Non-Invasive Technologies for Condition Monitoring of Synchronous Motors

John Sjölander
Abstract

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The modern industry today is highly dependent on electric motors of different types and sizes. Synchronous motors are used in applications where a fixed speed is desired. These machines are often found in high power applications where they are preferred over induction motors due to their higher efficiency. Synchronous motors represent large investments and typically drive processes where downtime results in significant capital losses. Thus, detecting faults at an early stage can help avoid catastrophic failures and be useful in the scheduling of maintenance. In order to detect faulty conditions before they terminate in a failure, machine operators must perform some kind of monitoring on the machines. Typically, the more critical the machine is for a process, the more effort is put on monitoring it. Before building a monitoring system for a machine, one must first decide what parameters that should be monitored. The obvious desire is to find a parameter that is easy and cheap to measure and at the same time can give detailed information about the working state of the machine.

The aim of this thesis is to evaluate whether the exciter stator current is an adequate parameter to use within a monitoring system for synchronous motors. The evaluation has been made through simulations of two different setups: One using a synchronous motor in the 20 MW range fed by a synchronous machine type exciter. And the other using the same motor but instead fed by an induction machine type exciter. It has been found that the exciter stator current can be used for detection of faults associated to the rectifier and stator short circuit of the main machine stator winding. It has not been possible to detect turn-to-turn faults in the main machine rotor.

The work has been performed at ABB Corporate Research in Västerås from June until December 2013.
**Sammanfattning**

Dagens moderna industrier är i stor utsträckning beroende av elektriska motorer för att upprätthålla sina respektive processer. Stora synkronmotorer återfinns ofta i applikationer där de fyller funktioner som är kritiska för processen som helhet, exempel på tillämpningar för sådana synkronmotorer är bl.a. krossverk, valsverk och framdrivningssystem för stora båtar. Haverier och funktionsstörningar är ofta förknippade med stora ekonomiska förluster och inom industrin läggs stor möda på att undvika oplanerade avbrott.

*Condition monitoring*, eller tillståndsövervakning, är en process i vilken maskinparametrar övervakas för att man på så vis, långt i förväg, skall kunna detektera annalkande problem i en maskin. Vid korrekt utförd tillståndsövervakning, kan oförutsedda avbrott undvikas och man kan på ett bättre sätt planera för serviceingrepp etc. Vilka maskinparametrar som övervakas kan skilja sig åt mellan olika system, men det övergripande målet är alltid att få goda indikationer genom så enkla mätningar som möjligt.

Syftet med detta examensarbete är att utvärdera en nyligen föreslagen maskinparameter som indikator i ett tillståndsövervakningssystem. Den föreslagna parametern är matarens statorström som tros kunna innehålla många av de signaturer som finns i maskinens fältström, detta p.g.a. att båda dessa strömmar är magnetiskt kopplade till varandra genom mataren. Fördelen med att utföra mätningar på matarens stator istället för direkt på fältlindningen är att matarens stator är stationär vilket möjliggör enkel signalöverföring, medan mätningar på fältlindningen kräver avancerad trådlös signalöverföring mellan den roterande rotorn och den stationära analysutrustningen. Ansatsen att spåra signaturer via matarens statorström är ny och har såvitt författaren vet inte tidigare utvärderats i någon liknande studie.

Tillvägagångssättet för utvärderingen har varit att koppla samman en FEM-modell av motorn med en Simulink-modell av mataren. Genom att samköra dessa modeller tillsammans har signaturer inducerade i motorn kunnat spåras i matarens statorström. Samkörningen av två modeller baserade i olika program kallas Co-simulering och är en relativt ny företeelse inom industrin.

Resultaten från arbetet visar att felsignaturer inducerade i motorn i vissa fall kan spåras i matarens statorström vilket innebär att parametern kan vara intressant att använda vid design av kommando tillståndsövervakningssystem.
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1 List of abbreviations

Alternating Current AC
Artificial Intelligence AI
Condition Based Monitoring CBM
Condition Monitoring CM
Differential Algebraic Equation DAE
Direct Current DC
Embedded Temperature Detector ETD
Fast Fourier Transform FFT
Induction Machine IM
Load Commutated Inverter LCI
Motor Current Signature Analysis MCSA
Partial Differential Equation PDE
Partial Discharge PD
Radio Frequency RF
Resistance Temperature Detector RTD
Synchronous Machine SM
Time Based Monitoring TBM
Time Frequency Decomposition TFD
Unbalanced Magnetic Pull UMP
2 Introduction

Today’s modern industry is heavily dependent on rotating electrical machines for various purposes. In Sweden it has been estimated that electric motors make up 40 % of the total electricity consumption [1]. Electrical motors come in various sizes and fulfill their function, either individually, or as a part of a more complex process involving multiple components. As the industry constantly evolves into a state of higher sophistication the latter implementation is becoming more and more common. This increase in complexity raises the demands on each individual component as malfunction might affect a whole process and become costly. The old principle of operation “run it until it brakes, then replace it” is no longer acceptable from an economical point of view. This is the development that has created the demand for condition monitoring (CM). Condition monitoring is a strategy for early detection of faulty conditions for electric machinery. If performed correctly CM have the possibility of reducing unexpected downtime of a machine and planning maintenance becomes easier [2].

2.1 Background

ABB have since many years provided products and services to the world market of power engineering, up to date with the latest research and standards. The majority of all motors in the world industry are induction motors and consequently, most of the public research and literature are devoted to this common type of motor. For some special applications however, synchronous motors are the natural choice. ABB have since a few years had a separate research program for CM of synchronous motors and the commercially available services will comprise synchronous motors as well as induction motors [3]. Most of the research work so far has been towards using the motors stator current and vibrations as indicators of failures.

When designing a system for CM one must first decide which parameters of the machine that should be monitored. The rotors field winding is positioned in the center of a synchronous motor and is consequently exposed to many of the electromagnetic abnormalities that are associated with its faulty conditions. Thus, the field winding current should be a good parameter for monitoring purposes, at least from a theoretical point of view. The exciters stator is magnetically coupled to the field winding and should therefore contain many of the same current signatures found in the field winding. The thought of being able to find detailed signatures through simple measurements is very appealing to any designer of a CM system.

Recent work at ABB CRC in Sweden, has suggested that the stator current of the exciter indeed might be an interesting parameter for future designs of CM services; having the advantage of easy accessibility.
2.2 Objective and disposition

The aim of this thesis is to further investigate the use of the exciter stator current as a monitoring parameter for CM systems, applied on synchronous motors. In order to better understand the different aspects of CM the thesis will begin with a literature review. The review will be made from a holistic perspective of CM, focusing on synchronous motors and non-invasive monitoring technologies.

A Simulink model of the exciter will be developed for evaluating the exciter stator current as an indicator of faulty conditions. This model will then be used as part of a platform where the behavior of the main machine during normal- and faulty conditions is modeled in FEM software. Co-simulation means that the two models are cooperating through the simulation, sending and receiving parameters from each other in each time step. In this way, a realistic model of the whole system (main machine connected to the exciter) can be obtained. This platform will then be used for determining the adequacy of using the exciters stator current as a monitoring parameter. Adequacy is in this thesis regarded both from a qualitative and quantitative point of view, leading to the following question formulation:

Is it possible to detect faulty conditions from the signatures of the field winding?

If so, how well are the signatures from the field winding maintained through the exciter?

2.3 Limitations

The different aspects of CM are extensive and in order to delimitate the scope of this thesis some details should be pointed out:

All simulations has been made on motors running at steady state, operations during transients has not been evaluated.

The analytical model of the exciter is simple and does not take into account magnetic saturation and the slotting effect in the current.

The model of the actual induction machine type exciter is fed by a LCI, see chapter 3.2.2. However, it has been modeled as an ideal sinusoidal voltage source. A consequence of this is that harmonics due to the switching frequencies are not considered in the model.

Regulators used for maintaining desired excitation of the synchronous machine has not been considered in the models.
3 Background theory to the work

The purpose of this chapter is to provide some background theory about rotating electrical machines and their auxiliary equipment. This theory will then be used for presenting condition monitoring, its role within today’s industry and its implementation on synchronous motors.

3.1 Introduction to rotating electrical machines

Rotating electrical machines are widely used in many of today’s industries. The two most frequent types are synchronous machines and induction machines. Both of these can be designed either for generator mode, where power is produced, or motor mode, where power is consumed. All rotating machinery must be able to create positive or negative torque in order to operate in either mode. The relationship between power (P) and torque (τ) is:

\[ P = τω \]  

(1)

Mechanical angular velocity is here denoted ω. One important difference between synchronous- and induction machines is by which physical principles the torque is created.

The simplest induction machine (IM) only has a squirrel cage rotor with no external current supply. When an alternating current (AC) is supplied to the stator windings this will create a magnetic field in the air gap, rotating in time with the AC oscillations. This rotating magnetic field will induce a current in the squirrel cage rotor bars according to Lenz’s law. This current will in turn create a magnetic field surrounding the rotor bars according to Amperes law. The cause of induced current in the rotor bars is the rotating magnetic field induced by the stator current. The change in rotor bar current will cause a torque between the stator and rotor, causing the rotor to start turning in the direction of the stators rotating magnetic field. This principle of operation illustrates one of the key terms for an induction machine, the slip. The slip is defined as the difference between the stators synchronous speed and the rotors operational speed. A greater slip will induce a larger current in the rotor bars and thus increase the torque. This increase can go on until the machine has reached the “pull out torque”. After this point has been reached the coupling between stator and rotor will be lost and the rotor will start to rotate uncontrollably. The benefits of induction machines are mainly their robustness in construction and inexpensive price [4]. Figure 1 shows the torque, slip diagram for a typical induction motor operating at constant speed. This diagram shows that the torque is a function of the slip.
A synchronous machine (SM) can have either an excited rotor or a non-excited rotor. A non-excited rotor typically has a set of permanent magnets supplying a magnetic field, whereas an excited rotor has an auxiliary current supply used for magnetization. Since the magnetization is made separately there is no need for a slip. Therefore, the rotor is magnetically coupled to the stator windings and rotates in synchronism with the stator magnetic field. The internal voltage of the machine and the external voltage of the grid can be represented as phasors in a diagram. The angle between these two phasors is called the load angle and is denoted $\delta$. An increasingly positive load angle will increase the torque produced by the machine, whereas an increasingly negative load angle will increase the torque consumed by the machine [5]. Figure 2 shows the torque, load angle diagram for a typical synchronous machine operating at constant speed. The figure shows that the torque is a function of the load angle.

Figure 1. Torque, slip diagram for an induction machine operating at constant speed.
By analyzing the equivalent circuit for a synchronous machine with internal voltage $E$ and synchronous reactance $X$, connected to an external grid with voltage $V$, one can derive the following equations for active power ($P$) and reactive power ($Q$) delivered to the grid:

$$P = 3 \frac{|V||E|}{X} \sin \delta$$  \hspace{1cm} (2)  

$$Q = 3 \frac{|V|}{X} (|E| \cos \delta - |V|)$$  \hspace{1cm} (3)  

During steady state operation the resistance of the stator windings is much smaller than the reactance, in the equations above the resistance of the stator windings is therefore neglected. The amplitude of the machines induced voltage $E$ is a function of the magnetization current and $X$ is a machine parameter approximated as constant. If the external grid voltage $V$ is constant and the amount of torque is a function of the load angle $\delta$ it is obvious that the amount of reactive power, delivered or produced, can be adjusted through the magnetization of the rotor [5].

Synchronous motors are usually more expensive than induction motors due to their higher complexity. They do however possess some properties that make them more suited for certain applications. Operation at different power factors is a feature that is made possible through the separate magnetization of the rotor. Many industrial facilities contain inductive motor loads that require reactive power support from the local utility system. By operating synchronous motors with a leading power factor, the overall power factor can be shifted toward unity. Synchronous motors can also withstand great load torque variations without losing speed. They provide a high starting torque and they are very efficient compared to induction motors [6].
Induction motors are cheap, robust and can be found more or less everywhere within the modern industry with numerous applications. Synchronous motors are usually chosen for those applications where their performance is superior to induction motors, e.g. where high starting torque is required or where load torque variations are not allowed to affect the speed of the motor. Size might also be a reason for choosing a synchronous- rather than an induction motor due to the higher efficiency and reduced losses. Typical applications for synchronous motors are: crushers in mining and cement industries, extruders, chippers and grinders in the paper industry, rolling mills in the metal industry and for maritime propulsion systems [7].

The differences in construction between synchronous- and induction motors obviously affect both failure modes and available monitoring technologies for each type of motor. The part that differs most between the two types is the rotor which contains more components in a synchronous motor, e.g. an exciter and a rectifier.

3.2 The exciter of a synchronous machine

The most basic property of a synchronous machine is that, during steady state, the rotor shaft of the machine rotates in synchronism with the stator current. In order to produce torque, the machine must have a set of magnets in the rotor that can interact with the time varying magnetic field, induced by the alternating current in the stator. The rotor magnets can either be permanent magnets or electro magnets [7]. The aim of this thesis is to evaluate condition monitoring strategies based upon exciter stator current. Since this current is non-existing in a non-excited rotor, the thesis will not further discuss non-excited rotors.

The current, necessary to drive the electro magnet, can be made accessible in the rotor either by using an exciter with brushes and slip rings or by using a brushless exciter. The exciter that utilizes brushes and slip rings to transfer direct current into the rotor can be fed with a direct current created outside of the rotor itself. This is often considered beneficial in terms of simplicity of construction. The drawbacks of this design are much associated with the large amount of maintenance that needs to be performed regularly. The slip rings and brushes are worn down with time and accumulate dust that can cause problems for the machine if not proper maintenance and cleaning is performed on a regular basis [8].

3.2.1 Brushless exciter - Synchronous machine type

The most common brushless exciter type works as an “inside out” synchronous machine. “Inside out” refers to the fact that the electro magnets are mounted on the exciter stator and the windings on the rotor whereas the typical synchronous machine has the opposite relation between magnet and windings. The exciter rotor is usually mounted on the same shaft as the main synchronous machine which is illustrated in Figure 3.
The exciters stator winding, surrounding the electro magnets, is typically fed by a separate DC regulator. Inside of the exciter stator is the rotor with windings mounted around its circumference. As the windings rotate inside of the stators magnetic field an alternating current will be induced in the rotor windings. Since the field winding of the main synchronous machine must be fed with a direct current, the AC produced from the exciter rotor is directly rectified. This rectified current coming from the rectifiers DC terminals can then be used to supply the main machine field winding [7] [8].

A basic schematic of a brushless excitation system is presented in Figure 4. Figure 5 and Figure 6 show the stator and rotor of a brushless exciter for a synchronous motor.
3.2.2 Brushless exciter - Induction machine type

In addition to the SM type of brushless exciters, which by far is the most common type, there also exists an IM type of brushless exciter. The only differences between these types are in which way the current is induced in the exciter rotor windings. Where the SM type has electromagnets fed by a DC, the IM type has stator windings fed with alternating current, typically from a Load Commutated Inverter (LCI). The AC frequency delivered by the LCI can be adjusted towards the rotational speed of the main machine. In this way a slip between stator and rotor can be obtained and this will induce a current in the exciter rotor windings [10].
A schematic of this kind of exciter would look identical as for the SM type presented in Figure 4. The only difference would be that the exciter stator windings are fed by an AC from a LCI rather than a DC which is the case in the SM type exciter.

3.3 The diode bridge rectifier

The diode is a semiconductor that only conducts in one direction. By putting six diodes in the configuration shown in Figure 4, a three phase rectifier can be made. A rectifier is used for making DC out of an AC input. The rectifying process works in the following way:

The three phases are assumed to be balanced sine waves as shown in Figure 7.

![Illustration of operation for a six pulse rectifier.](image)

Fundamental electric theory states that current will flow from high potential to low potential in an electric circuit. The highest potential is denoted $V_{\text{max}}$ and the lowest $V_{\text{min}}$ in Figure 7. By subtracting $V_{\text{min}}$ from $V_{\text{max}}$, $V_{\text{DC}}$ is obtained and this is the largest difference in potential that the circuit will see. Obviously, the current will flow according to this difference. By looking at Figure 4 and Figure 7 at the same time, one can conclude that the diodes will conduct according to Table 1.
Period | Conducting diodes
---|---
0° - 30° | From d3 to d2
30° - 90° | From d1 to d2
90° - 150° | From d1 to d6
150° - 210° | From d5 to d6
210° - 270° | From d5 to d4
270° - 330° | From d3 to d4
330° - 360° | From d3 to d2

Table 1. The conducting scheme of diodes in a six pulse rectifier.

It can be seen, that for during a period of 360° the output voltage will contain six pulses, hence the name six pulse rectifier. It is worth to point out that the magnitude of the output DC ripple in Figure 7 is affected by the load that is connected to the DC output. A large inductive value for the load will cause a large voltage ripple and vice versa [11].

The diodes of the rectifier have a variety of failure modes which will now be discussed briefly. The failure modes that will be discussed are: shorted diode, open diode and shorted rectifier leg.

A shorted diode fault can occur if the diode is exposed to over-voltages or currents. This is often the result of an abnormal transient such as lightning strike or phase paralleling. Shorted diode is the most common mode of diode failure in brushless synchronous machine rotating rectifier assemblies. If a diode is short circuited, it will eventually burn open if no other failure occurs first. Broken or loose connections external to the diode may have the same effect as an open diode, even though the diode itself has not failed open. Other parts of the rectifier may also open or short circuit due to both mechanical and electrical faults [12].
Figure 8. A healthy diode bridge rectifier.

Figure 9. A diode bridge rectifier with one diode shorted.

Figure 10. A diode bridge rectifier with one diode open.

Figure 11. A diode bridge rectifier with one leg shorted.

Figure 8, Figure 9, Figure 10 and Figure 11 illustrate the most common failures that can occur in the rectifier. These are also the modes that will be analyzed through simulation later in the thesis. Please note that snubber circuits are not shown in the schematics above, they are however included in the simulation model.

All of the failure modes mentioned above will affect the excitation of the synchronous machine. Depending on the load and pre failure excitation, a failure of the rectifier may cause further failures or for the exciter or field winding [12].

3.4 Condition monitoring - A general description

Historically, condition monitoring was a technique that was developed in order to enable Condition Based Maintenance (CBM) of a machine. Before CBM was possible, the most common practice for maintenance was so called Time Based Maintenance (TBM). In TBM, the maintenance of a machine is performed either according to a fixed time schedule or after a
certain amount of running hours. Certain parts are typically changed or repaired at different intervals decided from previous experience. TBM has doubtlessly prevented many failures in the past but has also wasted a lot of time and money, due to changing and repairing components that were still in working condition. Unexpected downtime may also occur if the maintenance schedule is not properly elaborated or if the machine fails due to unpredicted causes. CBM on the other hand rather determine maintenance needs, based on the working state of the machine. With accurate monitoring, the machine operator will always know the working state of the machine. Maintenance can be planned accordingly and, ideally, no unexpected downtime will occur. If condition monitoring is performed adequately, it can benefit the user in reduced life cycle costs and help to avoid risks due to improper machine operation [13].

Seen from a functional point of view, CM is a process in which machine parameters are being monitored. These parameters should be of such a kind that a significant change is indicative of a developing faulty condition. CM is meant to be proactive, i.e. it should provide as early indications as possible. In this respect it can be distinguished from protection systems which are retroactive and does only come in to use once the failure occurs. Which parameters that can provide relevant information differ and depend on various aspects such as machine-design and application. An ideal system for condition monitoring should be able to provide:

- An early diagnosis of the inception of a problem
- A clear indication on the type of fault
- A quantification of the severity of the malfunction
- Identification of the root cause of a problem, including suggestions how to mend it and how to prevent its reoccurrence in the future
- A prognosis of the remaining life-time of the machine

The chain of obtaining and processing monitoring information starts with the collection of data. This can be done using either invasive or noninvasive techniques and it can be performed continuously or during specific intervals of operation. Obviously, the most desirable way to monitor a machine is to use data that is already available, using noninvasive techniques. However, in many cases interpreting the information may be difficult if the sensor is not placed in the optimal location or cannot measure the right physical quantity to detect a certain fault. Consequently, the best method to use is a tradeoff between simplicity of measurements and quality of the gathered data. The processing and analyzing of information obtained through CM can be made either on-site or off-site relative the machine. The general approach in condition monitoring is to obtain a clear diagnosis with a minimal number of measurements. This is necessary due to the goal: providing a cost effective monitoring system for the customer [14].
Figure 12 illustrates some of the properties of condition monitoring and puts it in relation to protection systems and life time estimations.

In order to further understand the industrial role for condition monitoring it is important to distinguish between root causes and failure modes. A root cause is the fundamental error that initiates a failure sequence, whereas the failure mode is what terminates it. Root cause analysis is the process in which a failure mode is backtracked to its root cause. This is important, for example when making improvements on machine designs.

When designing a condition monitoring system, the analysis must be done in the opposite direction, tracing how a failure develops and foresee how to detect it at an early stage [2]. Figure 13 illustrates the difference between CM and Root Cause Analysis.
3.5 Common failure modes

Before looking at the specific techniques used for CM it is wise to first consider what faults that occur and what causes these faults might have. Obviously, all rotating electrical machines are subjected to electrical stress. In addition, the machines internal losses cause increased temperature that might lead to thermal stress. Machine rotation and attractive forces between machine parts can produce mechanical stresses and many machines today are exposed to dirt and contaminations, resulting in environmental or chemical stress. These stresses can be further categorized and applied to different parts of a rotating electrical machine where they are likely to cause a failure. Nandi et al. have provided an extensive description of condition monitoring and fault diagnosis. The rest of this chapter is in large a summary of parts of this material [15].

3.5.1 Stator related faults

Stator related faults often depend on insulation degradation or failure. The main function of winding insulation is to withstand electric stress. In many cases however, it must also endure other stresses such as mechanical, thermal and chemical stress. The most prevalent reasons for failure in the stator are: high core or winding temperatures, slack core lamination, vibrations, loose bracings of end windings, contamination, delamination and electrical discharges. The severity of these faults often increase with time, beginning as undetected turn-to-turn fault and develop into major phase-to-ground or phase-to-phase fault.
3.5.2 Rotor related faults
Something important to bear in mind is that the rotor design differs a lot between induction- and synchronous machines. Cracked rotor bars or end ring faults are common in induction machines. They can also occur in SM: s (where they only sometimes are used), albeit more rarely. This is because the rotor bars in a SM are only stressed during startup and transients, whereas they are stressed during all operation in an IM. Improper machine operation, such as frequent stall or excessive starting and stopping of the machine, may cause over currents in the rotor bars. These over currents will heat the rotor bars and possibly lead to failure. The rotor of a synchronous machine has a more advanced design with electric windings in addition to rotor bars. These windings are exposed to many of the stresses that were mentioned for the stator windings. The failure modes for the rotor also range from simple turn-to-turn faults to full short circuit of the pole. The cause for rotor related faults is often: thermal stress, mechanical dynamic stress such as centrifugal force or Unbalanced Magnetic Pull (UMP), improper manufacturing, contamination, corrosion or fatigue.

3.5.3 Bearing faults
The bearings are a crucial part for any rotating machine and can fail due to several reasons. Some of these reasons are corrosion, contamination, improper lubrication or improper installation. Once a bearing has been damaged this will be displayed as either vibrations in the machine or eccentricity defects of the connected parts. Increased temperature due to friction is also a useful indicator. Bearing faults are sometimes difficult to evaluate in terms of severity since the vibrations in the machine can be both amplified and suppressed from rotational speed and other properties of the machine. The machine vibrations can sometimes decrease even though a failure is imminent. One important thing to bear in mind on this point is that most large synchronous motors are equipped with sleeve or journal bearings which are less likely to fail than e.g. roller bearings.

3.5.4 Eccentricity related faults
Machine eccentricity is a condition of unequal air gap between the stator and rotor. There are two types of air gap eccentricity: static air gap eccentricity and dynamic air gap eccentricity. Static eccentricity may be caused by ovality of the rotor core or by improper positioning of rotor and stator parts during fabrication. If the rotor shaft assembly is sufficiently stiff, the level of static eccentricity does not change. Dynamic eccentricity either means that the center of the rotor is misaligned with the center of rotation, or that the rotational center and geometrical center of the rotor are misaligned from each other (whirling motion). This misalignment may be caused due to several factors such as: bent rotor shaft, bearing wear and mechanical resonance at critical speed. In reality, both static and dynamic eccentricities tend to coexist. A small level of static eccentricity often exists, even in newly fabricated machines.
This defect causes a steady one directional pull that in the long run, can bend the rotor shaft or wear down the bearings. Unless detected early, these effects may lead to a stator to rotor rub causing a major breakdown of the machine.

3.6 Condition monitoring technologies

Numerous methods are being used for monitoring electrical machines. A few of them are listed below:

- Electromagnet field monitoring, using search coils and hall effect sensors
- Temperature monitoring via hot spots, thermal imaging or bulk measurement
- Infrared recognition
- Radio frequency emission monitoring
- Vibration monitoring
- Acoustic noise monitoring
- Chemical analysis
- Motor Current Signature Analysis (MCSA)
- Models supported by Artificial Intelligence (AI) and fuzzy logic

A much commonly implemented monitoring technique so far in the history of CM has been MCSA, which is very well established for IM. This technique is built upon analyzing various frequency components in the machine currents. Sometimes a FFT analysis of the sampled current can provide sufficient information to determine the condition of the machine. Other forms of MCSA instead use the higher order spectrums, such as: bi-spectrum or tri-spectrum of the current for a frequency analysis. The higher order spectrum provides additional phase information that the FFT does not. This phase information can be used in post processing in order to increase the signal to noise ratio. Some advanced models involve historical analysis of current samples in order to decide specific patterns that may suggest a faulty condition. These models often use AI or fuzzy logic to find such patterns and require solid knowledge about the physics of the failure in order to relate certain signatures to specific faults [15].

Detecting a faulty condition at an early stage often includes capturing weak signals distorted by noise and much effort is put into appropriate signal processing. The way to design a successful system for condition monitoring is to find which parameters that can be easily measured and at the same time provide as much useful information about the fault as possible [14].

The goal of this section is not to give a fully detailed description of every available technology; the scope of such a task would be overwhelming. The aim is rather to provide a general picture about which parameters that can provide certain information and in which ways this information can be processed.
3.6.1 Stator related faults

As mentioned during the description of stator- and rotor related faults, over temperature is a common cause for failure. Monitoring of temperature can be made in several ways and the method of use is often a tradeoff between simplicity and accuracy. Local measurements are precise and easy to perform but will only provide local information. Bulk measurements on the other hand can provide a general picture for the machine temperature but are usually harder to perform and run the risk of overseer local hot spots. The simple way of measuring the temperature locally is to use thermocouples, Resistance Temperature Detectors (RTD) or Embedded Temperature Detectors (ETD). The temperature of a machine can vary depending on location. This fact need to be considered when determining the placement of such devises. Local temperature monitoring is primarily used for the stator since transmitting the signals from the rotor can be difficult [2].

Local measurements are often reliable but the detectors might not be located at the hottest point. Thermal imaging is a technique in which a thermal model of the machine is fed with various parameters and the model then predicts the temperature at several key points. A successful and accurate model has been built using only ambient air temperature and stator current as in parameters [16].

A third way of monitoring temperature is bulk measurements. This is typically performed on the coolant fluid and a sudden increase of temperature clearly indicates machine overload or insufficient cooling. The main drawback of this type of monitoring is the insensitivity to local overheating. Effort has been devoted to finding a method where many local temperatures can be obtained from devices embedded in the bulk of the machine. One suggested strategy is to use fiber optics embedded in the machines windings and to use its temperature sensitive properties to determine local overheating, only by this single measurement [17].

3.6.2 Rotor related faults

The faulty condition of broken rotor bars has been thoroughly investigated for induction machines and detecting these faults is often relatively easy. In an IM, the magnetic field induced in the stator must rotate asynchronously with the one induced in the rotor; otherwise no torque will be produced. This implies that there will be two rotating magnetic fields present in the air gap of an induction machine. One induced by the AC in the stator winding, and another one induced by the current in the rotor squirrel cage. If any of the bars in the squirrel cage break, this will cause an asymmetry in the magnetic flux induced by the rotor. No current will flow through the broken rotor bar and thus, the magnetic field around this bar will be weakened. This asymmetry in the resulting magnetic flux can be detected in various ways. One of the most common techniques is MCSA [13].
The rotor bars in a synchronous machine are only used during start up and for transient suppression. During normal operation the magnetic fields of both the rotor and the stator rotate synchronously and no asymmetry can be detected using the same techniques as for an induction motor. The startup procedure of some synchronous motors however, is very similar to the one of an induction motor. These synchronous motors are initially supplied with an alternating stator current but no auxiliary excitation of the rotor. Instead a current will be induced in the damper bars in the same way as it is induced in a squirrel cage, creating a torque that will make the rotor start to rotate. Once the magnetic fields of both the rotor and the stator are rotating more or less synchronously, the rotor field winding is excited, pulling the rotor into synchronism. Some researchers have successfully been able to detect broken damper bars during this startup process of a synchronous motor using MCSA combined with TFD tools [18].

The machine currents are not stationary during startup and therefore a simple FFT might not be the best tool for analysis. Time Frequency Decomposition tools, for example wavelet analysis, takes into consideration that signals do not need to be neither infinite in time, nor periodic. The traditional FFT is typically represented by a two dimensional plot with frequency on the x-axis and amplitude on the y-axis. The TFD-tools instead represent the analyzed signal with a three dimensional plot where time and frequency are displayed on the x- and y-axis, and the amplitude is displayed on the z-axis. Using this tool the researchers have been able to detect the broken damper bars by looking at certain patterns that appear in the three dimensional description of the signal [18].

Most of the technologies mentioned for monitoring the stator winding can theoretically also be used on the rotor winding. This is however, rarely done since measurements on the rotor are inevitably more difficult to perform online due to the rotation [2].

### 3.6.3 Bearing faults

The bearings in a rotating electrical machine can either be a rolling element bearing, a ball bearing or a sleeve bearing. In the first two types, metal balls or rolls are mounted between an inner and outer ring enabling these to spin independently of each other. Because of their construction, these types of bearing generate precise, identifiable frequencies in the vibration spectra that can easily be calculated beforehand. In a sleeve bearing the shaft is supported by a fluid film pumped, by the motion of the shaft, at high pressure into the space between bearing liner and shaft. Identifiable, specific frequencies are hard to determine in these kinds of bearings since the oil film effectively attenuates them, especially higher frequencies. The detection of a faulty bearing is most commonly done by monitoring vibrations. Some simple systems use only a FFT to decide when a fault is impending. Other more advanced systems instead use TFD analysis [19].
The frequency content of the motor current can evolve over time as the operation conditions of the motor changes. A group of researchers divided the motor operation into different modes, in which operation was considered normal and the current approximately stationary. Within each of these modes they used statistical tools in order to determine key frequencies, indicating faults, and threshold amplitudes for the key frequencies. In this way they were able to detect faults that would be impossible to detect using standard frequency domain tools [20].

### 3.6.4 Eccentricity related faults

The detection systems for eccentricity faults, most commonly rely on MCSA or spectral analysis of the machine vibrations. Both static and dynamic eccentricities will affect the air gap flux and this will be displayed more or less prominent in the machine current. This area has been thoroughly investigated for induction machines but the literature also covers synchronous machines [21].

The relation between number of poles and number of stator slots affect which harmonics that will be visible in the spectrum and this sometimes makes it difficult to distinguish between static and dynamic eccentricity. Vibrations in a rotating machine can occur from the attractive forces between core and end windings of the stator and rotor. Eccentricities between rotor and stator will cause oscillating forces which can be detected in the form of vibrations. Similar to the MCSA systems described above, this area is well covered for induction machines and less for synchronous machines. The literature concludes that mainly axial vibrations are detectable for synchronous machines whereas radial vibrations are not easily detectable [22].

It should be mentioned, that vibration transducers are delicate and expensive. They also have special installation requirements to avoid damage due to shock and vibration [2].

Other approaches, such as monitoring the stator voltage or shaft voltage also exist, but these techniques are so far only on an experimental stage and have so far not proved to be effective [23].

The background theory that has been presented so far, states that one of the key challenges in condition monitoring is to obtain clear indications of failures through simple measurements. In the literature review, no previous attempts of obtaining motor related failure signature through the exciter stator current have been found. In order to further evaluate the feasibility of this concept, simulations will be performed in the next section of the report. Two types of faults are to be evaluated; faults of the rectifier and faults of the main machine.
Any fault of the rectifier will cause a significant change of the field winding current. This severeness of the fault makes it possible to model the field winding as a time constant R-L load instead of modeling it with more sophisticated tools such as FEM. In addition, the faults of a diode are easy to determine according to the previously presented theory. All in all, this means that an evaluation of the three faults presented in section 3.3 quite comprehensively comprises all failures that are likely to occur in the reality.

Faults associated to the main machine are more intricate than the ones of the rectifier. This makes it more important to catch all the details of the fault. A more accurate representation of the load is needed and can be obtained by modeling the machine with FEM software. More information about FEM software will follow in the method section of the thesis. Possible faults of the main motor are larger in number and also harder to predict considering the complexity of the machine. Given the aforementioned conditions regarding main machine failures, it is easily realized that even a large amount of different simulations could never fully comprise all failures that can occur in the machine. Furthermore, simulations using FEM are quite time consuming. Two main machine faults have been chosen for the simulation part; partial short circuit of one stator winding and a turn-to-turn short circuit of the field winding in one rotor pole. These faults are both regarded as common, which is the main reason why they were chosen.
4 Method

Some basic theory for rotating electrical machines and their supporting equipment has now been presented along with a brief insight in the field of condition monitoring. The general idea of condition monitoring, failure modes and finally condition monitoring techniques has been presented. The proposal of this thesis is to use the exciter stator current as an indicator for various faulty conditions. The failure modes to be evaluated concern both the synchronous motor and the exciter with auxiliary equipment. The next part of the thesis will describe the methods that were used for analyzing the different failure modes.

The whole CO-simulation platform can be divided into three parts; the Simulink model, the FEM model and the communication module through which the CO-simulation is made possible as is shown in Figure 14.

![Figure 14. The CO-simulation platform.](image)

4.1 The Simulink model

The Simulink model developed during this thesis was built using the power systems toolbox. The power systems toolbox has good support for most electrical machines, loads and sources, making it easy to build a model without defining your own circuit equations. The layout of the model is quite simple.
The exciter is represented by either a three-phase synchronous machine (platform using the SM type exciter) or a three-phase wound rotor induction machine (platform using the IM type exciter). Both of these machine models have angular velocity $\omega$ and a voltage supply as in parameter and real machine data such as number of poles, reactance etc. are specified in each model. The three phases from the machine model is then connected to a three phase diode bridge rectifier which is identical in both platforms. The only components of the rectifier are the diodes which also have real values for forward voltage drop and on resistance. The DC output of the rectifier is then connected to the field winding which is modeled as an R-L load. The impedance of the field winding was set to a constant value. All machine data and values used in the model have been provided by ABB supervisor Pedro Rodriguez.

![Figure 15. A snapshot of the Simulink model (SM type exciter). The red square marks out which components that are used for the communication with the FEM software. Voltage measurements sent to the workspace and current obtained from the workspace.](image)

### 4.2 The FEM model

The FEM model that represent the main machine actually in itself consists of two models, one field model and one circuit model. The field model is a geometrical model where the different materials are represented by their respective properties. The field model looks like a two, or three dimensional cross section of the machine, perpendicular to its rotational axis, where rotor poles, stator slots, conductors etc. are shown. The software uses this model by dividing it into many small pieces (finite elements). Maxwell’s equations, which are the fundamental equations to describe electromagnetic phenomena’s on the macroscopic level, are set up for each node. Mathematically speaking this model yields a large number of Partial Differential Equations (PDE: s).
The circuit model of the machine is a lumped parameter model where the different physical devises are generalized and represented by basic elements; resistances, capacitances, inductances and sources. The network equations are set up through nodal analysis (Kirchhoff’s laws).

Mathematically speaking this model yields a large number of Differential Algebraic Equations (DAE: s). During simulation the software solves the different sets of equations, PDE: s and DAE: s, by coupling them together. The exact procedure in which this coupling is made is complex and many different techniques exist. By repeating these calculations over a time series where the rotor position is changed in the field model currents in all conductors can be calculated [24].

The FEM model can also simulate faulty conditions of the machine. Shorted turns are modeled by substituting the sides of a specific turn into a conductor in perfect short circuit [25].

The input to the FEM model is a field winding voltage, and the output is a field winding current. These parameters are updated every time step and exchanged through the communication module. The FEM software that has been used is ABB internal software and has been provided by ABB supervisor Pedro Rodriguez.

4.3 The communication module

In each time step, the FEM model takes its input values from an input file and output values are written to an output file. Both of these files are readable and editable using inbuilt Matlab functions such as txtread and txtwrite. This convenient feature was used when creating the communication module. A voltage measurement is made over the field winding in the Simulink model and sent to the Matlab workspace. A script in Matlab then writes this value into the FEM input file and then calls the FEM model to run for one time step. After this time step is performed, the same script reads the field winding current value from the FEM output file and sends this to the Simulink model which feeds it directly into the field winding through a current source.

One major advantage of this CO-simulation approach is its usability. Any information that is available in the FEM output file can easily be called for in Matlab, and an engineer without much previous programming experience can easily modify the communication module according to own preferences. The drawback is mainly execution speed which is multiplied around five times due to the Matlab script.
4.4 Simulation of diode faults

The initial simulations were made with respect to faults in the diode rectifier, and performed by using the Simulink model only. It was decided that the main field winding could be modeled as an R-L load where both these parameters were kept constant in time. Because of this assumption the FEM-model was not necessary for performing the simulations and simulation time was greatly reduced. The two different models were then run for each of the four modes previously presented in Figure 8, Figure 9, Figure 10 and Figure 11.

Analysis of the signatures were made using FFT. The signals were sampled during 0.5 s with a sampling frequency of 6000 Hz. This gives a FFT resolution of 2 Hz and an upper limit of 3000 Hz.

4.5 Simulations of main machine faulty conditions

The faulty conditions of the main machine are more complex than the ones associated with the diode bridge. The impedances of windings will change in time and in addition to this flux waves in the air gap of the machine might induce additional current in the different conductors. It was decided that the best way to model these faults was to use FEM software. A full CO-simulation was run, using Simulink, FEM and communication module simultaneously according to their previous description. Once the whole time series has been run, the resulting signatures from the field winding current and the exciters stator current were analyzed using FFT. The signals were sampled during 0.5 s with a sampling frequency of 6000 Hz. This gives a FFT resolution of 2 Hz and an upper limit of 3000 Hz.
5 Results

5.1 The CO-simulation approach

Before looking at the explicit results from the different simulations it might be interesting to see what actually differs between the CO-simulation approach and the original approach where the field winding voltage was held constant through the whole simulation. The high inductance of the field winding will cause a large voltage ripple and this indeed affects the field winding current. It has been found that both lower- and higher order harmonics have increased in the CO-simulation approach in both models. This is expected since the FEM software takes slotting effects of the stator into consideration. In the IM type exciter model, a large number of “noise like” harmonics are induced in the field winding current due to the asynchronous rotation of the exciter.\(^1\)

5.2 Results from the simulations

The analysis that was made for both exciter models, in totally seven different conditions and from two different measurement points rendered quite a few plots which are all presented in the appendix along with a brief description and discussion for each of them. To get a better overview, a summary of the analytical results is presented in Table 5 and Table 6. In order to understand the meaning of the colored shapes, an explanation is given in Table 2 and Table 3. A summary of all seven conditions is given in Table 4.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Green Square]</td>
<td>This means that the signature associated to this fault is very prominent in the analysis and can easily be distinguished from noise etc.</td>
</tr>
<tr>
<td>![Yellow Circle]</td>
<td>This means that the signature associated to this fault is fairly prominent in the analysis and can be distinguished from noise etc.</td>
</tr>
<tr>
<td>![Red Diamond]</td>
<td>This means that the signature associated to this fault is not at all prominent in the analysis and cannot be distinguished from noise etc.</td>
</tr>
</tbody>
</table>

Table 2. Description of the quantitative aspects made in the analysis of results.

\(^1\) Plots supporting this statement have been obtained in the post process tool in the ABB internal software. They can therefore not be presented in this version of the report.
Symbol Explanation

This means that the signature associated to this fault clearly resemble what can be expected from a theoretical point of view. Harmonics occur where they are expected etc.

This means that the signature associated to this fault somewhat resemble what can be expected from a theoretical point of view. With additional information about the machine the harmonics can be theoretically motivated.

This means that the signature associated to this fault does not resemble what can be expected from a theoretical viewpoint. Harmonics do not occur where they are expected etc.

Table 3. Description of the qualitative aspects made in the analysis of results.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Description</th>
<th>Simplified simulation</th>
<th>Full Co-simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Healthy rectifier</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Shorted diode</td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>3</td>
<td>Open diode</td>
<td>●</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Shorted leg</td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>5</td>
<td>Normal operation</td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>6</td>
<td>Partial stator short circuit</td>
<td></td>
<td>●</td>
</tr>
<tr>
<td>7</td>
<td>Turn-to-turn rotor short circuit</td>
<td></td>
<td>●</td>
</tr>
</tbody>
</table>

Table 4. Summary of the different conditions investigated.
<table>
<thead>
<tr>
<th>Condition</th>
<th>Qualitative detectability</th>
<th>Quantitative detectability</th>
<th>Detectable by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy rectifier</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Shorted diode</td>
<td>![Green]</td>
<td>![Green]</td>
<td>Lower order harmonics associated with the rectifier</td>
</tr>
<tr>
<td>Open diode</td>
<td>![Green]</td>
<td>![Green]</td>
<td>Lower order harmonics associated with the rectifier</td>
</tr>
<tr>
<td>Shorted leg</td>
<td>![Green]</td>
<td>![Green]</td>
<td>Lower order harmonics associated with the rectifier</td>
</tr>
<tr>
<td>Healthy machine</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Partial stator short circuit</td>
<td>![Green]</td>
<td>![Yellow]</td>
<td>Lower order harmonics associated with the main machine</td>
</tr>
<tr>
<td>Rotor turn-to-turn fault</td>
<td>![Red]</td>
<td>![Red]</td>
<td>Faulty condition not detectable</td>
</tr>
</tbody>
</table>

Table 5. Summary of the analytical results for the SM type exciter. * means healthy condition and these simulations are only used for comparisons to faulty conditions.
<table>
<thead>
<tr>
<th>Condition</th>
<th>Qualitative detectability:</th>
<th>Quantitative detectability:</th>
<th>Detectable by:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy rectifier</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Shorted diode</td>
<td>○</td>
<td>♦</td>
<td>Lower order harmonics associated with the rectifier</td>
</tr>
<tr>
<td>Open diode</td>
<td>○</td>
<td>♦</td>
<td>Lower order harmonics associated with the rectifier</td>
</tr>
<tr>
<td>Shorted leg</td>
<td>○</td>
<td>♦</td>
<td>Lower order harmonics associated with the rectifier</td>
</tr>
<tr>
<td>Healthy machine</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Partial stator short circuit</td>
<td>○</td>
<td>○</td>
<td>Lower order harmonics associated with the main machine</td>
</tr>
<tr>
<td>Rotor turn-to-turn fault</td>
<td>◇</td>
<td>◇</td>
<td>Faulty condition not detectable</td>
</tr>
</tbody>
</table>

Table 6. Summary of the analytical results for the IM type exciter. * means healthy condition and these simulations are only used for comparisons to faulty conditions.

All of the faults regarding the six pulse rectifier are fairly easy to detect in both simulation platforms. The partial stator short is also detectable using both platforms whereas the turn-to-turn fault of the rotor does not give any signature on neither the exciter-, nor the field winding current. The qualitative detectability decreases for the platform using the IM type exciter. This is due to the higher complexity of the signatures that this kind of exciter produces. Both the slip and the frequency of the supply will displace the position of harmonics, making the post analysis more complicated.
6 Concluding remarks

6.1 Discussion

The initial literature survey that formed the theoretical framework of this thesis, found that the technique of analyzing current signatures in order to determine and evaluate faulty conditions for an electric machine, has been used for quite some time. It did however not find any previous attempts of doing this analysis on the exciter stator current which has been the suggested parameter within this thesis.

The results from this thesis suggest that some faulty conditions indeed can be detected using this approach. The simulations were performed on two different setups, each using a different type of exciter. It should be emphasized that the analysis of signatures differs a lot between these two exciter models and that the post analysis is significantly more complex when using an IM type exciter. Bearing in mind that the supply for the IM type exciter is somewhat simplified, not taking switching frequencies of the inverter into consideration, the results might be a bit optimistic at the moment.

6.2 Sources of error

6.2.1 Simplified simulations

The model that has been used for these simulations is rather simple, basically only consisting of a synchronous machine model, a rectifier and an R-L load. Simulink machine models have been used together with real machine parameters. The only parameter that is regarded as slightly approximate is the impedance of the field winding which is also held constant in time. The resulting signatures for any of the three faults that were analyzed are however very clear. It is very likely that even if the impedance value would be changed significantly, the signatures would still be sizeable.

6.2.2 Full CO-simulation

The platform that is used for these simulations uses a FEM model of the motor as a load, instead of the R-L load that was used in the simplified simulations. This way of modeling the load greatly increases the accuracy of the model but also introduce the possibility of numerical errors due to the use of FEM. Also in this model the impedance of the field winding is a major issue since the Simulink model uses a fixed value for it when determining the voltage for the next time step. From the author’s point of view, this is regarded as the largest source of uncertainty in the platform as a whole.

An attempt has also been made to verify a good performance of the FEM model. For all three conditions, in which full CO-simulation has been used, the motor has been run at three different
operational points where both power output and power factor has been varied. The resulting currents, voltages and torques have then been analyzed using the inbuilt post processing tool of the FEM software. This analysis show that the performance of the motor show good consistency with the operational point in which it is operated. This should verify that no numerical errors are affecting the FEM model as it presently is used.\textsuperscript{2}

6.3 Future work

From the authors point of view, the most significant improvement of the CO-simulation platform would be to implement new impedance values of the field winding in every time step. A more accurate impedance value would also result in a more accurate value for the field winding voltage that would then be used in the FEM model. Adding these calculations to the present platform would be very easy to do with just some minor changes in the code.

It would also be interesting to run the model for other types of motor faults. This could further clarify which types of faults that induce signatures in the field winding current, and also how severe they must be in order to be visible in the exciter stator current.

Finally, it must also be made clear that the method of using distinct harmonics to indicate a certain fault is easy in a simulation environment, but not necessarily in reality. The cause of a specific harmonic can in reality have many different causes, some predictable but others highly unpredictable. Considering this fact it is obvious that simulations must be verified towards experimental results before any firm conclusions can be made.

\textsuperscript{2} This analysis has been made using internal ABB software. It can therefore not be published in this version of the report.
7 References


8 Appendix 1

This appendix will provide a full documentation of the analysis that was made for all the conditions (healthy and faulty) discussed in chapter 5.2. The intention is that the appendix will support the statements that were presented in the summary of results (Section 5).

The analysis was made on two models (IM and SM type exciter), for seven different conditions (see Table 4), and with two different measurement points (exciter stator and field winding). Presentation in both time and frequency domain was also found to be relevant. This means that a total number of 56 plots need to be presented. When making this appendix the intention has been to present all plots comparable to each other in one single figure. All figures are saved in vector format; meaning that zooming with a maintained good resolution is possible as long as the document is read electronically. Please bear in mind that the clearness of the figures might be affected if the document is printed, especially in gray scale.
8.1 Simulation of diode faults in a SM type exciter

The four following figures will show the analysis which was made for the simplified simulations in the SM type exciter platform. Figure 16 show the exciter stator current in frequency domain and Figure 17 show the exciter stator current in time domain. Figure 18 show the field winding current in frequency domain and Figure 19 show the field winding current in time domain.

The faults are associated with the rectifier and will disturb the normal rectification process. An open diode will prevent any current from flowing through its branch in the rectifier leg. A shorted diode on the other hand will allow current to flow in both directions through its leg branch and a shorted leg will provide an additional path for the current between two legs. All three legs are connected to three phases in balance which means that the same kind of harmonics will be induced regardless which specific diode or leg that are short circuited. Any of the faults will affect the voltage differences in the rectifier, the on- and off-states of the diodes will either be prevented or affected and the rectifier will simply not work properly.

During healthy condition, the only harmonics in both exciter stator current and field winding current are multiples of the sixth order; this is in good accordance with the theory presented for a six pulse rectifier that was given in section 3.3. Any of the faulty conditions will induce large lower order harmonics in the signal. This can be concluded by looking at either measurement point in both time and frequency domain. Yet another conclusion that can only be seen in frequency domain is that the shorted leg fault, only induce second order harmonics whereas both the other faults also induce first order harmonics.

A comparison of the two measurement points show that both provide more or less the same information, both in terms of qualitative and quantitative detection; meaning that the harmonics are of the same magnitude and occur at the same frequencies. Either one of the two measurement points have a good possibility of providing clear and strong signatures for any of the faulty conditions.
Figure 16. FFT analysis of the exciter stator current, all conditions that were run in the simplified simulations for the SM type exciter. It can be seen that the only visible harmonics during normal operation are multiples of the sixth order (zoom right). All faulty conditions are detectable through the lower order harmonics; diode faults by first order and above and shorted leg fault by second and above (zoom left).
Figure 17. Waveforms of the exciter stator current, all conditions that were run in the simplified simulations for the SM type exciter. It can be seen that during any faulty condition, the current ripple increase drastically.
Figure 18. FFT analysis of the field winding current, all conditions that were run in the simplified simulations for the SM type exciter. It can be seen that the only visible harmonics during normal operation are multiples of the sixth order (zoom right). All faulty conditions are detectable through the lower order harmonics; diode faults by first order and above and shorted leg fault by second and above (zoom left).
Figure 19. Waveforms of the field winding current, all conditions that were run in the simplified simulations for the SM type exciter. It can be seen that during any faulty condition, the current ripple increase drastically.
8.2 Simulation of diode faults in an IM type exciter

The four following figures will show the analysis which was made for the simplified simulations in the IM type exciter platform. Figure 20 show the exciter stator current in frequency domain and Figure 21 show the exciter stator current in time domain. Figure 22 show the field winding current in frequency domain and Figure 23 show the field winding current in time domain.

The faults are associated with the rectifier and will disturb the normal rectification process. An open diode will prevent any current from flowing through its branch in the rectifier leg. A shorted diode on the other hand will allow current to flow in both directions through its leg branch and a shorted leg will provide an additional path for the current between two legs. All three legs are connected to three phases in balance which means that the same kind of harmonics will be induced regardless which specific diode or leg that are short circuited. Any of the faults will affect the voltage differences in the rectifier, the on- and off-states of the diodes will either be prevented or affected and the rectifier will simply not work properly.

One thing that should be pointed out is that the exciter stator current is an AC in this type of exciter (Compared to DC in the SM type exciter). This is important to bear in mind when searching for the fault associated harmonics. Post process analysis has shown that any harmonic in the exciter stator current will be displaced by the voltage supply frequency of the exciter. I.e. if the voltage supply frequency of the exciter is x Hz, and a harmonic is expected to occur at frequency y Hz, the harmonic will actually occur at frequency \((x\pm y)\) Hz in the FFT of the exciter current. This can be verified by looking at Figure 20.

In a similar way, harmonics in the rotor field winding current will also be slightly displaced due to the slip between stator and rotor. The first harmonic is expected to occur at frequency 60 Hz but it actually occur around 63 Hz which is the expected frequency plus slip frequency. Second order harmonics are expected at 120 Hz but actually occur around 126 Hz and so on. This can be verified by looking at Figure 22.

During healthy condition, the only harmonics in both exciter stator current and field winding current are multiples of the sixth order; this is in good accordance with the theory presented for a six pulse rectifier that was given in section 3.3. Any of the faulty conditions will induce large lower order harmonics in the signal. This can be concluded by looking at either measurement point in both time and frequency domain. Yet another conclusion that can only be seen in frequency domain is that the shorted leg fault only induces second order harmonics, whereas both the other faults also induce first order harmonics.

A comparison of the two measurement points show that both provide more or less the same information, both in terms of qualitative and quantitative detection; meaning that the harmonics are of the same magnitude and occur at the same frequencies. Either one of the two measurement points have a good possibility of providing clear and strong signatures for any of the faulty conditions.
Figure 20. FFT analysis of the exciter stator current, all conditions that were run in the simplified simulations for the IM type exciter. It can be seen that all harmonics are displaced by the frequency of the exciters voltage supply. This is important to bear in mind when searching for fault associated harmonics in the current. In addition, it can also be seen that the only visible harmonics during normal operation are multiples of the sixth order (zoom right). All faulty conditions are detectable through the lower order harmonics; diode faults by first order and above and shorted leg fault by second and above (zoom left).
Figure 21. Waveforms of the exciter stator current, all conditions that were run in the simplified simulations for the IM type exciter. It can be seen that during any faulty condition, the current ripple increase drastically.
Figure 22. FFT analysis of the field winding current, all conditions that were run in the simplified simulations for the IM type exciter. It can be seen that all harmonics are displaced by the slip frequency between rotor and stator. In addition, it can also be seen that the only visible harmonics during normal operation are multiples of the sixth order (zoom right). All faulty conditions are detectable through the lower order harmonics; diode faults by first order and above and shorted leg fault by second and above (zoom left).
Figure 23. Waveforms of the field winding current, all conditions that were run in the simplified simulations for the IM type exciter. It can be seen that during any faulty condition, the current ripple increase drastically and the average level is shifted downwards.
8.3 Simulation of main machine faulty conditions using a SM type exciter

The four following figures will show the analysis which was made for the Co-simulations in the SM type exciter platform. Figure 24 show the exciter stator current in frequency domain and Figure 25 show the exciter stator current in time domain. Figure 26 show the field winding current in frequency domain and Figure 27 show the field winding current in time domain.

The faults are associated with the main machine faulty conditions; meaning that the signatures in this kind of simulation occur due to electromagnetic abnormalities in the main machine rather that the exciter which was the case in the previous simplified simulations. The FEM software provides an accurate description of the main machine and account for e.g. stator slotting during calculations. The ripple due to stator slotting (see Figure 27, normal operation) is small in magnitude and will not be visible in the exciter stator current. When a turn of a stator winding is shorted, this will create a loop in which current will flow and deform the magnetic field in the air gap. A turn-to-turn fault in the rotor winding will change the inductance value of the winding. Some current will only circulate in the loop, reducing the average value of the field winding current.

During healthy condition, the only harmonics visible in the exciter stator current are multiples of the sixth order; this is in good accordance with the theory presented for a six pulse rectifier that was given in section 3.3. These harmonics are however not visible in the rotor field winding, suggesting that the inductance value of the field winding is higher than expected and even out the effect of the varying field winding voltage. During the partial short circuit of the stator winding, harmonics around 120 Hz occur. These are due to the current circulating in this “stator loop”. The fact that these harmonics occur at 120 Hz is due to the geometry and design of the motor and has nothing to do with the exciter / rectifier assembly which also happen to be operating on the same frequencies.

A comparison of the two measurement points show that both provide more or less the same information, both in terms of qualitative and quantitative detection; meaning that the harmonics are of the same magnitude and occur at the same frequencies. Either one of the two measurement points have a good possibility of providing clear and strong signatures for any of the faulty conditions.
Figure 24. FFT analysis of the exciter stator current, all conditions that were run in the Co-simulations for the SM type exciter. It can be seen that the only visible harmonics during normal operation are multiples of the sixth order (zoom right). The short circuit of the stator winding (denoted stator fault in the plot) are detectable through the harmonic around 120 Hz (zoom left), whereas the turn-to-turn fault in the rotor show no visible signatures at all.
Figure 25. Waveform of the exciter stator current, all conditions that were run in the Co-simulations for the SM type exciter. It can be seen that only the short circuit of the stator winding (denoted stator fault), induces significant signatures in the exciter stator current.
Figure 26. FFT analysis of the field winding current, all conditions that were run in the Co-simulations for the SM type exciter. It can be seen that only the short circuit of the stator winding (denoted stator fault), induces significant signatures in the exciter stator current.
Figure 27. Waveform of the field winding current, all conditions that were run in the Co-simulations for the SM type exciter. It can be seen that during short circuit of the stator (denoted stator fault) the current waveform is significantly deformed. During turn-to-turn faults in the rotor only some minor drop in magnitude occurs in the field winding current.
8.4 Simulation of main machine faulty conditions using an IM type exciter

The four following figures will show the analysis which was made for the Co-simulations in the IM type exciter platform. Figure 28 show the exciter stator current in frequency domain and Figure 29 show the exciter stator current in time domain. Figure 30 show the field winding current in frequency domain and Figure 31 show the field winding current in time domain.

The faults are associated with the main machine faulty conditions; meaning that the signatures in this kind of simulation occur due to electromagnetic abnormalities in the main machine rather that the exciter which was the case in the previous simplified simulations. The FEM software provides an accurate description of the main machine and account for e.g. stator slotting during calculations. The ripple due to stator slotting (see Figure 31, normal operation) is small in magnitude and will not be visible in the exciter stator current. When a turn of a stator winding is shorted, this will create a loop in which current will flow and deform the magnetic field in the air gap. A turn-to-turn fault in the rotor winding will change the inductance value of the winding. Some current will only circulate in the loop, reducing the average value of the field winding current.

One thing that should be pointed out is that the exciter stator current is an AC in this type of exciter (Compared to DC in the SM type exciter). This is important to bear in mind when searching for the fault associated harmonics. Post process analysis has shown that any harmonic in the exciter stator current will be displaced by the voltage supply frequency of the exciter. I.e. if the voltage supply frequency of the exciter is x Hz, and a harmonic is expected to occur at frequency y Hz, the harmonic will actually occur at frequency (x±y) Hz in the FFT of the exciter current. This can be verified by looking at Figure 28.

During healthy condition, the only harmonics visible in the exciter stator current are multiples of the sixth order; this is in good accordance with the theory presented for a six pulse rectifier that was given in section 3.3. These harmonics are however not visible in the rotor field winding, suggesting that the inductance value of the field winding is higher than expected and even out the effect of the varying field winding voltage. During the partial short circuit of the stator winding, harmonics around 120 Hz occur. These are due to the current circulating in this “stator loop”. The fact that these harmonics occur at 120 Hz is due to the geometry and design of the motor and has nothing to do with the exciter / rectifier assembly which also happen to be operating on the same frequencies.

A comparison of the two measurement points show that both provide more or less the same information, both in terms of qualitative and quantitative detection; meaning that the harmonics are of the same magnitude and occur at the same frequencies. Either one of the two measurement points have a good possibility of providing clear and strong signatures for any of the faulty conditions.
Figure 28. FFT analysis of the exciter stator current, all conditions that were run in the Co-simulations for the IM type exciter. It can be seen that the only visible harmonics during normal operation are multiples of the sixth order (zoom right). The short circuit of the stator winding (denoted stator fault in the plot) are detectable through the harmonic around 120 Hz (zoom left), whereas the turn-to-turn fault in the rotor show no visible signatures at all.
Figure 29. Waveform of the exciter stator current, all conditions that were run in the Co-simulations for the IM type exciter. A slight deformation of the exciter stator current occur during short circuit of the stator winding (denoted stator fault), whereas the turn-to-turn fault in the rotor show no visible signatures.
Figure 30. FFT analysis of the field winding current, all conditions that were run in the Co-simulations for the IM type exciter. It can be seen that only the short circuit of the stator winding (denoted stator fault), induces significant signatures in the exciter stator current.
Figure 31. Waveform of the field winding current, all conditions that were run in the Co-simulations for the SM type exciter. It can be seen that during short circuit of the stator (denoted stator fault) the current waveform is significantly deformed. During turn-to-turn faults in the rotor only some minor drop in magnitude occurs in the field winding current.