to detect broken bearings in a permanent magnet synchronous motor is tested. The motor operates under varying speed. This study concluded that the Gabor Spectrogram was best suited for fault detection purposes, and that this method could be used as a precise tool to identify the fault harmonics created by a damaged bearing.

In this report the different analysis techniques will not be further described. The purpose of this section is only to show that motor current can be used for fault detection and condition monitoring purposes even when the motor operates under non stationary conditions. It can also be mentioned that several suppliers of ESA/MCSA tools claims that their product can handle variable speed drives. Examples of such tools are presented in the next chapter.

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[2] EMI is a abbreviation of Electromagnetic interference.

6.2.3 Synchronous motors

MCSA was originally designed for testing of induction motors, hence it is best suited for this type of motor. According to ALL-TEST PRO (40) the method has limited applications on synchronous motors. ESA on the other hand, is according to Penrose (46), capable of analyzing the signals from these drives.

6.3 Torque, speed and power

Torque, speed and power are three mechanical variables that define the functional performance of rotating machinery. If the efficiency of rotating machinery is to be determined, these variables have to be measured or found by other means. The relationship between the three is shown in the formula below.

$$P = T \cdot \omega$$

Where:

P=Shaft power

T=Shaft torque

ω=Angular velocity

These three variables have previously been measured by the use of different sensor mounted onto the equipment, but electric motor technology has introduced the possibility to derive these values without extra sensors. This is a big advantage since the need for expensive sensors are removed and because the mounting of the sensors can be both difficult and time consuming.

Torque

Torque measurements can be done in several ways. Four different torque transducer technologies are given by Bishop (47). These are based on measures of surface strain, twist angle or stress measured somewhere in the transmitting region of the shaft. The use of the mentioned transmitters and technologies can be avoided when an electric motor is the driving device. Based on the same theoretical background as the first torque controlled VFDs, it is possible to calculate and monitor shaft torque by using measured values of the stator current and voltage. According to Ernesto J. Wiedenburg (48) the first off-the-shelf solution using the instantaneous torque signal for diagnostics and maintenance purposes was at the marked in 1999.

The torque can, as mentioned above, be calculated on the basis of measured values of current and voltage. More specific, the real component of the current and flux derived from the voltage signal is used. With these values a signal equal to air gap torque can be developed according to Norman (49).

In a test performed by Shahin et al., (50) the electric machine is used as a torque sensor through the electromechanical torque to detect gearbox faults. They concluded that the sensibility of some of the frequency components in the estimated torque is comparable to those found by mechanical sensors. It is also stated that this torque estimation can give information concerning shaft, bearings and gearbox fatigue of complex electromechanical systems, both for stationary and non-stationary systems.

The instantaneous torque signature has also proven its capability to detect failure in pumps and fans. Two examples given by Wiedenburg (48) are:

The endbell of a large submerged pump had fallen off. This gave a less laminar flow into the pump. As a result the cavitation increased and the water flow decreased. This situation was detected by comparing the faulty pumps torque signal to the torque signal of a healthy pump. The torque signal was derived from the current and voltage of the motor. In the figure below torque signal for the healthy pump is shown at the left side while the signal from the failed pump is shown on the right side. The different is significant. The faulty pump has a lower torque level and a significant amount of torque ripples.

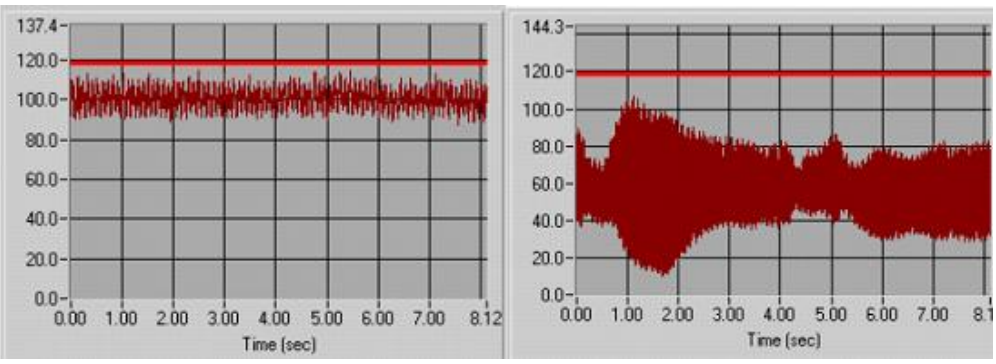


Figure 6.10: Torque signature for pump.

The torque signature of a duct mounted fan was monitored as two different failure modes where introduced. The first was unbalance which showed up as a 1x peak in the torque spectrum. It was found that the amplitude of this peak was a reliable measure for the severity of unbalance. The second failure introduced was a bearing failure in the outer race. The failure was in the third stage so and the BPFO was clearly visible in the torque signature. Sidebands where also observed at two times the running speed.

The torque signal has also shown ability to detect looseness of motor and sand production in pump driven by a VFD (51).

Speed

By using the electrical signals of a motor it is possible to find the rotational speed, thus direct measurements by the use of equipment such as shaft mounted speed encoder or tachometer is avoided (52). This is according to Phumiphak and Chat (52) an advantage since these methods decrease the reliability and increase the cost. The same authors propose a method for speed estimation using MCSA which has accuracy approximately within 2 rpm. This method was tested for induction motors operating with various load torques and frequencies. However, it is not known whether or not it can be applied to synchronous motors.

As some mechanical faults introduce load torque and speed oscillations the speed can be used for fault detection. Baptiste et al. (53) presents a method where the estimated rotating speed is used to detect bearing faults. The speed is estimated by use of the electrical signals.

Power

The work delivered by the motor can be calculated on the basis of the two values described above, speed and torque. It might be possible to find it directly from the motors current and voltage signals, but I have not found any descriptions on how this is done. However, the important thing is that monitoring tools such as DriveMonitor can provide this value for the motor, thus performance and efficiency analysis can be done for the system.

6.4 MCSA applied at rotating equipment

In the following sections some application examples of MCSA on rotating equipment are presented.

6.4.1 Pump

Centrifugal pumps are a type of rotating equipment which is comparable to centrifugal compressors. The principle of operation is the same and the design is similar with rotor and impeller

Studies has according to D.A. Casada (54) shown that motor current and power analysis provides information that is complementary to that available from the conventional CM techniques such as pressure pulsation and vibration analysis. MCSA was not capable of detecting all conditions and defects that traditional approaches such as vibration analysis was capable of. However, it was more sensitive for some conditions than most other methods, and easier to implement.

The study concluded that it is both feasible and cost effective to monitor a pump through the motor data and that the motor is effective at transducing torsionally related load phenomena’s. The conclusion of this study was that MCSA:

Can effectively be used to detect problems related to:

- Alignment
- Pump hydraulics

Not effective for detection of:

- Mechanical unbalance (when located at driven side if coupling)
- Bearing faults

In a case study presented by (55) wear in an electrical submersible pump was detected by MCSA. They way the wear was detected was by trending the current spectrum. In figure 6.11 the current spectrum of the worn pump is compared to the current spectrum from four months earlier, when the condition was good. The change, indicated by the red area, is clearly visible, so this method seems to be quite good. It also shows that MCSA is capable of detecting failures that don't show up as specific components at given frequencies. The damage found after removal was radial wear on the pump stage hubs and shaft/bushing wear.

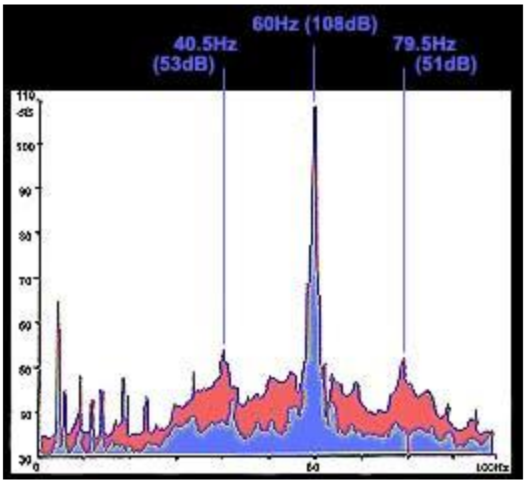


Figure 6.11: Current spectrum of worn pump.

6.4.2 Compressor

ORNL has performed studies on CM of compressors by the use of ESA and CSA. Both centrifugal and axial type compressors have been studied, and the test has shown that ESA is useful for detection of several conditions and even better for detection of certain load-related problems than other single sensor measurements.

In a test performed by ORNL rotating stall was induced on a large axial flow compressor. The purpose of the test was to see if this condition could be detected by using ESA. The test showed that the motor was, according to Welch et al. (56), a superior transducer for detecting this condition. This test resulted in the installation of several motor current based alarm systems in the plant where the test where performed. Figure 6.12 shows the demodulated motor current of the compressor, both during normal operation and during rotating stall. The frequencies related to stall can clearly be seen. This shows that ESA has the potential to detect flow related problems in dynamic compressors.

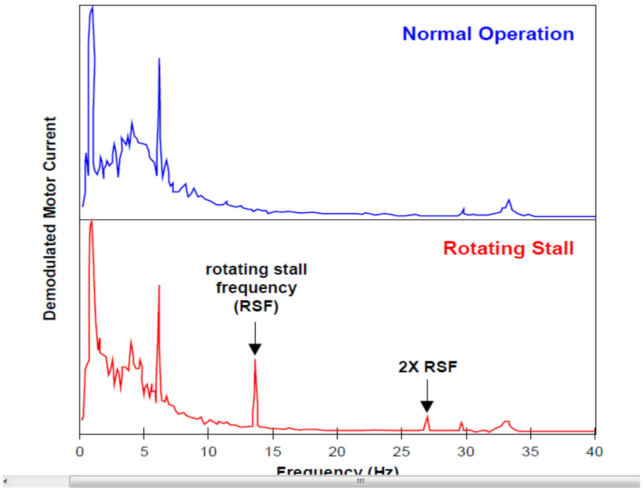


Figure 6.12: Current spectrum showing compressor rotating stall.

6.5 Comments

From the theory presented above it has been shown that ESA and MCSA techniques are capable of handling data from both induction and to some degree synchronous drives, operating under stationary and non stationary conditions. Theoretically it is also capable of detecting a large part of the failures through the entire system presented earlier in this report as well. If this is possible to do in real life, under actual operating conditions, is more uncertain. One reason for this is that some of the methods are from laboratory test with optimal conditions.

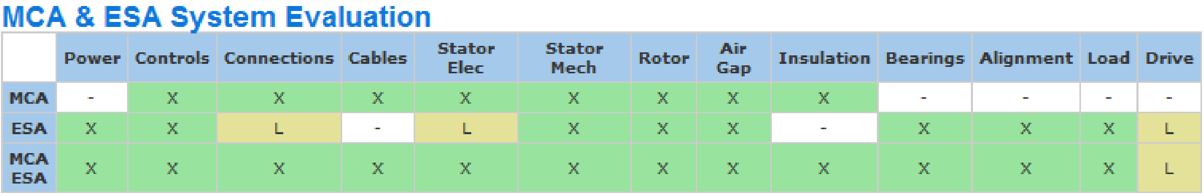
ESA seems to be a very interesting tool for compression systems with electrical drive. It can probably not replace existing technology such as vibration analysis, but can give complementary information. As an example, the vibration data normally collected is overall values with no possibility to extract the frequency spectrum. So if an increase in the overall vibration levels is indicated, ESA technology could be applied to check the frequency spectrum and search for failure signatures. In addition the possibility for calculation of output power is valuable and needed information for performance monitoring purposes. So if possible ESA methods should be applied to such systems.

7 CM tools using electrical signals

In this chapter some existing condition monitoring tools that make the use of electrical signals are presented along with the theory available. When selecting what tools to present I have chosen the systems that have the capability to detect failures in a larger part of the system than the motor.

7.1 ALL-TEST PRO tools

ALL-TEST PRO delivers a wide range of tools for trouble-shooting of electrical equipment and systems. The tools include both on and off-line testing equipment and makes use of techniques such as MCA and ESA. The off-line testing is done by MCA while the on-line testing is performed by the use of ESA. The instruments and solutions from ALL-TEST PRO is applied in a wide range of industries such as oil and gas, aerospace, nuclear energy and wind energy. The figure below shows what ALL-TEST PRO (16) claims that their solutions are capable of. Green indicates that a developing fault can be detected and trended for CBM or PM purposes. Yellow indicates that the fault can be detected, but trending or early warning is not possible.



MCA & ESA System Evaluation

	Power	Controls	Connections	Cables	Stator Elec	Stator Mech	Rotor	Air Gap	Insulation	Bearings	Alignment	Load	Drive
MCA	-	X	X	X	X	X	X	X	X	-	-	-	-
ESA	X	X	L	-	L	X	X	X	-	X	X	X	L
MCA ESA	X	X	X	X	X	X	X	X	X	X	X	X	L

Figure 7.1: ESA and MCSA capabilities.

It can be mentioned that in a figure shown previously the same company has marked of ESA with an X and the color green when it comes to drive applications. The reason for this is unknown, but it might be that, as mentioned before, developments in the technology have made it more suitable for drive fault detection.

7.1.1 ALL-SAFE PRO

This tool is an online testing tool using ESA. The theory found on this tool was very limited, but it is an extension of their ATPOL tool, so I assume they operate in the same way. The ATPOL tool performs a root mean square demodulation process on the signal to remove the large line frequency component and provides a better signal to noise ratio for the components. It is possible to observe the running speed, gear mesh frequencies, drive train components and gear rotational speeds from the signals after the demodulation. FFT is used to separate the variable frequencies of the signal. The tool is capable of detecting:

- Stator electrical and mechanical problems.
- Rotor bar problems.
- Air gap issues.
- Mechanical component health including balancing and alignment, bearings and driven equipment.

ALL-SAFE PRO is a tool which can be permanently installed. The sampling for one test takes about one minute, and test can be performed as often as one wish. The system can be applied at variable frequency drives and does actually have the possibility to troubleshoot the VFD’s operation.

7.1.2 Motor Circuit Analysis

Motor Circuit Analysis (MCA) is a de-energized test method which can be performed directly at the motor or from the motor control center (MCC). According to ALL-TEST PRO (16) the advantage of testing at the MCC is that the entire system is evaluated. This includes the connections and cables between the test point and the motor. The test takes a couple of minutes to perform.

Principle of operation

ALL-TEST PRO provides a MCA tool. According to ALL-TEST PRO the instrument apply a low voltage AC signal through the motor windings and measure the response in each. The signals possible to measure include the phase angle (Fi), the current/frequency response (I/F), the impedance (Z), the resistance (R) and the inductance (L). Faults in the windings leads to variances in the response of the applied signals. If three phase equipment is tested the response of each of the phases are compared to the other two. By this and the use of simple rules the condition is determined. Trending of the results is also possible for CBM or PM purposes. To detect the different faults the following is analyzed and evaluated:

- Winding faults: The unbalance between phases for Fi and the current/frequency response.
- Conductor to ground issues: Insulation to ground test.
- Connection issues: Phase resistance.
- Rotor problems: Inductance.
- Contamination or over-heating of windings: Inductance and impedance matching.

As this method can detect many of the same faults as ESA it can be used to confirm the findings from the ESA.

7.2 Drive monitor

Drive monitor is a condition monitoring and customer support system developed by ABB Medium Voltage (MV) Drives in cooperation with ABB Corporate Research in 2005. It has since then been installed at several installations worldwide (57). Experts from ABB can go online, get real time data, and assist the customer with fault finding and diagnostics. In 2008 ABB received Frost & Sullivan "2008 Excellence in Condition Monitoring of the Year Award" for their Drive Monitor.

Its basic function is to monitor the converter of a drive to detect changes in its status. According to ABB millisecond-based sampling rates are provided, and year-based scheduling is possible. The system is flexible, so that extra diagnostic packages can be added. By adding these DM can monitor other shaft train components such as the motor and driven machine. Additional measurements of values such as vibrations and temperature can be included and trending of data is possible for detection of deteriorating equipment conditions. DM is capable of detecting both electrical and mechanical problems.

Shortly described it consists of a hardware module, which can be installed inside the drive, and software which automatically collects and analyzes the signals from the selected parameters. The setup, as shown in figure 7.2, allows for real time remote access to the drive. Output parameters are such as phase current, voltage and shaft speed and torque.

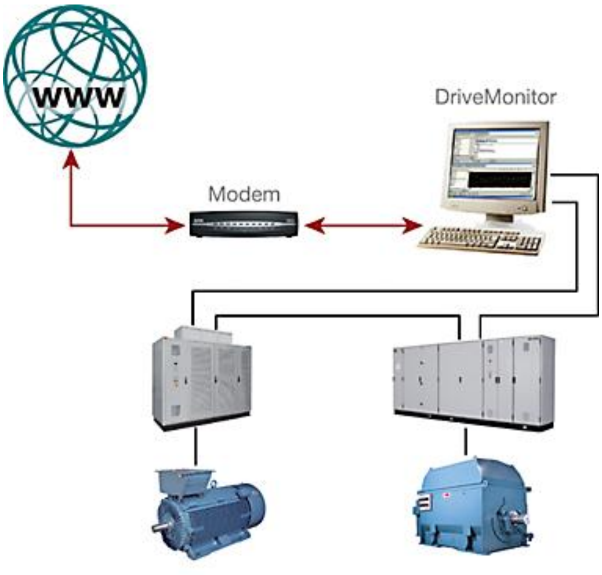


Figure 7.2: DM system setup.

7.2.1 System scalability

ABB states that DriveMonitor is a tool with good scalability. This is an important ability for a CM tool and is described in the following with examples from DM.

There are three dimensions describing systems scalability. These are shown in figure 7.3 and are diagnostics complexity, data sources and number of assets. The three are described in the following. The theory is mostly gathered from (58) and a presentation received from ABB.

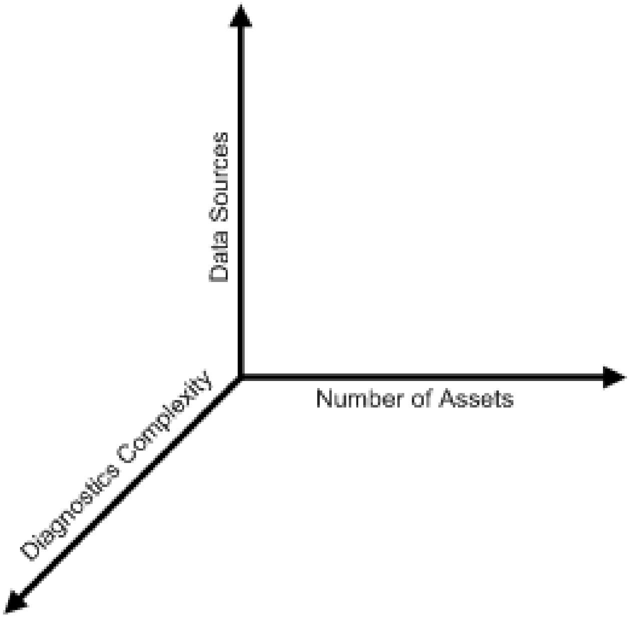


Figure 7.3: Dimensions of scalability.

Number of Assets

This dimension describes the comprehensiveness of the system, ranging from a single asset, such as a drive, to the entire production line with several assets. DM has good scalability as it can monitor:

- A single asset, e.g. the converter.
- Several assets such as those in the torque delivery line. Assets included here can be transformer, converter and motor.
- The entire process with torque delivery line and driven equipment such as compressor.

Diagnostics complexity

This dimension addresses the various levels of knowledge content and diagnostics functions. DM has the possibility to perform analyses with a wide range of complexity as it can make the use of:

- Simple threshold alarms.
- Trend alarms.
- Toolbox-based rules.
- Statistical processing tools such as PCA.
- Dedicated diagnostics packages for e.g. vibration analysis and bearing failure detection.

Data sources

This dimension addresses the availability of data, from utilization of what's already there to extension of additional measuring systems. DM can make the use data from many sources and assets as mentioned earlier, from both on and off-line measurements. These can be imported manually or automatically and continuous monitoring is possible.

7.3 Motor Condition Monitor

Motor Condition Monitor (MCM) is a product developed by Artesis. The patented technology is a result of a decade long research effort. The tool is made for condition monitoring of three phase systems such as generators, electric motors, the driven equipment and the driven process. The technology has been applied to a wide variety of applications. Examples are:

- Space shuttle main engine
- Helicopter engines
- Gas turbines
- Compressors
- Pumps

The tool was according to Van der Valt and Duyar (59) developed to eliminate the shortcomings of both the vibration and current signature analysis systems, and the principles underlying the operation are different from both of these. These shortcomings are according to (59) that:

- Current signature analysis requires expert personnel for data interpretation and it is time consuming. In addition it has difficulties determining if an abnormal signature is caused by motor related problems or unexpected voltage harmonics.
- Vibration analysis needs sensors which can be expensive, difficult to position and install, can only detect mechanical problems and finally the results needs to be analyzed by trained personnel.

The hardware part of MCM is manufactured as a small, box-shaped device, as shown in figure 7.4.

Figure 7.4: Motor Condition Monitor.

7.3.1 Principle of operation

MCM uses the electric motor as a transducer and measures current and voltage. The MCM unit is connected to the motor supply cables, thus all costs and problems related to equipment mounted sensors are avoided. It uses a model based fault detection and diagnostic approach with reference mathematical models of the equipment being monitored. These models are built during a learning phase which starts once the equipment is installed. According to (60) the mathematical model consists of a set of differential equations, which describe the electromechanical behavior of the system, and mean values with standard deviations. The model takes into account all speed and load variations experienced during the learn mode, so no manual configuration is needed. This model represents the normal operating conditions of the system. The results are stored in an internal database.

Once the learning period is done MCM switches over to normal operation. In this phase the MCM produces a series of new mathematical models of the system. This are compared to the reference model to detect deviations, and thereby faulty conditions. The magnitude and length of the deviation contributes to the determination of fault level.

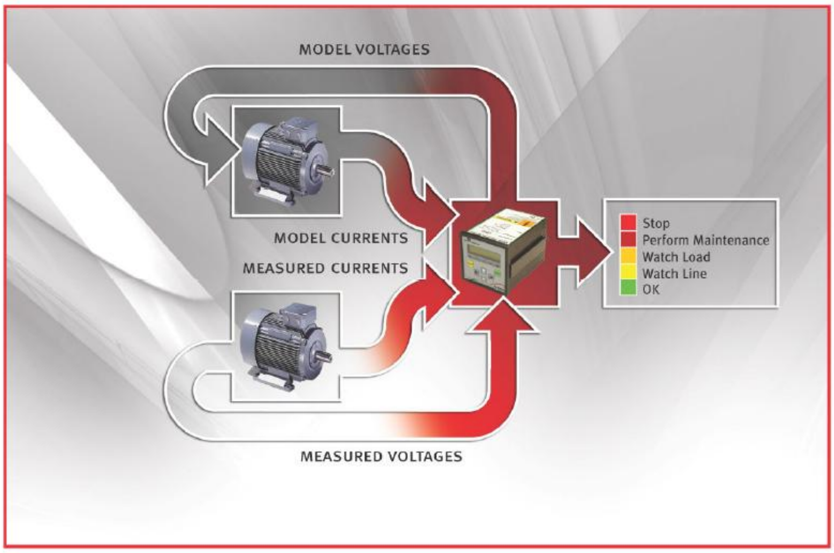


Figure 7.5: MCM operational principle (60).

22 different (model) parameters are monitored and compared. These are divided into three groups according to (60).

Group 1: This group contains 8 parameters that are called the electrical parameters. These are network equivalent parameters correlated to the physical parameters of the motor such as inductance and resistance. Group 1 parameters are sensitive to electrical faults developing in the motor, but might also give an indication of mechanical problems such as imbalance. The group can be further divided into two groups. The first, containing electrical parameters 1-4, indicates problems related to rotor, stator and winding. The second, containing electrical parameter 5-8, indicates electrical supply parameters.

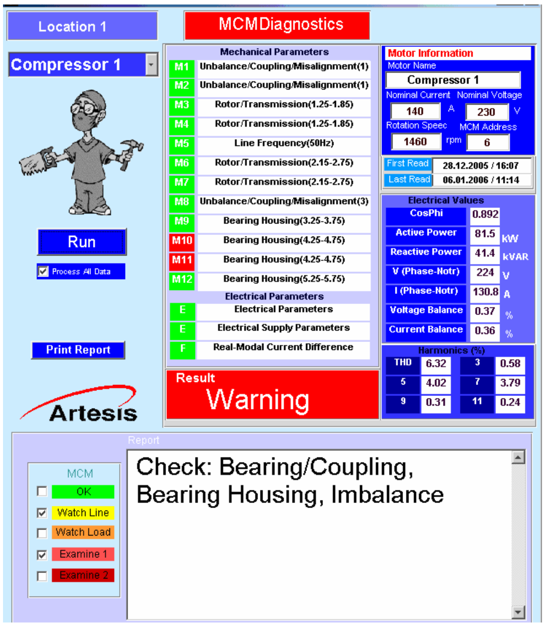
Group 2: This group contains 12 parameters related to mechanical issues such as bearing problems, misalignment, load imbalance and coupling problems. The parameters in this group are obtained from the frequency spectrum of the electrical signals. This is similar to current signature analysis, but MCM uses the spectrum obtained from the difference between the modeled current and the actual current.

Group 3: This group contains two parameters called fit parameters or residuals. They are sensitive to changes in the behavior of the system. The residuals are deviations between the currents calculated by the model and the actual currents.

The system also monitors the supply voltage and load conditions. If the load conditions deviate from the observed behavior during the learning period a warning is issued.

7.3.2 Application example

This example is given by (59). This compressor was in use at a battery manufacturer plant. Alarms where set off for mechanical parameters 10 and 11. They both continually increased during a time span of several months, which indicated a developing fault. The diagnostic report showed that these mechanical parameters correspond to frequencies for bearing housing faults. This diagnosis where confirmed during maintenance and repair. The two figures below shows the condition report from MCM and the trend plot for the two deviating parameters.



Mechanical Parameters

M1	Unbalance/Coupling/Misalignment(1)
M2	Unbalance/Coupling/Misalignment(1)
M3	Rotor/Transmission(1.25-1.85)
M4	Rotor/Transmission(1.25-1.85)
M5	Line Frequency(50Hz)
M6	Rotor/Transmission(2.15-2.75)
M7	Rotor/Transmission(2.15-2.75)
M8	Unbalance/Coupling/Misalignment(3)
M9	Bearing Housing(3.25-3.75)
M10	Bearing Housing(4.25-4.75)
M11	Bearing Housing(4.25-4.75)
M12	Bearing Housing(5.25-5.75)

Electrical Parameters

E	Electrical Parameters
E	Electrical Supply Parameters
F	Real-Modal Current Difference

Result
Warning

Motor Information
Motor Name: Compressor 1
Nominal Current: 140 A
Nominal Voltage: 230 V
Rotation Speec: 1460 rpm
MCM Address: 6
First Read: 28.12.2005 / 16:07
Last Read: 06.01.2006 / 11:14

Electrical Values

CosPhi	0.892	
Active Power	81.5	kW
Reactive Power	41.4	kVAR
V (Phase-Notr)	224	V
I (Phase-Notr)	130.8	A
Voltage Balance	0.37	%
Current Balance	0.36	%

Harmonics (%)

THD	6.32	3	0.58
5	4.02	7	3.79
9	0.31	11	0.24

Check: Bearing/Coupling, Bearing Housing, Imbalance

Figure 7.6: Report from MCM.

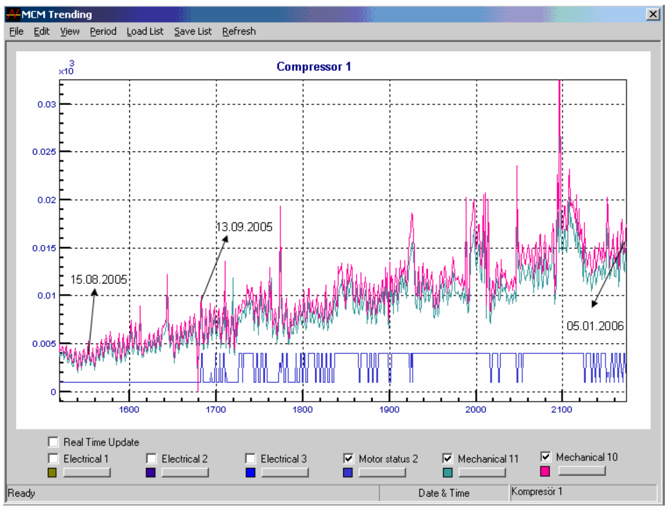


Figure 7.7: Trend plot for mechanical component 10 and 11 from MCM.

7.4 Advanced Motor Diagnostic Option

The Advanced Motor Diagnostic Option (AMD) is a tool which combines the power analysis capabilities of PS400 from Summit Technology with the on-line motor diagnostics software EMPATH from Framatome ANP, now AREVA.

EMPATH is a tool that uses MCSA for detection of damage and deteriorating system condition. The name EMPATH is an abbreviation of Electric Motor Performance Analysis & Trending Hardware. The EMPATH system, according to (61), consists of a laptop computer with their signal conditioning board, a 16-channek, 16-bit A/D card, and the special software for data readout and storage.

AMD can, according to (62), detect or give indications of the following load related conditions for both induction and synchronous drives:

- Looseness *
- Gear meshing *
- Gear box faults *
- Base looseness *
- Misalignment
- Unbalance
- Bearing damage

*(operator can detect by watching graphs)

7.4.1 Principle of operation

The tool, as mentioned above, uses MCSA- filtering at the data. The data gathered is all three phases of voltage and current. The input data is analyzed by the means of Fast Fourier Transform (FFT). The system is configured in such a way that both periodical and continuous data collection can be performed.

7.5 Discussion

The theory presented above is mostly provided by the vendors of the tools. Since they wish to sell their products the theory given by them is off course focusing on the positive aspects of the product and all the possibilities. Limitations are not mentioned although there most likely are some. In addition the description of how the tool is functioning, with algorithms and other details, is not presented. This is most likely because they wish to protect their technology.

However, the products presented here show that CM by the use of electrical drive signals is an area with big possibilities. It also shows that the technology to perform such CM on compression systems is both existing and commercially available.

8 Approach for system CM

In this chapter the theory presented previously concerning failure detection methods are used to propose an approach for condition monitoring of the entire compression system, including motor, gear and compressor. Since most of this will be a summary of previous chapters it is kept short.

As a basis a scalable tool such as DriveMonitor from ABB should be used. The reason for this is that several data sources have to be combined as well as different processing methods and levels of calculation complexity. The different datasets will be from measures of e.g. vibrations, temperatures, pressures and electric signals. Thermodynamic calculations, FFT or other methods for the electrical signals and simple threshold values for temperatures describes the range of calculations and diagnostic complexity needed.

By having a tool such as DM the need for several user interfaces are removed. This has traditionally been the case when monitoring such systems, as one tool is needed for thermodynamic calculations, one for vibration data and yet another for the electrical motor. Yet another reason for this is that data from the different methods can be combines as described later on.

The optimal case would be if ESA could provide all the diagnostic capability needed to monitor the entire process and all assets. This would give large savings as no additional sensors would be required. This is however not the case. As explained earlier the method might have the capability of finding compressor and gear issues, but when it comes to compressors the method seems to be insufficient. Therefore all the traditional sensors should be included. As the setup for performance monitoring is explained earlier this will not be repeated here. A typical setup for vibration monitoring is shown in chapter 10. Bearing temperatures for compressor bearings should also be included. With these in place and ESA technology as well the following approach could be used:

Compressor

Compressor thrust bearings monitored by temperatures with overall vibration monitoring as secondary method.

Compressor journal bearings monitored by overall vibration level with temperature as secondary method.

Fouling, erosion and seal failure monitored by calculations of thermodynamic relations and efficiencies.

Compressor rotor condition can be monitored by the use of vibration analysis. ESA data can for these problems possibly contribute with complementary information through the frequency spectrum as explained earlier.

For overall system efficiency and mechanical efficiency the thermodynamic calculations can provide the power supplied to the gas, while ESA can provide the shaft power. In addition the speed, power and torque signal derived from the electrical signal can provide valuable information on the general operating condition of the system. An example of such is mentioned in chapter 10 where speed oscillations are detected.

Gear

Gear failures seem to be more detectable by the use of ESA than compressor problems. However, since it is a bit uncertain just how capable it is at detecting all problems, overall vibration should be measured here as well. Gear meshing frequencies should be monitored by ESA.

Electrical motor

For the motor ESA seems to be capable of being the main CM method. Both mechanical and electric issues can be detected early by the use of ESA. The bearings vibration level should though be monitored as a “back up”

8.1 Comments

This “new” approach for CM of the system pretty much the same as the old approach as few, if any, sensors can be replaced by the ESA. The main reason for this is that it was hard to find actual confirmation of the ESA technology’s capabilities. It does however, even if applied as explained in this chapter, give great advantages. The diagnostic capability will be greatly improved by the high resolution spectrum provided by the electric signal. While it with only the measures of overall vibration level seems to be hard to diagnose a failure and find the root cause, the chances of doing so with ESA seems promising. Another advantage is the data provided from ESA concerning speed, torque and power. So by applying such a monitoring scheme I believe that the capability to detect failures at an early stage is a bit improved, while the chances for a correct diagnosis of the problem are much better.

9 Early Fault and Disturbance Detection

Early Fault and Disturbance Detection (EFDD) is a process monitoring tool currently being developed in collaboration between Statoil and ABB as a result of the TAIL IO[3] collaboration, where ABB has been responsible for the software development and Statoil has provided process data and presented demanding plots (63).The ambition was to design a PM tool that was both data driven and generic. The purpose of the tool is according to Meland and Lunde (64) to detect and localize faults and system disturbances at an early stage of their development. By doing this the goal is to achieve reduced downtime, optimized production and improved maintenance strategies [4 forprosjekt]. The name EFDD is simply made up of the methods involved in the tool. There are two modules, the Early Fault Detection module and the Disturbance Detection module. These two modules will be described in the following sections. Some of the theory is found in the EFDD help file.

9.1 How it works

The EFDD tool is according to Lunde et al. (63) based on black box methods. No detailed system or process knowledge is needed to build models. This is advantageous since process models are difficult and resource demanding to develop, and often inaccurate. However, the user is allowed to incorporate model knowledge, primarily by the use of virtual tags. In these tags known dependencies can be included. Yet another way to incorporate system and process knowledge is by limiting the models operating region to ensure acceptable model accuracy.

EFDD is a data driven tool and everything it does is based on data. All analysis operations require data input, provided by datasets. These datasets are sequences of data describing the process or system that are to be analyzed, most often organized in one or more time series, describing the process development over time. It is also possible to analyze more general data sequences that are not pure time series as long as the data is organized so that a sample describes a snapshot in time, space, or other according to Lunde[help file].

The system has three main components [help file] as shown in figure 9.1. These are:

1. The process database: this is where the input data is found. May be any third party database with an OPC-HAD interface. Data can also be loaded from file.
2. The EFDD program: A stand-alone application used for system configuration and data analysis.
3. The EFDD database: where all EFDD parameters and analysis results are saved.

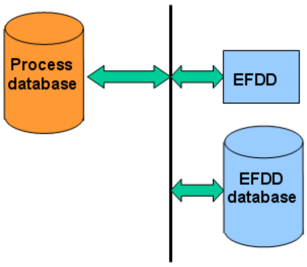


Figure 9.1: EFDD main components.

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[3] TAIL IO collaboration consists of Statoil and the companies ABB, IBM, SKF and Aker Kværner. The purpose is to develop routines for integrated operations and thereby reduce production losses and costs and better the HSE conditions.

The hierarchical structure of the software is shown in figure 9.2. The different levels have the following function, explained in descending order:

- Plant level: In figure 9.2 named Demo plant. This is the top level and is according to Lunde (63) a main grouping node. It typically contains all systems in a production site such as a processing plant or an offshore platform.
  - System level: In figure 9.2 named System 27. This is a part of a plant that can be naturally grouped. This can be a process segment such as gas compression or a group of similar equipment such as all heat exchangers.
    - Sub system: In figure 9.2 named Compressors, gear and turbine. Since a system can be large it would be advantageous to split it into smaller, more manageable sub-systems. It is at this level tags are defined and data is loaded. The two modules of EFDD can be seen as the next level.

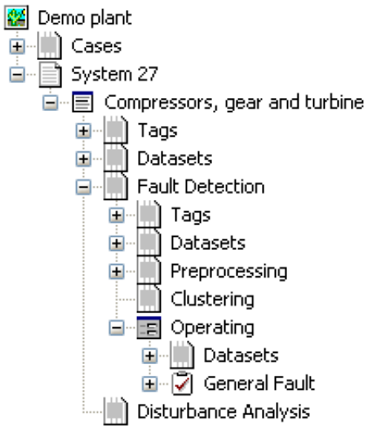


Figure 9.2: EFDD system hierarchy (64).

9.1.1 Workflow

As mentioned earlier EFDD is made up of two modules. The first is the Fault Detection module which according to Meland and Lunde (64) employs a quantitative model-based diagnostic method according to Venkatasuramanian's classification of machine diagnostics, while the second, Plant-wide Disturbance Detection is process history based. By having two modules with different approaches different problems can be addressed and solved. Figure 9.3 shows a waterfall model of the data flow in EFDD. The workflow is described in the following sections along with more detailed descriptions of the modules.

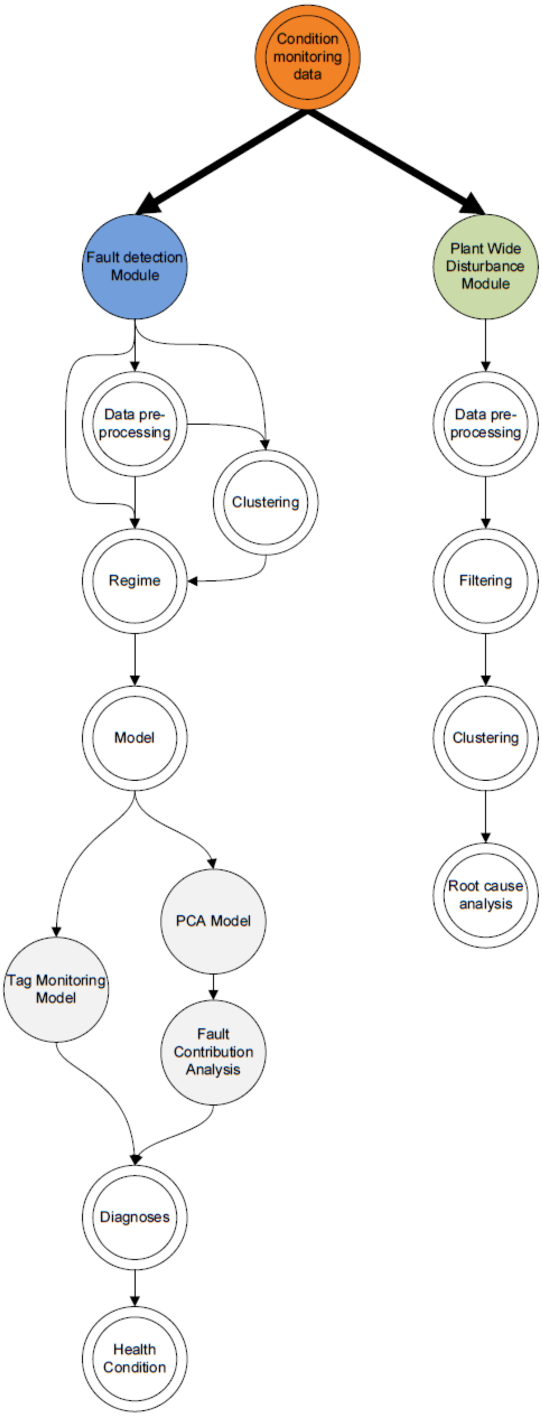


Figure 9.3: EFDD Data Flow (64)

9.1.2 Getting started

Once the process part that is to be monitored is identified a new sub system can be established. When this is done the next step is to select tags and import datasets. The dataset imported at this stage will serve as reference dataset (explained in the next section) and build the basis for the models used later on, so it is important to find a proper dataset. This dataset should according to (64) represent some variability within the data, but also display steady state properties. To cover the different operating conditions encountered by the system and get an idea of the variability a long time period is recommended. This could be of low resolution. Datasets with shorter time periods and higher resolution can be loaded later on.

In addition to the imported tags it is possible to create virtual tags. For pump or compressor applications a typical virtual tag could be the pressure increase. Once the virtual tag has been defined a dataset for this tag can be created.

Once the tags are selected and datasets imported the next step is building models by the use of one out of the two modules.

9.1.3 Early Fault Detection

The EFD module builds steady-state process models based on historical process data. To do this there is no need for detailed process knowledge except for determining which process variables to include in the analysis. The system is designed to model dependencies in a multivariable process. The model is build by the use of raw process data. The data which the model is built upon is called the reference dataset and is normally assumed to represent the normal operating condition, but models for faulty conditions can also be made. This model building is a onetime operation which should be performed by an expert user who got knowledge of both the process and the EFDD theory.

Once one or more models are built new datasets can be imported and tested against the models to see if the actual process behavior is consistent with the model estimates.

Pre-processing and data clustering

Once the datasets has been imported into EFDD and the EFD module is to be used there are two optional operations available as shown in figure 9.3. These are data pre-processing and data clustering. The pre-processing stage gives the opportunity to apply standard manipulation operations such as adding noise and offset. To remove outliers filters can be applied. If the clustering step is used, filtering can be performed on the basis of the created clusters.

Regimes

The next step is the regime. The regime is according to lunde et al. (63) used to characterize the boundaries of the models operating region. It picks out the data relevant for a model. An example of the use of a regime would be a system with different operating conditions. In this case a regime could be made for each of these if one model is not capable of describing the entire operating range perfectly.

The regimes are configured by use of Principal Component Analysis (PCA) to a selection of tags from a reference dataset.

Once the regime is defined the boundaries has to be set. This is rules for which data that can pass or not. In EFDD this can be decided by three regime types. They are:

Unlimited: All data can pass through the regime.

Statistical limits: Uses a multiple of the standard variation of the projected data as an acceptance criterion.

Range limits: Only includes data within a certain percentage of the projected data range.

Model

As shown in figure 9.3 two options are available for modeling, PCA Model and Tag Monitoring Model. The first option uses Principal Component Analysis (PCA) to build a model. PCA is a dimensionality reduction technique. It produces a lower-dimensional representation in a way that preserves the correlation structure between the process variables, and is optimal for capturing the variability in the data (65). Once the model is built new data can be imported and compared to it. The difference between the models estimate and the imported data is called the residual.

The second option, Tag Monitoring Model, monitors the individual signals rather than a model with several signals as input. This is a statistical Process Control method that indicates a fault if a statistical variance limit is exceeded.

Diagnoses

The model described above has the ability to detect that something is wrong and identify which sensor that is the cause of problem. This function has the intention of recognizing what is wrong. To do this EFDD uses the residual as a fault signature. Signatures occurring are compared to a database of configured diagnoses and similar residuals re listed. This function is suited for diagnosis of recurring faults.

9.1.4 Plant-wide Disturbance Analysis

When a single source of variation occurs in a plant it could manifest itself as a widely distributed disturbance, giving several oscillating or disrupted measurements. In such a case, finding the root cause is very difficult. With this as motivation ABB has developed PDA, which is a program intended to automatically detect disturbances and determine the root cause. The PDA module performs signal analysis in the frequency domain to detect the source of the disturbance. This method only analyze the suspicious dataset itself, and does not learn from previously run analyzes. Due to this it is not that suited for detection of developing faults and trending. The theory presented below is found mainly in the article Peak performance (66).

Clustering

The clustering process in PDA can be done in two ways as shown in figure 9.4. The first method to cluster tags is by Oscillating clusters. In this method tags with similar oscillation frequencies are grouped together. The detection is done by a calculated oscillation index.

The second method identifies and groups tags with similar power spectra by using the load vector from a spectral PCA analysis. The spectral clusters are presented in several ways. One of these is in a hierarchical tree.

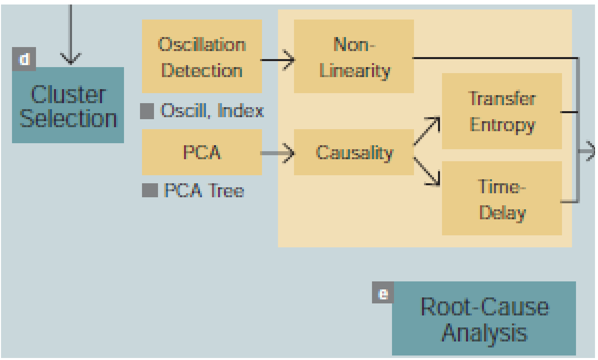


Figure 9.4: PDA methods (66).

Root Cause Analysis

As can be seen from figure 9.4 there are two main methods for root cause analysis. The first one, following the Oscillation Detection, is Non-Linear Root Cause Analysis. A process plant will typically act as a low pass filter. This means that the non linearity of measurements will decrease and oscillations will be smoothed when the distance to the source increase.

The second method, following the PCA analysis, is causality analysis. In this method the relationship between tags are investigated by comparing time delay or transfer entropy. Time delay comparison is based on the principle that a disturbance often can be observed at different process variables with a time lag. Further it is assumed that the variable closest to the root cause will show the disturbance before the once further away. The transfer entropy technique s a statistical method which provides a measure for the dependencies between two variables by use of probability density functions for the two variables. This is capable of detecting dependencies the time delay method is incapable of.

9.2 Comments

EFDD is a complex tool with many possible application areas. Compared to the scalability criteria presented in the DM theory part, it seems as EFDD has good scalability in two of the three dimensions. The two are data sources and number of assets. The reason for this is that EFDD can monitor single assets, such as a heat exchanger, or entire processes. It is flexible concerning data sources as described previously. When it comes to the last of the three, I am a bit more uncertain. The diagnostics complexity varies a lot as one choose between the simple tag monitoring solution or other methods such as PCA or PDA, but if this is sufficient to fulfill this criteria is uncertain. It is a possibility to define simple models in the virtual tag option, which in a way introduces the possibility for model based methods as well.

10 The system

In this chapter a compressor driven by a variable speed drive (VSD) is studied. The system will be briefly described along with the available tags and their measured parameter. The reason for the brief system description is that analysis is to be done in EFDD, which uses a “black box” approach as mentioned earlier, and because a generic description of motor, gear and compressor is given earlier in the report.

In addition to the traditionally monitored tags, such as vibration, displacement, temperature and flow, the system is monitored by the use of Drive Monitor (DM). The advantages of the data supplied by DM will be discussed. Finally the process parameters are imported to EFDD for analysis.

Observed problem

During an extensive logging of the monitored system parameters gained from DriveMonitor it was observed oscillations with 16 Hz frequency in the compressors speed and torque. Such oscillations are unwanted in the system since it might lead to fatigue damage to shaft and other components.

10.1 System description

The system consists of an ethanol compressor, driven by a variable speed electric motor, connected by a gear. A simple sketch is shown in figure 10.1. The gear increases the motor speed to drive the compressor at the wanted speed.

10.1.1 Tags

A complex system such as this, with many components and rotating parts, is heavily instrumented, and a lot of tags are available for condition monitoring purposes. The measured values are of process variables such as gas temperature, flow and pressure as well as mechanical properties like displacement and vibrations. In the following section some of the main tags are listed and explained. Their position in the system is also shown. The tags are available through APIS process explorer.

In addition to the ones available some parameters of the electric drive system has also been logged for the compressor in a time period. Examples of these are motor speed, torque and the three phase currents. The sampling intervals of these parameters are in the range of 0.1 to 0.2 ms.

The bearings of the system are seems to be equipped with temperature transmitters as well. These were not imported, but this should be done.

Some tags or values not available were mass flow rate, gas density and composition. As I understand the compressors way of operation, the density or composition of the gas will have an impact on the power consumption. So without these values important relations could be missed or performance parameters hard to find.

General tags

The tags below are general values available in the database.

- 25SIC8666: Speed setpunkt til VSD
- 25ZT8664: Opening anti-surge valve
- 25KA802_rpm_dm: 16 Hz component from effect spectrum of compressor running speed.
- DP1: virtual tag made in EFDD. Is the difference 25PT8660 minus 25PT8657, thus the differential pressure over the compressor, or in other words the pressure increase supplied by the compressor.
- 25JT8626: Shaft effect compressor. Unit is MW.
- 25ST8287: Engine speed in RPM.
- 25ST8327: Shaft speed (high speed shaft) in RPM

Tags related to gas properties

The tags related to gas properties available in the system are listed below. These tags are the ones suited for performance monitoring.

On the upstream side of the compressor the available tags are:

- 25TT8652: Temperature transmitter.
- 25FT9078: Flow transmitter.
- 25PT8670: Pressure transmitter.
- 25FT8655: Flow transmitter.
- 25TT8656: Temperature transmitter.
- 25PT8657: Pressure transmitter.
- 25PDT8658: Pressure diff. transmitter.
- 25PDT8767: Pressure diff. Transmitter.
- 25HV8653: Hand control valve (open/closed).

Downstream of the compressor the following tags are available:

- PT8660: pressure transmitter
- 25TT8659: Temperature transmitter
- 25TT8661: Temperature transmitter

Vibration

In addition to the abovementioned tags the system is equipped with vibration measures for motor, gear and compressor. The placement of these is shown in figure 10.1. The units for the following tags are µm if nothing else is stated. The values from the vibration transmitters are some kind of average or overall value, so they cannot be analyzed with the methods described earlier with the purpose of finding such values as bearing defect frequencies (BDF's).

Motor:

- 25YT8283X: Displacement transmitter. VT. 25YA8283X in APIS.
- 25YT8283Y: Displacement transmitter. VT. 25YA8283Y in APIS.
- 25YT8285X: Displacement transmitter. VT. 25YA8285X in APIS.
- 25YT8285Y: Displacement transmitter. VT. 25YA8285Y in APIS.

Gear:

- 25YT8323: Charge amplifier. VT. 25YA8323 in APIS. Mounted on frame for gear. Unit is mm/s.
- 25GT8309A: Displacement transmitter. GT. 25GA8309A in APIS. Mounted on TH.B. Low speed shaft, free end.
- 25GT8309B: Displacement transmitter. GT. 25GA8309B in APIS. Mounted on TH.B. Low speed shaft, free end.
- 25YT8316X: Displacement transmitter. VT. 25YA8316X in APIS. Mounted on JB. High speed shaft, coupling end.
- 25YT8316Y: Displacement transmitter. VT. 25YA8316Y in APIS. Mounted on JB. High speed shaft, coupling end.
- 25YT8321X: Displacement transmitter. VT. 25YA8321X in APIS. Mounted on JB. Low speed shaft.
- 25YT8321Y: Displacement transmitter. VT. 25YA8321Y in APIS. Mounted on JB. Low speed shaft.
- 25YT8325X: Displacement transmitter. VT. 25YA8325X in APIS. Mounted on JB. High speed shaft, free end.
- 25YT8325Y: Displacement transmitter. VT. 25YA8325Y in APIS. Mounted on JB. High speed shaft, free end.
- 25YT8329X: Displacement transmitter. VT. 25YA8329X in APIS. Mounted on JB. Low speed shaft, coupling end.
- 25YT8329Y: Displacement transmitter. VT. 25YA8329Y in APIS. Mounted on JB. Low speed shaft, coupling end.

Compressor:

- 25GT8274A: Displacement transmitter. Gauge transmitter. 25GA8274A in APIS. Mounted on TH.B.
- 25GT8274B: Displacement transmitter. Gauge transmitter. 25GA8274B in APIS. Mounted on TH.B.
- 25YT8276X: Displacement transmitter. Accelerometer. 25YA8276X in APIS. Mounted on JB.
- 25YT8276Y: Displacement transmitter. Accelerometer. 25YA8276Y in APIS. Mounted on JB.
- 25YT8278X: Displacement transmitter. Accelerometer. 25YA8278X in APIS. Mounted on JB.
- 25YT8278Y: Displacement transmitter. Accelerometer. 25YA8278Y in APIS. Mounted on JB.

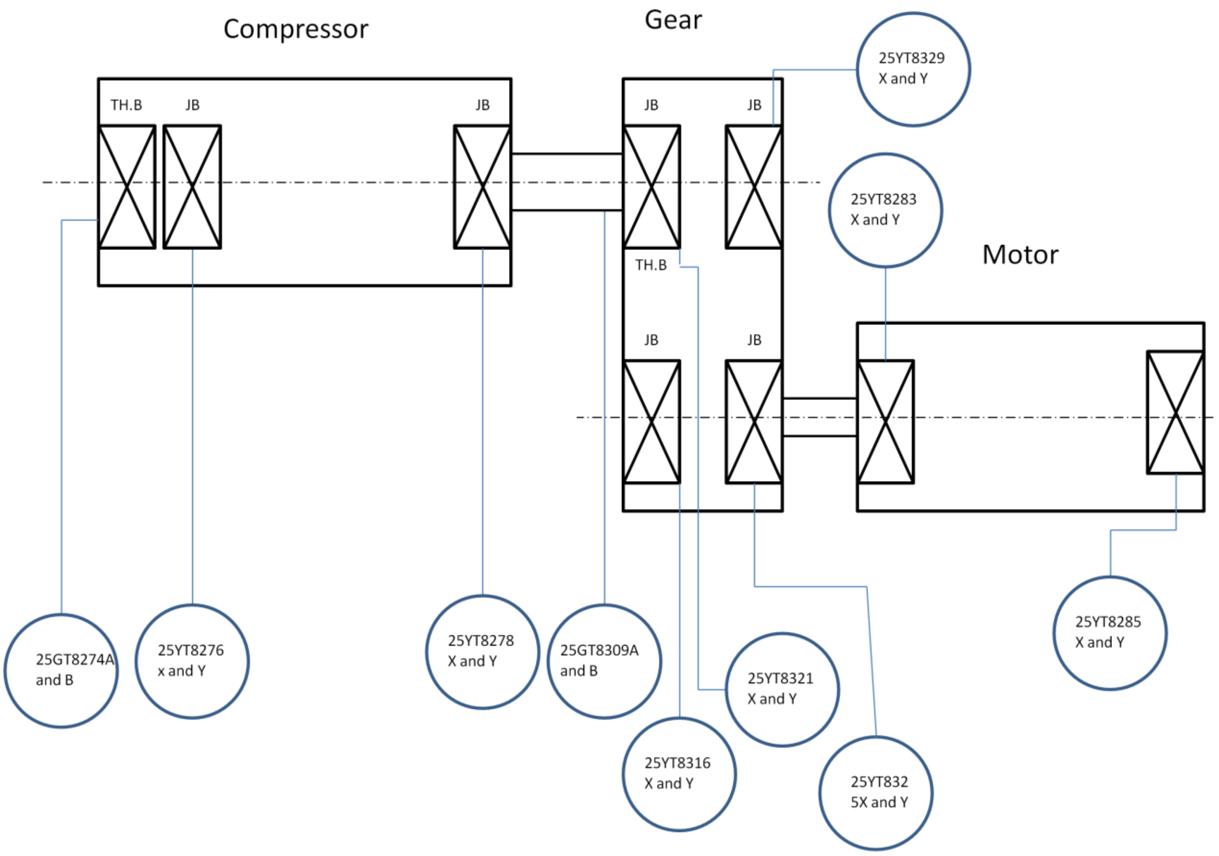


Figure 10.1: Vibration monitoring of System 25.

10.2 EFDD analysis

Having identified some of tags describing the main process parameters and variables, the next step is to import them to EFDD and analyze them. This section describes the workflow to do so. I was not able to perform a complete analysis in EFDD, but the part I did is describes as well as some ideas on how the rest can be done.

1. Create new sub system. Names this System 25.
2. Load data for System 25 from OPC database. For data loading the sample interval, start date and stop date has to be selected. The sample interval was set to 20 minutes due to the fact that this is the sample interval for tag 25KA802_rpm-dm which had the longest time interval between samples. The start and stop date was found by studying the data in APIS, trying to find an area of stable operation without starts and stops. In addition it would be of interest to find a time period covering several operating areas. The period chosen was from the 25th of December 2009 to the 29th of December 2009. Figure 10.2 below shows three tags from this period. The green line is the flow, the yellow is compressor speed and the blue motor speed. The plot of these values shows that there are several different operating regions. Once the abovementioned values are set the next step is to choose which tags to load. In this case all the tags listed for the system is loaded. The result of this operation is that a dataset named RAW 25.12.2009 00:00 is created.

☒	APIS.Kollsnes.25FIC9078	111,07		interpolative:good
☒	APIS.Kollsnes.25ST8287	1418,19		interpolative:good
☒	APIS.Kollsnes.25ST8327	10632,25		interpolative:good

30.12.09 11:35:02 I6 days I 01:00

Figure 10.2: Tag data displayed in APIS.

3. Once the dataset is imported there are two main choices. The data can be analyzed in the Fault detection module or the Disturbance analysis module. The two models and their functionality are explained earlier in the report.

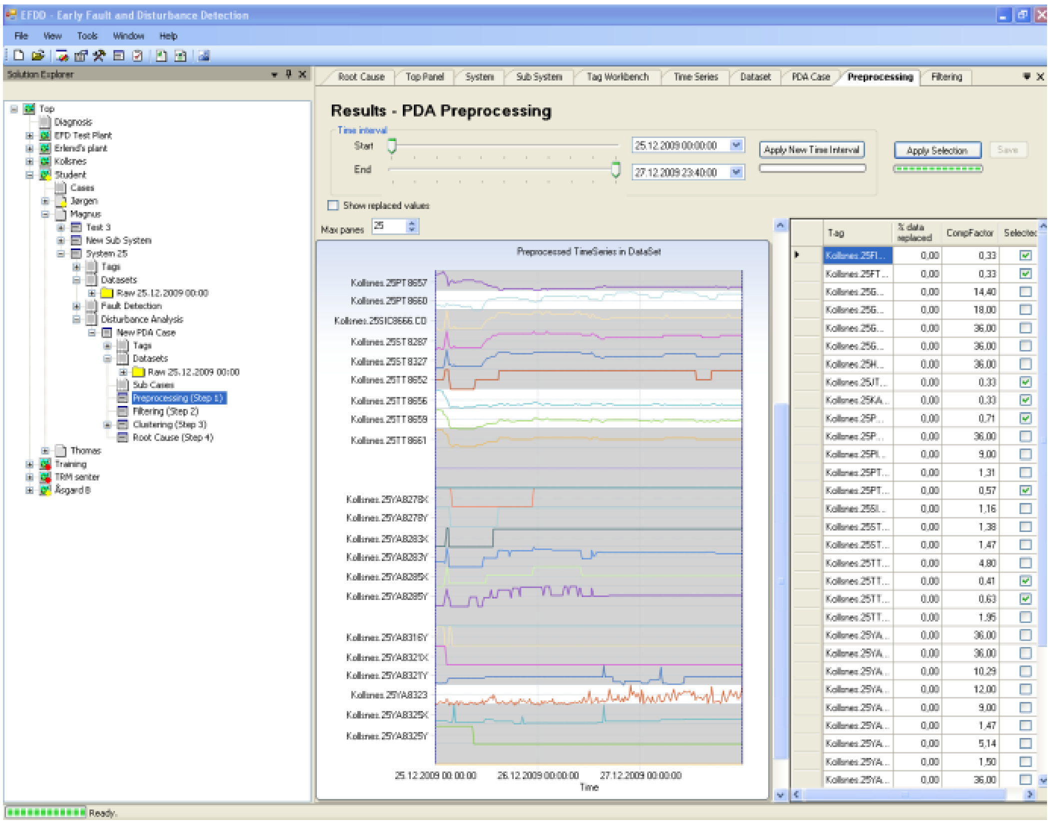
10.2.1 Disturbance analysis

This analysis was performed with help from skilled personnel at Statoil, and the purpose was to see if it was possible to detect any disturbances connected with the 16Hz oscillations previously mentioned.

This method should be well suited for a system such as this, with many components and many sensors all describing parts of a process line. Ideally, and if available, the entire process with values from higher up the gas flow path should have been included as well as further down. Examples of such are scrubbers and heat exchangers. However, for fault detection of mechanical issues in the compressor, gear and drive itself, the provided and mentioned tags should be sufficient.

First a new PDA case is started. Then the four steps are performed in the order shown in figure 9.3.

The preprocessing is done by choosing time interval. A screenshot from the preprocessing stage can be seen in figure 10.3. The whole period was chosen.



Results - PDA Preprocessing

Time interval
Start 25.12.2009 00:00:00
End 27.12.2009 23:40:00

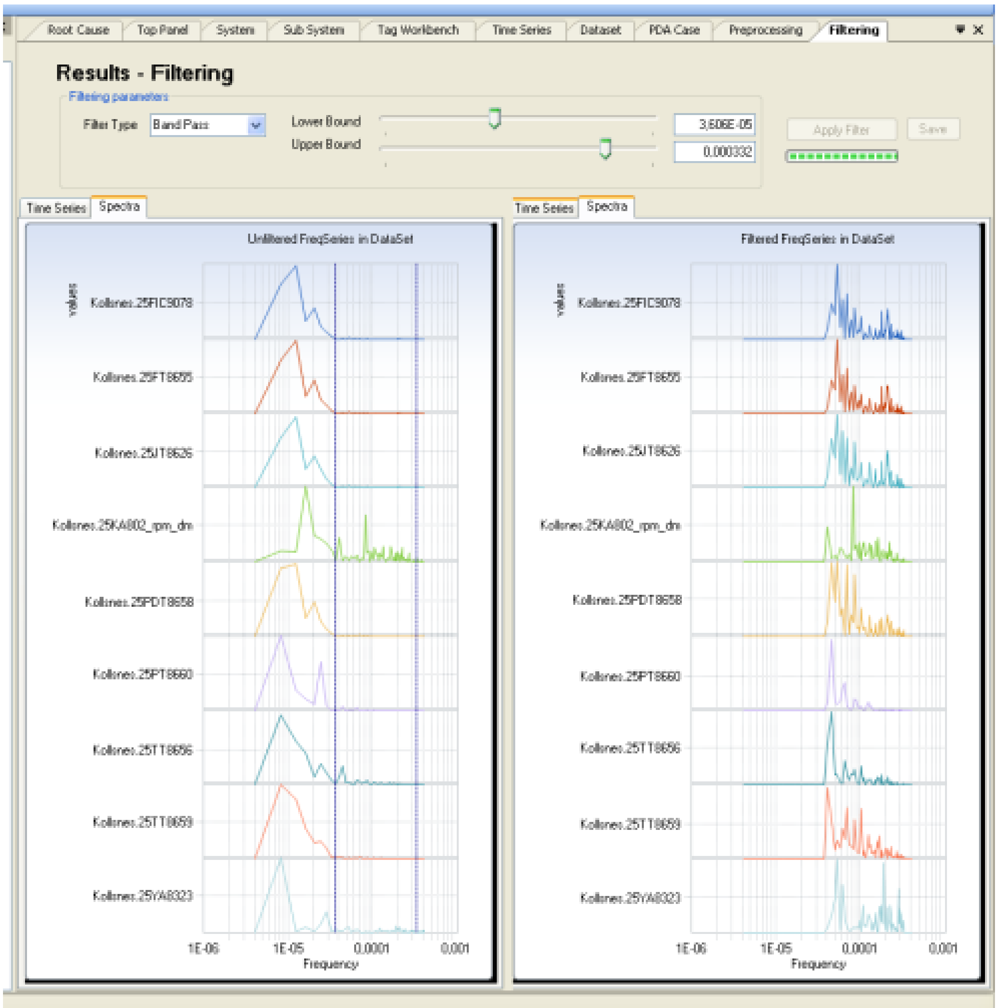
☐ Show replaced values

Max panes 25

Tag	% data replaced	CompFactor	Selected
Kollsnes.25FI...	0,00	0,33	☑
Kollsnes.25FT...	0,00	0,33	☑
Kollsnes.25G...	0,00	14,40	☐
Kollsnes.25G...	0,00	18,00	☐
Kollsnes.25G...	0,00	36,00	☐
Kollsnes.25G...	0,00	36,00	☐
Kollsnes.25H...	0,00	36,00	☐
Kollsnes.25JT...	0,00	0,33	☑
Kollsnes.25KA...	0,00	0,33	☑
Kollsnes.25P...	0,00	0,71	☑
Kollsnes.25P...	0,00	36,00	☐
Kollsnes.25PI...	0,00	9,00	☐
Kollsnes.25PT...	0,00	1,31	☐
Kollsnes.25PT...	0,00	0,57	☑
Kollsnes.25SI...	0,00	1,16	☐
Kollsnes.25ST...	0,00	1,38	☐
Kollsnes.25ST...	0,00	1,47	☐
Kollsnes.25TT...	0,00	4,80	☐
Kollsnes.25TT...	0,00	0,41	☑
Kollsnes.25TT...	0,00	0,63	☑
Kollsnes.25TT...	0,00	1,95	☐
Kollsnes.25YA...	0,00	36,00	☐
Kollsnes.25YA...	0,00	36,00	☐
Kollsnes.25YA...	0,00	10,29	☐
Kollsnes.25YA...	0,00	12,00	☐
Kollsnes.25YA...	0,00	9,00	☐
Kollsnes.25YA...	0,00	1,47	☐
Kollsnes.25YA...	0,00	5,14	☐
Kollsnes.25YA...	0,00	1,50	☐
Kollsnes.25YA...	0,00	36,00	☐

Figure 10.3: Screenshot from EFDD during preprocessing for PDA.

The filtering was done with a band pass. The selected band can be seen in figure 10.4 below along with the filtered signal. The reason for choosing this was to filter out the high peaks seen to the left on all the unfiltered signals.



Results - Filtering

Filtering parameters

Filter Type: Band Pass

Lower Bound: 3,606E-05

Upper Bound: 0,000332

Figure 10.4: Filtering in PDA.

This analysis did not detect any disturbances in the system. It can be mentioned that I was unable to perform the transfer entropy part of the Causality Analysis with the imported data as the dataset was too small. This method required 10 000 samples, something this dataset did not contain since the time interval was as long as 20 minutes over a period of only 4 days.

10.2.2 Fault Detection

The fault detection module has as mentioned previously two monitoring approaches. For the system in this report both seems to have some advantages. I did not perform any analysis in this module so in the following some thoughts and ideas of the possibilities and limitations are presented.

Tag Monitoring

This method does seem like a perfect way of monitoring vibration data and temperatures of bearings and motor. This is however not necessarily the case as machine speed changes, since this also will cause these variables to change. However, if threshold values exist they could be used, thus the Tag Monitoring would provide a simple way of monitoring that max vibration levels and temperatures not are exceeded.

Principal Component Analysis

This method seems to be the one in EFDD best suited for fault detection in a complex system such as this since it is capable of detecting dependencies and correlations between a large set of variables. Since the system has several operating conditions and the behavior most likely is non-linear several regimes must be made. This is as described earlier done by PCA. The use of PCA to define operating modes is also done by Matrikon (34), who states that this method was well suited for this task.

The parameters most suited to define the regime are as I can see it the rotational speed, the flow, power consumption for the motor or differential pressure. These parameters should also be connected by performance equations and compressor affinity laws.

By defining different operational modes, most likely to be different rotational speeds, the problem mentioned concerning the vibration levels dependency of the speed will hopefully be solved.

Some virtual tags that it would be interesting to create are:

- The relationship between compressor torque and speed is quadratic, as the torque is proportional to the square of the speed. This means that the compressor power is proportional to the speed in the third order. So tags consisting of compressor speed, simply RPM^2 and/or RPM^3 could be relevant for the analysis.
- If it is possible to get a tag describing the mass flow it could be of interest to make a virtual tag describing the power supplied to the gas. This tag will be of most interest if gas conditions and composition is quite constant or input values are available. However it would possibly have been better if such a value could have been imported to EFDD from a specialized tool for performance calculations.

10.3 Comments

As mentioned earlier the initial model building should be performed by an expert user with knowledge of the system and EFDD. This became clear to me while trying to perform analysis in EFDD. To get to know the tool and its functionality was time consuming. But even though I did not complete the analysis of this system I believe EFDD would be able to detect many of the possible failures encountered in such a system.

As a final thought considering the analysis of such a system it would be interesting if some of the functionality from DM could be implemented in EFDD.

11 Conclusion

The objective of this thesis was to investigate the different approaches to condition monitoring that utilized the electrical signals available from an electric motor, and to see if these where suited to monitor a compressor. As a result of this I was supposed to suggest new approaches for condition monitoring.

A method named Electrical Signature Analysis has been described. The method uses the electric motor as a transducer to detect faults, both electrical and mechanical, through a system. It is a non-intrusive method where current and voltage signals from the motor control center are used. Small changes in these signals generated by torque or air gap variations as a result of faults in the system are detected by the use of amplitude demodulation and Fast Fourier Transform or other similar techniques to perform spectral analysis. The fact that different failure modes show up at different frequencies in the current spectrum makes it possible to find the root cause. The method can also provide values of motor speed, torque and power.

It has been showed that ESA is capable of detecting most failures in the motor itself including mechanical problems. It is also possible to detect failures in gears with ESA. Applied at compressors it has proven the ability to detect flow related phenomenons. It is also showed how problems related to the impeller can be detected by observing the blade passing frequency in the current spectrum.

A new approach for condition monitoring by implementing ESA was proposed. This method utilizes most of the traditional CM method such as vibration analysis and performance monitoring, but ESA introduces some new possibilities, especially for diagnosis of failures by the use of the frequency spectra.

A condition monitoring tool named EFDD has been presented, and a short analysis has been performed by the use of it. Even though no conclusion was possible to make from the analysis EFDD seems to be well suited for fault detection in the presented system, especially when power and speed are available from the motor.

The use of electric motor data to monitor compression system condition show great potential and is absolutely an area worth investigating more thorough. If the technology can prove its capabilities it might replace vibration analysis in many instances.

11.1 Further work

Most of this report and the conclusions is based on theory with some application examples. This theory should be validated. To do this further work should include actual testing of a compressor driven by an electric motor by the use of an expert ESA tool.

The analysis in EFDD should also be completed. This would also involve trying to find the “missing” tag related to gas flow and properties.

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