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ON IMPACTS AND RIDE-THROUGH OF VOLTAGE SAGS EXPOSING LINE-OPERATED AC-MACHINES AND METAL PROCESSES

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To my wife

Jessica

Abstract

During the last decade, power quality has been recognised as a global problem. Among different types of power quality problems, voltage sags have been identified to be one of the most severe problems for different process industries. The most common reason to voltage sags is lightning strikes in power lines. Protection equipment, usually located at switchyards, disconnect faulted power lines as soon as possible, which is approximately 100 ms. Thus, the duration of voltage sags are approximately 100 ms. The sensitivity to voltage sags of electrical equipment in process industries can be observed as for instance malfunction, automatic turnoff or damages.

This thesis gives an overview of three metals processes with focus on the sensitivity to voltage sags and interruptions. The inherent energy in the process is used to find the sensitivity. This energy may also be used to obtain "ride-through" for the processes. The three metals processes are a blast furnace process, a hot rolling mill process and a cold rolling mill process. The main attention in this thesis is paid to the blast furnace process, which is powered by a line-operated synchronous machine.

The thesis shows that the protection equipment for electrical machines can be adjusted to avoid unnecessary shutdowns. It is also explained why there are high torque and currents during voltage sags as well as after voltage sags. It is shown that the first peak torque and current during the voltage sags is almost proportional to the voltage change, that is the voltage magnitude before the voltage sag minus the voltage magnitude during the voltage sag. The first peak torque and current after the voltage sag depends sinusoidal-like on the duration of the voltage sag and almost proportional to the voltage change during the voltage sag. There is no flux saturation during voltage sags, however after voltage sags saturation is very likely to occur. The thesis explains why and also how the flux is changed during and after voltage sags.

The duration of voltage sags is in many cases set by the protection equipment located in switchyards. It is shown that the durations of voltage sags can be changed to durations that will cause less peak torque and current after voltage sags for line-operated AC-machines. It is also shown how this is theoretically achieved.

Keywords: Rolling mill, Blast furnace, Power Quality, Synchronous machine, Asynchronous machine, Voltage sag, Voltage interruption, Ride-through, Process disturbances, Simulation, Modelling

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Roebel SK is thanked for all enjoyable activities. Please never stop with them, it is the soul of the division!

Finally, I would like to express my deepest gratitude for all support to my wife Jessica, my parents Inger and Jan Carlsson, and my parents-in-law Marie-Louise and Berndt Malmquist.

Stockholm, November 2003

Fredrik Carlsson

Contents

Chapter 1

Introduction

This chapter introduces the reader to the power quality problem of voltage sags and in which way it creates problems in some metals industries. Furthermore, the chapter discusses the impact of voltage sags and how to solve certain related problems. Finally, the scientific contributions of the author are given together with a list of publications.

1.1 Background

During the last decade, power quality has been recognised as a global problem [1] - [4]. Among different types of power quality problems, voltage sags have been identified to be one of the most severe problems for different process industries. The interest for power quality issues is, however, not shown only by process industries. Power suppliers, governments, universities, and households have also taken part in the discussions. The increased attention to power quality probably results from the fact that there are more electrical equipment that is sensitive to low power quality than before and that more electrical equipment is contributing to low power quality. The sensitivity of electrical equipment can be observed as for instance malfunction, automatic turnoff or damages. Power quality is a general term related to voltage and current disturbances. To mention some of the power quality issues, there are voltage sags, undervoltages, overvoltages, voltage interruptions, transients, flicker, harmonics, and frequency variations. The definitions of these can be found in standards, but it is laws and regulations that control what power quality level suppliers and end users must follow. As an example, according to the standard SS EN 50 160 the supplied voltage level to households in Sweden shall be between 207 and 253 volts (230 ± 10%) [5]. Voltages outside these limits are considered as low power quality, and voltages within these limits are considered as good power quality. It is obvious that both the supplier and the user can influence this voltage level; users can do it for instance by connecting equipment that suddenly draws large currents from the power grid.

The most common reason to voltage sags is lightning strikes in power lines. Other common reasons to voltage sags are equipment failures, accidental contact with power lines, electrical machine starts, etc [6]. Statistics show that approximately 50% of the instances of low power quality are related to voltage sags [7]. They also occur most frequently during working hours [8]. In Sweden and other European countries, thunder is concentrated to summer time, which results in more lightning strikes in power lines during this period. The lightning strikes in power lines cause short circuits, which in turn cause voltage sags. The voltage magnitude is lower for a consumer when a strike is closer to the consumer [4]. Protection equipment, usually located at switchyards, disconnect faulted power lines, such as short circuits. This is performed by measuring the voltage and when the voltage is changed in a way that is interpreted by computers (or analogue devices) as a short circuit, a signal is sent to breakers that will disconnect the line. This process of interpretation and disconnecting the line, takes approximately 100 ms, which explains why most voltage sags have a duration of approximately 100 ms. Another way to say this is that it is the protection equipment in the switchyards that decides the duration of the voltage sag. This thesis shows how this may be used to reduce the impacts of voltage sags on line-operated AC-machines.

Faster fault detection may lead to a reduction of the duration of voltage sags [9]. This increases the capability of synchronous machines to ride-through voltage sags, which is shown in this thesis. When the power quality is degraded to a certain level, protection equipment automatically turns off electric units to avoid failure or incorrect operation. Later on, when the power quality is restored, the electric units are restarted, which in some cases may take several hours. This may involve large costs for the owner due to production losses and/or work hour losses.

Since large production losses may occur due to voltage sags, there is a demand for equipment supporting production units to “ride-through” voltage sags. “Ride-through” means that an electric unit is not stopped during a voltage sag. Several studies investigating the possibilities of obtaining “ride-through” for electrical machines using different techniques have been presented in the literature. Among others there are studies on active rectifiers [10], ultracapacitor based systems [11], and pulse width modulation (PWM) systems [12]. These studies are focused either on (a) control of adjustable-speed drives (ASD) with power electronics or (b) the use of energy storage capability in the capacitor within the power electronics or (c) uninterruptible power supply (UPS) connected to the power electronics. Large electrical machines that operate at very high power are often not fed by power electronics. In these cases, the drives are line-operated and no speed control for the drive exists. Power electronic equipment is expensive and is not generally available for very high voltages. This thesis attempts to show how a ride-through can be obtained without using the techniques just mentioned, focusing on the settings in protection equipment instead. However, a UPS for the protection equipment and control equipment is strongly required. With this method, only programming, software changes or control unit changes have to be made, and consequently a low-cost method is obtained for handling voltage sags, and thereby increasing the reliability of the process.

This thesis gives an overview of three metals processes with focus on the sensitivity to voltage sags and interruptions. The inherent energy in the process is used to find the sensitivity. This energy may also be used to obtain "ride-through" for the processes. The three metals processes are a blast furnace process, a hot rolling mill process and a cold rolling mill process. The main attention in this thesis is paid to the blast furnace process, which is powered by a line-operated synchronous machine.

1.2 Contributions

The scientific contributions included in this doctoral thesis are identified as six items, which are summarised and listed below. These items are discussed in Chapter 3 and Chapter 4.

1. The voltage sag sensitivity for a hot rolling mill (publication 10), a cold rolling mill (publication 9) and a blast furnace process (publication 8); in particular the mechanical stop times for the processes when the power is switched off.

2. Optimisation of the protection equipment (depending on the voltage sag magnitude and duration) for a synchronous machine, to keep synchronism when possible and to trip when not possible (publication 8 and 2). This is currently run as a project to implement at SSAB Oxelösund Sweden.

3. Tripping irregularities are explained, due to the voltage magnitude before the voltage sag (publication 2). The tripping discussed is due to overcurrent protection and has little to do with the possibilities for the machine to ride-through voltage sags. It is applicable to both synchronous and asynchronous machines.

4. Explaining by equations, the behaviour of the stator flux during and after voltage sags in synchronous (publication 4) and asynchronous (publication 3) machines. Also, deriving when saturation after voltage sags will occur for the machines. It is also shown that saturation does not occur during the voltage sag itself.

5. Explaining how torque and current peaks depend on the voltage sag duration and magnitude (publication 5). Investigating different types of voltage sag, like the three-phase, two-phase and single-phase cases, categorised as voltage sag types A – G (publication 7).

6. Reducing peak torques and currents due to voltage sags for line-operated alternating current electrical machines (using the knowledge from number 4), by controlling the voltage sag duration in the power grid.

7. Explaining how torque and current peaks depend on the duration and magnitude for overvoltage transients (publication 6).

1.3 Outline of the thesis

This doctoral thesis is divided into three chapters, with 10 publications included at the end. A brief outline of these chapters and publications is listed below.

Chapter 1 introduces the thesis and puts it into the context of power quality, process industries, and electrical machines. Furthermore, the chapter discusses its impact and some solutions. Additionally, scientific contributions by the author with a list of publications are included.

Chapter 2 describes two types of metal processes, which are studied in this thesis. These are the rolling mill and the blast furnace. It is meant to be a basic introduction for the reader who is not familiar with this field.

Chapter 3 explains how the stator flux in AC machines is changed during and after voltage sags. Furthermore, it is explained why and for which conditions the stator flux saturates and also when it produces high torque and current. It is also shown that a ride-through is possible if the tripping level of the protection equipment is chosen adequately.

Chapter 4 makes use of the information from Chapter 3 to show that it is possible to predict which voltage sag durations that are less severe for the machine. These durations may be possible to produce in the grid, and it is explained how that may be achieved.

Chapter 5 summarises this doctoral thesis, draws conclusions of the most important results from the work and provides suggestions for future work.

Publication 1 illustrates how the stator flux in a synchronous machine changes during voltage sags. These changes result in torque peaks. An analytical time dependent expression of the stator flux during three-phase, two-phase and single-phase voltage sags explains the behaviour of synchronous machines and why there are high torque and current peaks during voltage sags. Simulations verify the expressions, and illustrate the dependence of torque and current peaks on voltage sag duration and magnitude.

Publication 2 discusses the voltage magnitude before the voltage sag. Undervoltage tripping is one way of protecting equipment from getting damaged due to overcurrent during voltage sags. However, the undervoltage protection is usually set to break at an absolute voltage magnitude instead of at a relative voltage magnitude change. This may lead to both unnecessary tripping and non-tripping when necessary.

Publication 3 gives a basic understanding of how voltage sags change the stator flux in line-operated asynchronous machines and under which conditions saturation occurs. Most voltage sags cause saturation. Flux saturation results in both high currents and torque; these may accelerate the aging of the machine.

Publication 4 illustrates how the stator flux in a synchronous machine changes during voltage sags. It is shown that for certain voltage sags, there will be flux saturation. Flux saturation causes both large currents and torque; these may accelerate the aging of the machine. The results are compared to the case when saturation is disregarded. This study includes only three-phase symmetrical voltage sags.

Publication 5 shows when there are torque and current peaks for voltage sags of types A - G for synchronous machines. An expression of the stator flux during and after voltage sags explaining why there are high torque peaks is derived. Simulations verify this and illustrate the torque and current peaks dependence of voltage sag duration and magnitude. A general conclusion is that the peak torque depends on the sag magnitude and sinusoidal on the duration.

Publication 6 discusses overvoltage transients. Voltage transients is an important part in the area of power quality. Transient overvoltages cause machine tripping due to breaking by overvoltage protection, which may lead to production losses. Apart from that, large torque peaks that may cause damage to the shaft or equipment connected to the shaft. High current peaks occur as well, which leads to thermal heating and tension. This paper shows on what conditions transients cause high peak torques and currents for synchronous machines, which is explained by a simple theory. Simulations verify the theory, and illustrate the influence of the transient duration and magnitude on the peak values of torque and current.

Publication 7 shows how the torque depends on both the duration and the magnitude of voltage sags. First, a simple theory is presented, and then to verify the theory, simulations of a blast furnace blower located at the steel plant SSAB Oxelösund Sweden are performed. A line-operated salient-pole synchronous machine powers the blower, which feeds the blast furnace with air. The conclusion is that voltage sags with durations equal to multiples of a whole cycle generate minimum torque peaks, and the maximum torque peaks are generated by voltage sags with durations equal to half cycle plus multiples of a whole cycle.

Publication 8 studies the blast furnace process in the steel plant SSAB Oxelösund, located in Sweden. A line operated synchronous machine powers the blower, which feeds the blast furnace with air. The results show how sensitive the process is to voltage problems. By adjusting the settings of the protection equipment the number of unplanned stoppages may reduce.

Publication 9 investigates the cold rolling mill at the company Outokumpu Copper in Sweden. Calculations of time constants have been done for the process and these are compared to the duration times of common voltage sags. In the worst case, a 10% voltage sag will shut down the cold rolling mill. The cold rolling mill will then be at standstill for approximately half a second. Suggestions of methods to reduce the problem of the process in connection with voltage sags are presented.

Publication 10 studies the hot rolling mill at the steel mill SSAB Oxelösund in Sweden. Calculations of time constants are done for the process and these are compared to the duration times of measured voltage sags at the same industry. In the worst case, a voltage sag duration time of 10 ms may shutdown the rolling mill process. Suggestions of methods to reduce the problem of the process in connection with voltage sags are presented.

1.4 List of publications

This doctoral thesis includes the following list of publications, which all have been published in conferences. The author of the thesis has done all the works in these publications. Co-authors of the publications have contributed with ideas and proofreading the publications.

1. F. Carlsson and C. Sadarangani: *"Behaviour of synchronous machines subjected to voltage sags of type A, B and E"*, submitted to Energy conversion March 2002, comments received in May 2002, resubmitted with correction May 2002, comments received in July 2002, resubmitted in September 2002, comments received in October 2002, resubmitted in December 2003.
2. F. Carlsson: *"Explanations to irregularities in the dependence between voltage sag magnitude and the tripping level for line-operated synchronous machines"*, Published in the Proceedings of the IEEE Industry Applications Society, IAS, Salt Lake City, 12-16 October 2003.
3. F. Carlsson: *"Saturation in Asynchronous Machines due to Voltage Sags"*, Published in the Proceedings of the European Conference on Power Electronics and Applications, EPE, Toulouse, France, 2-4 September 2003.
4. F. Carlsson: *"Saturation in Synchronous Machines due to Voltage Sags"*, Published in the Proceedings of the IEEE International Electric Machines and Drives Conference IEMDC, Madison, Wisconsin, USA, 1-4 June 2003.
5. F. Carlsson: *"Behaviour of Synchronous Machines during Voltage Sags"*, Published in the Proceedings of the International Conference on Electrical Machines, ICEM 2002, Brügge, Belgium, 25-28 August 2002.
6. F. Carlsson: *"Behaviour of Synchronous Machines subjected to Transient Overvoltages"*, Published in the Proceedings of the Nordic Workshop on Power and Industrial Electronics (NORpie), Stockholm, Sweden, 12-14 August 2002.
7. F. Carlsson, H. -P. Nee and C. Sadarangani: *"Analysis of peak Torque of Line-operated synchronous Machines subjected to symmetrical Voltage Sags"*. Published in the Proceedings of the IEE International conference on Power Electronics and Electrical Machines (PEMD), Bath, United Kingdom, 16-18 April 2002.
8. F. Carlsson, C. Sadarangani and B. Widell: *"Impacts of voltage sags on a blast furnace process"*. Published in the Proceedings of the Cigre Symposium, KTH, Stockholm, Sweden, 26 June 2001.

9. F. Carlsson, B. Widell and C. Sadarangani: *"Ride-through investigations for a cold rolling mill process"*. Published in the Proceedings of the Electro Motion Symposium 2001, Bologna, Italy, 19-20 June 2001.
10. F. Carlsson, B. Widell and C. Sadarangani: *"Ride-through investigations for a hot rolling mill process*". Published in the Proceedings of the International Conference on Power System Technology, Perth, Australia, 4-7 December 2000.

The author of this doctoral thesis has also been part of some other publications made during the Ph.D. studies, which are listed below. These are not included in this thesis, since the contents (11 - 16) are covered by other publications included in this thesis or not part of this doctoral work (17 and 18).

11. F. Carlsson: *"Behaviour of synchronous machines subjected to transient overvoltages"*. Published in the Proceedings of the 10th International Conference on Harmonics and Quality of Power, Oct. 6-9 2003, Volume 2, pages 724 –729.
12. F. Carlsson, J. Engström and C. Sadarangani: *"Torque Variations during and after Voltage Sags for a Synchronous Machine"*. Published in the Proceedings of the International conference on electrical engineering and technology (ICEET01), Dar es Salaam, Tanzania, 10-11 September 2001.
13. F. Carlsson, J. Engström and C. Sadarangani: *"Simulations of a synchronous machine affected by voltage sags"*. Published in the Proceedings of the European Conference on Power Electronics and Applications (EPE), Graz, Austria, 27-29 August 2001
14. F. Carlsson: *"Impacts of voltage sags on metal processes"*. Licentiate Thesis, ISSN 1404-8248, TRITA-EME-0102, KTH, Royal Institute of Technology, Stockholm, March 2001.
15. F. Carlsson and J. Engström: *"Simulations of Ride-through Possibilities for a Line Operated Synchronous Machine",* Published in the Proceedings of the International Conference on Power System Technology, Perth, Australia, 4-7 December 2000
16. F. Carlsson, *"Återinkoppling av Blåsmaskin 7 SSAB Oxelösund under drift"*. Department of Electrical Engineering, KTH, Stockholm, Sweden. In Swedish only. Internal report A-EMD-9901, 1999.
17. P. Kjellqvist, F. Carlsson and S. Östlund: *"Control and design requirements of an electromechanical actuator for active suspension of rail vehicles"*. Published in the Proceedings of the European Conference on Power Electronics and Applications, Lausanne, Switzerland, 7-9 September 1999.
18. P. Kjellqvist, S. Östlund and F. Carlsson: *"Electromechanical actuator for active suspension in rail vehicles"*. Published in the Proceedings of the Electrical Machines and Drives Conference, Canterbury, UK, 1-3 September 1999.

Chapter 2

Metals processes

The purpose of this chapter is to provide a basic introduction to three metals processes. These are the blast furnace process and two rolling mill processes. It is explained in which way these processes are sensitive to voltage sags and how voltage sags cause considerable costs.

2.1 The blast furnace process

A blast furnace is used as one of the first steps in the chain of production of iron and steel from iron ore. It has been used for several centuries and is a mature process. Iron is mainly manufactured by feeding in ore and coke from the top of the furnace and by blowing hot air at approximately 1000 ºC into the bottom of the furnace. During this process, liquid iron containing approximately 4% dissolved carbon and a liquid slag is formed. The off gas from the process can be used as fuel and is drawn from the top of the furnace. Ore and coke feed material has piece size that allows the gas to flow through the furnace charge. The iron is melted and drained into large containers through draining holes. The diameter of a blast furnace is approximately six to nine meters and the height is in the order of twenty-five meters.

The process consists of a blower connected via a gearbox to a synchronous machine with ratings of 3.6 MW. The blower compresses and blows air via pipelines and stove heaters to the blast furnace. The flow is controlled by means of a valve. The stove heater contains thousands of tons of bricks, and maintains a temperature in the range of 1050 ºC – 1200 ºC, where the high temperature is produced by fire. In fact, there are four heaters, two of which airflow passes through, while the other two are being heated up. After one hour the temperature has dropped from 1200 ºC to approximately 1050 ºC in the stove heater, through which air has passed. At this instance there is a switch between them, and the airflow is directed to the other two heaters.

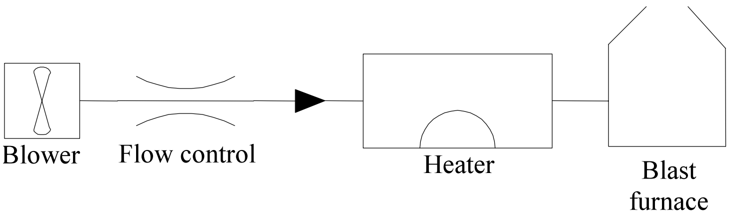


Figure 1: The blast furnace process system.

If the synchronous machine stops during production, the overpressure in the pipelines falls to zero in 15 - 30 seconds. This may result in production losses and risks of making the blast furnace unusable, due to iron solidifying in the air tuyeres of the blast furnace. The cost to build a new blast furnace has been estimated to €100 000 000 [13]. The normal case is that the blast furnace can still be used and it takes approximately 24 hours to get in production after a stoppage and the production losses per hour are approximately €10 000. The synchronous machine can withstand very deep voltage sags (to 60% of remaining voltage) of durations of at least 160 ms and even longer durations if the voltage sags are moderate in depth. The possibility to ride-through voltage sags is good.

2.2 The hot rolling mill process

A rolling mill rolls ingots of metals or alloys, which can be iron, copper, aluminium etc. The purpose of the rolling process is to make the material thinner. Since different metals have different hardness it is not common for a rolling mill to roll different metals, unless the degree of hardness is almost the same. There are many types of rolling. Some roll hot and some roll cold metals, some roll steel plates and some roll strip from coils. Since the hardness decreases with increasing temperature, the power of a rolling mill can be reduced if the metal is heated up before rolling. This saves energy for the rolling process. But on the other hand energy is needed to heat the metal. Which choice is made depends not only on energy costs, but also on how to achieve a good quality of the product. Figure 2 shows a typical rolling mill, which consists of two rolls with one metal slab in between. Above and below the rolls are large diameter backup rolls to limit roll bending from the roll force.

The studied hot rolling mill rolls steel plate and the process consists of two synchronous machines, each having a rating of 11.2 MW. The rolls are driven individually, each having one synchronous machine and one cyclo-converter. The drives are also able to operate at a peak power of 250% (26 MW) of rated power during times shorter than 20 seconds without exceeding the thermal limit of the machine. Since the load torque is very high in comparison to the stored kinetic energy of the mechanical system, it is likely that the rolls would stop quite fast during rolling, if the line voltage would suddenly disappear. The power is automatically switched off when the remaining voltage is below 70% of nominal voltage.

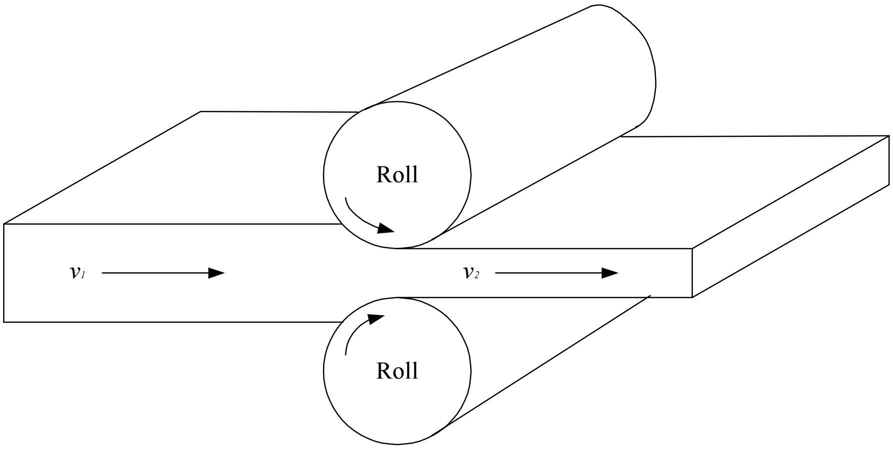


Figure 2: The hot rolling mill with two roles and one slab in between.

The main problem with voltage sags in a hot rolling mill is the downtime, which can be several hours, if the steel slab gets stuck between the rolls during the voltage sag. Since the steel slab has a temperature of approximately 1000 °C, the steel slab may deform the rolls due to the heating. During normal operation the rolls are cooled by water spray, but when the slab is stuck it is not possible to cool down the rolls at the contact area. This may lead to that the rolls have to be replaced with new ones. This process takes hours and costs money. The old rolls have to be reworked or discarded. Switching rolls costs approximately €10 000 and it takes usually eight hours to carry out the work. Production losses during the down time are estimated to €100 000 per hour. When the machines are shutdown the rolls could stop as fast as 10 ms, but usually it takes approximately 100 – 200 ms. The risk that a voltage sag occurs during the active rolling time and not during pauses depend on which schedule is performed. The difference is as big as 10% - 84%.

2.3 The cold rolling mill process

The studied cold rolling mill is a reversible single-stand cold rolling mill that rolls copper strips. The rolls are powered by four DC-machines having ratings of 400 kW each. The copper strip is delivered from a coiler and transmitted to another coiler after having passed the rolls. The coilers are also driven by one DC-machine each. DC-machines are in general more sensitive to voltage sags than AC-machines. A high and fast change in the DC voltage level for the machine will result in high positive or negative currents, since the voltage difference over the small armature resistance will be comparably high. The breakers are set to break when the current for a single machine is higher than 2000 A, which is just 2.5 times rated current. This means that when a voltage sag occurs, it is very likely that it is the overcurrent protection that shuts off the machines. If the machines are stopped during rolling, the copper plate may be deformed and has to be cut away. Production losses due to stoppages are however relatively small and have not been estimated. When the machines are shutdown, the rolls stop within a half to five seconds, depending on the rolling pass. The risk that a voltage sag that occurs daytime, occurs during operation is approximately 67%, since schedules starts every two hours and the active rolling time during the two hours is approximately one hour and twenty minutes.

Chapter 3

AC-machines subjected to Voltage sags

This chapter explains how the stator flux in AC machines is changed during and after voltage sags. Futhermore it is explained why and under which circumstances the stator flux saturates and also when it produces high torque and current. The tripping level for the AC-machine could be set adequately to make the AC-machine ride-through voltage sags when possible and trip when not possible.

3.1 Voltage sags

To investigate the effects of voltage sags and how to minimise their impacts on certain processes there is a need for a clear definition of the term voltage sag and also a way of expressing the voltage sag analytically. The definition of a voltage sag according to the IEEE standard, is a momentary decrease (10% - 90%) in the root mean square (rms) voltage magnitude where the duration is longer than a half cycle and less than one minute [14]. This means that the shortest voltage sag is 10 ms in a power grid where the frequency is $f = 50$ Hz. The definition of voltage interruption is a very large voltage drop (<10% remaining voltage). Voltage transients are shorter than a half cycle and undervoltages are longer than one minute. To prove that voltage sags are one important cause of unwanted process shutdowns, a measurement device was installed at SSAB Oxelösund in order to measure the magnitude and duration of the voltage sag. The measurement was performed during six months from March to August in the year 1999. Figure 3 illustrates the results from the measurements. The absolute date and time was recorded as well, and there was a good correlation with recorded stoppages of different equipment [15]. As can be seen from the figure, most of the voltage sags have a duration that is approximately 100 ms. Of the 29 records in the chart, only two occurred in March and the rest in June to August.

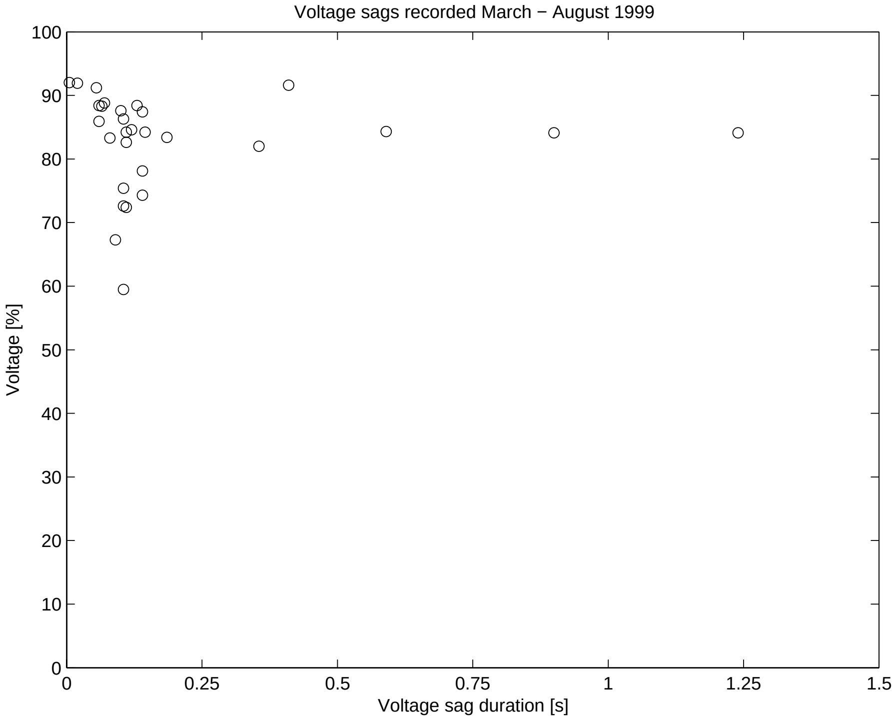


Figure 3: Voltage sags recorded during March – August 1999 at SSAB Oxelösund AB, Sweden.

This indicates that the fault reason is due to lightning strikes in power lines, since lightning strikes are more common in the summer time in Sweden. The voltage sag frequency that year during June to August is nine per month or twice a week. A rectangular voltage sag is a momentary voltage drop to a fixed level in the rms voltage and a momentary restoration of the voltage level at a certain later instant. This shape of voltage sags is very often used in simulations as it is very simple to use and it represents the worst case. In reality voltage sags are usually not so rectangular [16]. It should be mentioned that the term “voltage sag” is an IEEE standard, while the term “voltage dip” is an IEC standard [17]. In this thesis the IEEE standard is used. Figure 4 shows a symmetrical rectangular three-phase voltage sag to 60%. The duration of the voltage sag is 80 ms (four cycles).

Voltage sags have been classified in [18] to seven different types, called type A - G. These are faults to ground (A, B and E) or line-to-line in the power grid by three, two, or one phases. The voltage sag types C, D, F and G are typically observed after one or two Δ–Y transformers for the sag types B and E. If the line-to-line voltage is U_{ll} and the magnitude of the line-to-line voltage during the voltage sag is U_{sag}, a symmetrical voltage sag with the duration t_{sag} can be described by the voltage equation (1).

$$u(t) = U_{ll} - \left(U_{ll} - U_{sag}\right) \cdot \left(H(t) - H(t - t_{sag})\right) \qquad (1)$$

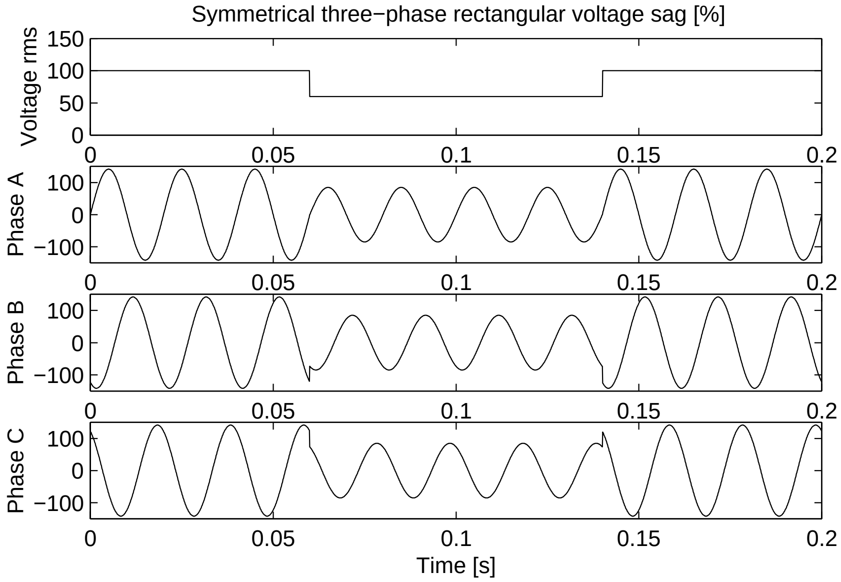


Figure 4: Shows a voltage sag to 60% of remaining voltage with a duration of 80 ms (4 cycles).

3.2 Tripping level settings in protection equipment

Voltage sags cause electrical machines to trip due to shutdown by protection equipment. Manufacturers install protection equipment to avoid damages of electrical machines or equipment connected to machines. This is good for users and makes it also possible for manufacturers to give warranties for electrical machines. Protection equipment consists of one or more protecting devices, depending on for instance the power of the electrical machine, application, environment etc. Typical devices are undervoltage protection, overvoltage protection, overcurrent protection, overtemperature protection, unsymmetrical current protection, etc. However, shutting down an electrical machine may cost a lot of money, since production losses may arise. In Chapter 2 some costs due to process shutdown are mentioned for certain metals processes. In general there are costs due to production losses, damages of the end product and damages of the process equipment, due to voltage sags.

Riding through voltage sags is one way to avoid unwanted stops. This may be achieved by changing the settings of the protection equipment. The ability of a drive to ride-through a voltage sag greatly depends on the tripping-point settings of the drive [19]. However, riding through a voltage sag may cause severe torque peaks. For synchronous machines, the transient air-gap torque can be as much as 30 - 40 times the normal torque [20].

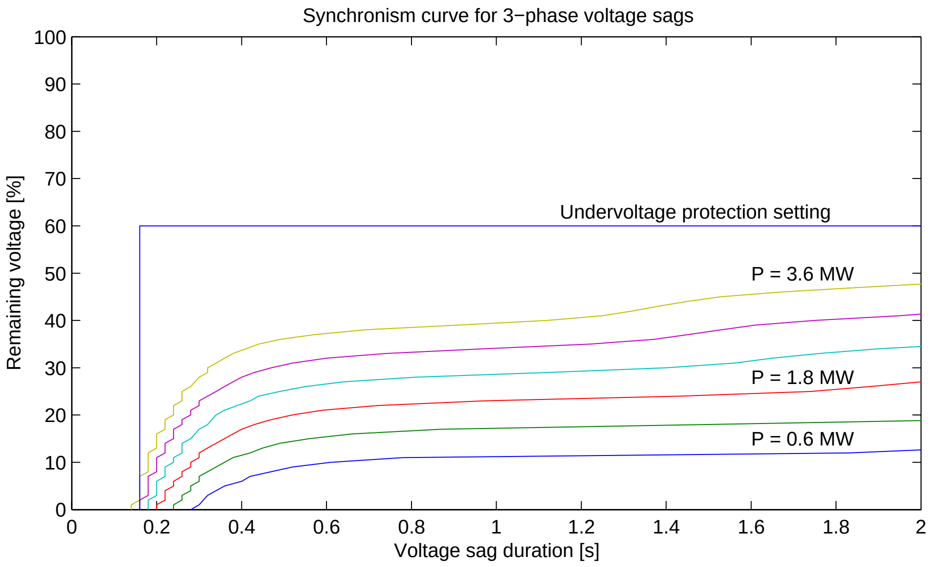
When a line-operated AC-machine is subjected to a voltage sag, there are in general four possible scenarios that can be anticipated:

1. The voltage sag causes tripping shortly after the voltage sag instant, due to breaking by the undervoltage protection or by the overcurrent protection. The case may force an industry to be inoperable for several hours, since the start-up time for electrical machines in the process industry may be several hours. This implies high costs for the industry due to subsequent loss in production. Transient torque and current occur during the non-disconnected time.
2. The voltage sag causes severe torque peaks, which may damage or fatigue the shaft of the machine or connected equipment. Damages lead to shutdown, which may prohibit production for weeks, since new equipment has to replace old.
3. The electrical machine rides through the voltage sag, but the connected process is disturbed in certain ways due to the transient torque, for instance the quality of produced material is reduced.
4. The machine rides through the voltage sag and no problems are observed.

Figure 5 shows results from simulations performed on a 3.6 MW line-operated synchronous machine powering a blast furnace blower located at SSAB Oxelösund. In this figure it is clear that the ability for the machine to keep synchronism depends on the load and the remaining voltage. In fact there is another factor as well, that is the voltage sag type. If the voltage sag is only two-phase or single-phase the ride-through ability increases considerably. The single-phase case is not included in the figure, since the synchronous machine is able to keep synchronism for all loads and for any remaining voltage magnitude. Another option to increase the ability to ride-through voltage sags is of course to increase the inertia. Connecting a flywheel to the shaft can for instance increase the ride-through capability.

The main idea is to shutdown the AC-machine only when it or its driven object may get damaged or if it is not possible to keep synchronism anymore for the synchronous machine. Electrical machines could get damaged due to overheating that could damage the windings or too much torque that fatigues/damages/breaks the shaft or coupling. The usual setting from manufacturers is to shutdown electrical machines when the voltage goes below 90%. This setting could be improved. Synchronous machines are usually able to keep synchronism for much lower voltages than that. For the studied synchronous machine the setting is 60%. The asynchronous machines do not need this type of setting, but it is still good to have a voltage meter so that the protection equipment can sense the origin of the fault. As a conclusion regarding the settings of the protection equipment, the following recommendations can be given for AC-machines:

- Undervoltage protection should be used to detect the voltage sag type and its magnitude.
- Undervoltage protection should be used to shutdown synchronous machines when it is known that they will not be able to keep synchronism anymore. Use the synchronism curves for the purpose. Asynchronous machines should not have this type of protection.
- Overcurrent protection and the thermal protection should be used to shutdown AC-machines to avoid damages.



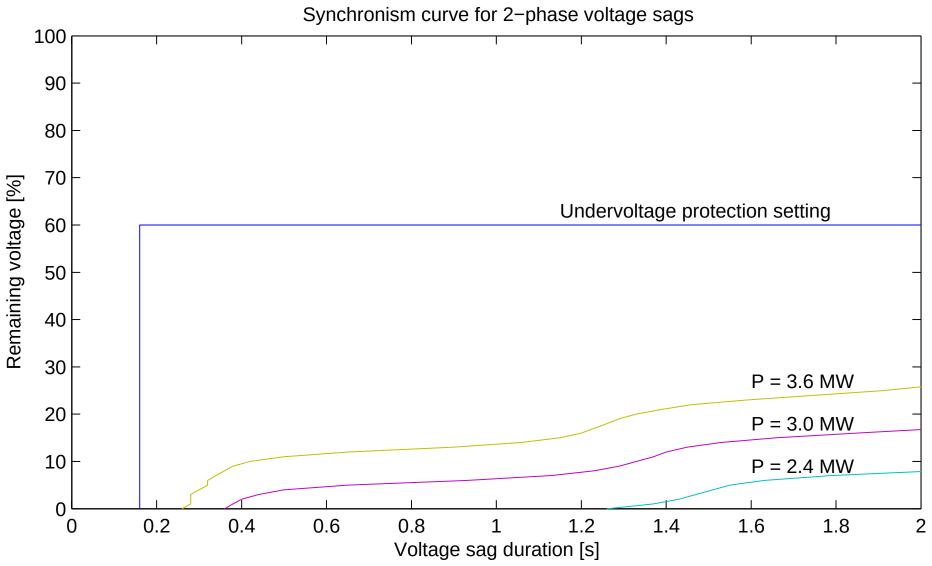


Figure 5: Shows the settings of the protection equipment ($t_{sag} > 160$ ms and $U_{sag} < 60\%$) and the ability of the synchronous machine to keep synchronism for different loads (0.6, 1.2, 1.8, 2.4, 3.0, 3.6 MW). The voltage sag types are a symmetrical three-phase voltage sag (sag type A) and a two-phase voltage sag (type E).

3.3 AC - machine model

To achieve a basic understanding of the behaviour of AC-machines subjected to voltage sags, a simple model of the AC-machine is required. It is then possible to do some simple mathematical calculations of the stator flux behaviour during and after voltage sags. From the simplified theory certain basic conclusions can be drawn, and later on simulations can be performed making use of more advanced models. It is shown that the conclusions from the simplified theory apply also for the advanced machine models. Alternating current electrical machines, such as the three-phase synchronous and asynchronous machines, are quite alike. They both have stator windings that produce a resultant fundamental magnetic field in one direction, from the three-phases. In the following simplified analysis, it is assumed that the windings are distributed completely sinusoidal, non-saliency, that the speed of the asynchronous machine is approximately synchronous, and that the speed is constant. The resultant magnetic field can be described in rotor co-ordinates, by using Park's power invariant dq-transformation. By using complex numbers, it is possible to set the real axis in the same direction as the direct axis and the imaginary axis in the same direction as the quadrature direction. The magnetic field vector can now be treated mathematically as a complex variable, which is far simpler. The stator flux in rotor co-ordinates Ψ_s^r as function of time in these AC-machines can be simplified to a first order linear differential equation (2) [Publication 3 and 4]. In this equation, $U^r(t)$ is the applied dq-voltage in rotor co-ordinates, ω is the electrical frequency and T_a is the time constant of the armature (stator) winding.

$$U^r(t) = \frac{d\Psi_s^r(t)}{dt} + (j\omega + T_a^{-1})\Psi_s^r(t) \tag{2}$$

Integrating-factor can be used to solve the above equation, and by rearranging, equation (3) is the result, where the stator flux Ψ_s^r is defined explicit.

$$\Psi_s^r(t) = e^{(j\omega + T_a^{-1})t} \cdot \int_{-\infty}^{t} U^r(\tau) \cdot e^{(j\omega + T_a^{-1})\tau} d\tau \tag{3}$$

Now, the voltage U^r is set to equal the symmetrical three-phase voltage sag in equation (1) and integrating the equation, leads to equation (4)

$$\Psi_s^r(t) = \frac{U_{ll} - (U_{ll} - U_{sag})\left[(1 - e^{-(j\omega + T_a^{-1})t})H(t) - (1 - e^{-(j\omega + T_a^{-1})(t - t_{sag})})H(t - t_{sag})\right]}{j\omega + T_a^{-1}} \tag{4}$$

Equation (4) consists of three terms, which are the stator flux before the voltage sag ($t < 0$), the stator flux change during the voltage sag ($0 < t < t_{sag}$) and the stator flux change after the voltage sag ($t > t_{sag}$). The two last terms will of course cancel each other out as $t \to \infty$. The stator flux before the voltage sag is of course constant since the machine is at steady state, and is lagging the voltage with almost 90°. This is not true during the voltage sag. As seen from the equation, the stator flux starts to rotate clockwise with a centre located at $U_{sag} / (j\omega + T_a^{-1})$. This centre will eventually be the new steady state location, assuming that the electrical machine is able to keep synchronous speed.

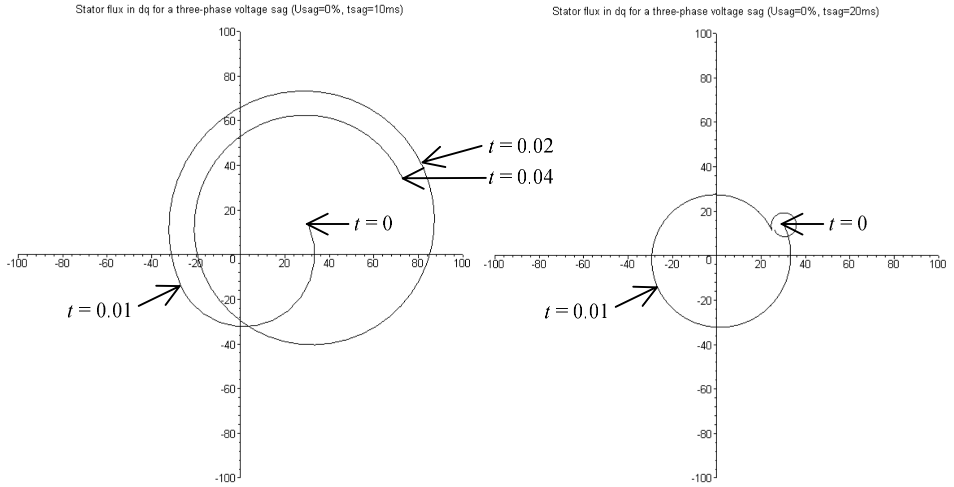


Figure 6: Shows the stator flux during a symmetrical three-phase voltage sag in a synchronous machine. The duration of the voltage sag is 10 ms and 20 ms respectively. The voltage during the sag is 0% (voltage interruption). Line-to-line voltage is U_{ll} = 10500 V, the electrical frequency is $\omega = 100\pi$ and the armature time-constant is $T_a = 0.1$ s. The load angle before the voltage sag is $\delta = 24°$.

One way to understand the rotating function is to examine the case when the voltage during the sag is zero. In this case, the stator flux will be locked in its position in the stator and slowly reduce in magnitude with the armature time-constant T_a. This means, that if it has a fixed direction in stator co-ordinates, the stator flux seen from the rotor will rotate in the counter direction (=clockwise, the rotor revolves counter-clockwise). During this process the stator flux will reduce, and will therefore not magnetically saturate during the voltage sag.

There is an instant when the voltage restores. At this instant, the stator flux is pointing in a direction, which depends on the duration (among other parameters) of the voltage sag. There are instants when the stator flux is pointing in the same direction as it was before the voltage sag. These instants exist when $e^{-j\omega t_{sag}} = 0$. This condition is fulfilled ones for each cycle, in other words it is fulfilled for each value obtained from equation (5), where f is the electrical frequency and c an arbitrary integer greater than zero.

$$t_{sag} = \frac{c}{f} \tag{5}$$

It is now interesting to study equation (4) for two different cases. The first case is when the voltage sag duration is a half cycle and the second case when the voltage sag duration is one cycle. Figure 6 shows the stator flux for these two cases and as predicted there is a huge difference. The stator flux after the voltage sag in the first case reaches almost three-times the steady-state flux, while in the second case, the stator flux is just somewhat higher. Obviously, the stator flux will saturate in the first case and will therefore not reach such high levels.

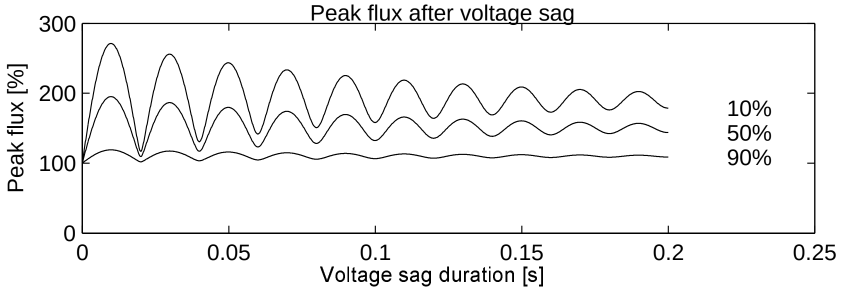


Figure 7: Peak flux for an unsaturated AC-machine after voltage sag as function of the voltage sag duration and the remaining voltage during the sag. The armature time-constant is $T_a = 0.1$ s.

3.4 Saturation in AC-machines

In the previous section, it was found that that saturation could occur after voltage sags. The peak flux for an unsaturated AC-machine after a symmetrical three-phase voltage sag is after some simplifications illustrated in equation (6) [Publication 4].

$$\hat{\Psi}_{pu} = 1 + (1 - \frac{U_{sag}}{U_{ll}}) \sqrt{1 + e^{-\frac{2t_{sag}}{T_a}} - 2e^{-\frac{t_{sag}}{T_a}} \cos \omega t_{sag}} \tag{6}$$

Figure 7 shows the plot of equation (6): that is the peak value of the stator flux as function of the remaining voltage U_{sag} during the voltage sag and the voltage sag duration t_{sag}. A symmetrical three-phase voltage sag that has the angle 360° (t_{sag} = 20 ms, 40 ms, 60 ms, etc) results in lowest peak flux and for the angle 180° (t_{sag} = 10 ms, 30 ms, 50 ms, etc) results in largest peak flux for a certain remaining voltage. Since saturation usually occurs when the flux is increased with only 5%, saturation may occur already for voltage sag with 95% remaining voltage. From Figure 7 it is possible to conclude that there will be saturation, high current and torque for voltage sags with duration that are not close to whole cycles.

3.5 Simulations

Simulating more advanced models of electrical machines is one way to get closer to reality. It makes it also possible to compare the synchronous and the asynchronous machine with each other. One other aspect is of course that it is not so easy to test voltage sags on real electrical machines, since they could get damaged. The data of the synchronous machine is from the blast furnace blower at SSAB Oxelösund and the data for the asynchronous machine is taken from an ABB machine. Table I shows that they are very similar, which makes them good for comparison.

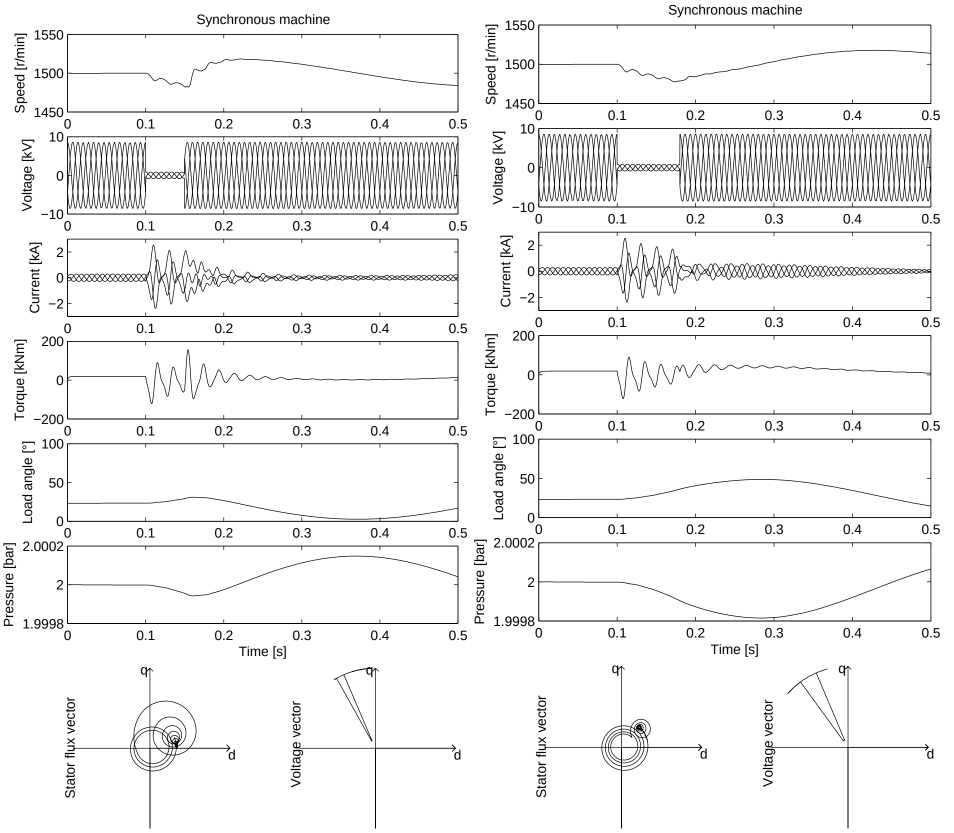


Figure 8: Shows two symmetrical three-phase voltage sags to U_{sag} = 10%. Duration is 50 ms and 80 ms. Shows speed, line-voltages, currents, air-gap torque, load angle, pressure in pipeline, stator flux and voltage.

TABLE I: RATED VALUES OF THE SYNCHRONOUS AND ASYNCHORNOUS MACHINE USED IN THE SIMULATIONS

QUANTITY	SYMBOL	SYNCHRONOUS	ASYNCHRONOUS	UNIT
Speed	n	1 500	1 493	r/min
Voltage (line-line)	U_{ll}	10 500	10 000	V
Current	I	228	241	A
Inertia (all)	J	960	960	kgm^2
Power	P	3 600	3 600	kW
Stator resistance	R_s	213	177	mΩ
Stator time constant	T_a	99	97	ms

Figure 8 shows two simulations of the synchronous machine and Figure 9 shows two simulations of the asynchronous machine, both subjected to two symmetrical three-phase voltage sags of different duration. The duration of the voltage sags are 50 ms respectively 80 ms. The behaviour of these electrical machines are similar; the duration that is 50 ms causes much higher stator fluxes, torque and currents after the voltage sag than the 80 ms case. Figure 8 includes the pressure in the connected process, that is the blast furnace with pipelines. The pressure changes less than 1‰, which means that the voltage sag is not a problem for the pressure in the pipeline.

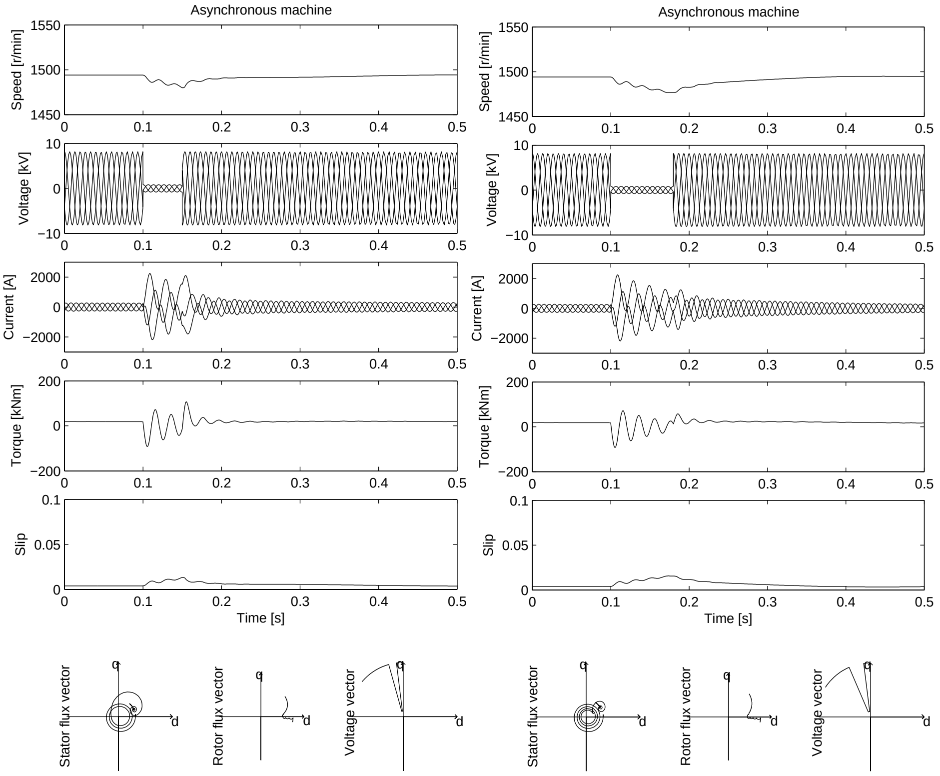


Figure 9: Shows two voltage sags to $U_{sag} = 10\%$. Duration is 50 ms and 80 ms. Asynchronous machine.

3.6 Peak torque and current

High currents and torque occur in electrical machines during and after transient conditions such as voltage sags. It is reasonable to believe that the first peak current and torque during a voltage sag is proportional to the voltage change, if saturation is neglected. However, the inductances in the machine change gradually to transient values, depending on the transient degree, so the dependence is not completely linear. The peak currents and peak torque during voltage sags are investigated with totally 33 simulations, 11 for each case with the voltage magnitude before and after the voltage sag $U = 110\%$, $U = 100\%$ and $U = 90\%$. The results of the simulations are compiled in Figure 10. The peak currents seem to follow straight lines, so there is an almost linear relation between the voltage sag amplitude and peak current after the voltage sag. Different voltage magnitude (90% and 110%) before and after the voltage sag are studied to investigate if these should be taken into consideration in the protection equipment for AC-machines. Undervoltage protection is used to avoid too much current in machines, however there is a huge difference in the current depending on the voltage before the voltage sag. It would be more effective to trip machines at a specific voltage change than at a fixed voltage level.

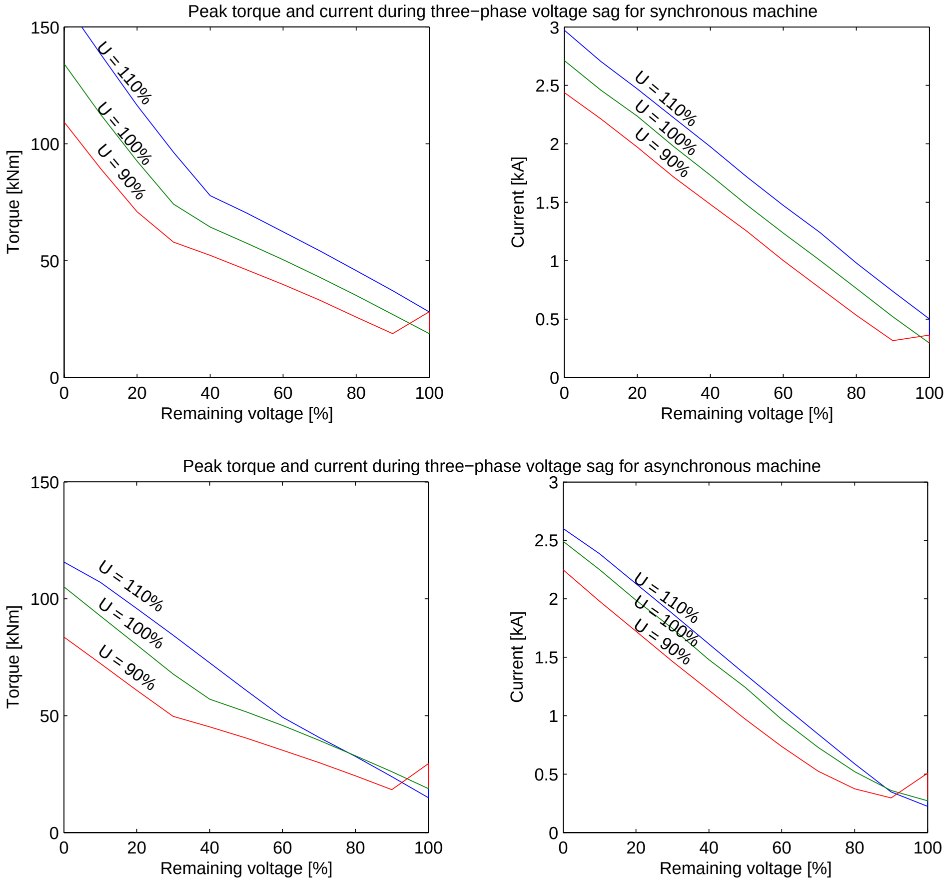


Figure 10: Peak torque and current during symmetrical three-phase voltage sags for three cases, where the voltage magnitude before the sag is 110%, 100% and 90%. The upper graphs show the synchronous machine and the lower graphs show the asynchronous machine.

This is one explanation to why machines sometimes trip from an overcurrent protection during voltage sags, while it sometimes rides-through the same voltage sag. One other explanation is of course that the load can be different, according to section 3.2.

The peak torque and current after symmetrical three-phase voltage sags with remaining voltage 90%, 70%, 50%, 30% and 10% are investigated for the synchronous machine in Figure 11 and for the asynchronous machine in Figure 12. After each simulation, the first peak torque and the first peak current were noted. It is clear that there is a sinusoidal-like dependence with a period time of 20 ms (one cycle). The worst case is clearly a voltage sag to 10% remaining voltage lasting 10 ms (one half cycle), where the peak torque for the synchronous machine is 200 kNm and the peak current is 2700 A. These values are approximately 10 times the rated values (23 kNm and 230 A). The curves are similar for the asynchronous machine, however the torque is reduced for longer voltage sags, due to the fast decrease of the rotor flux.

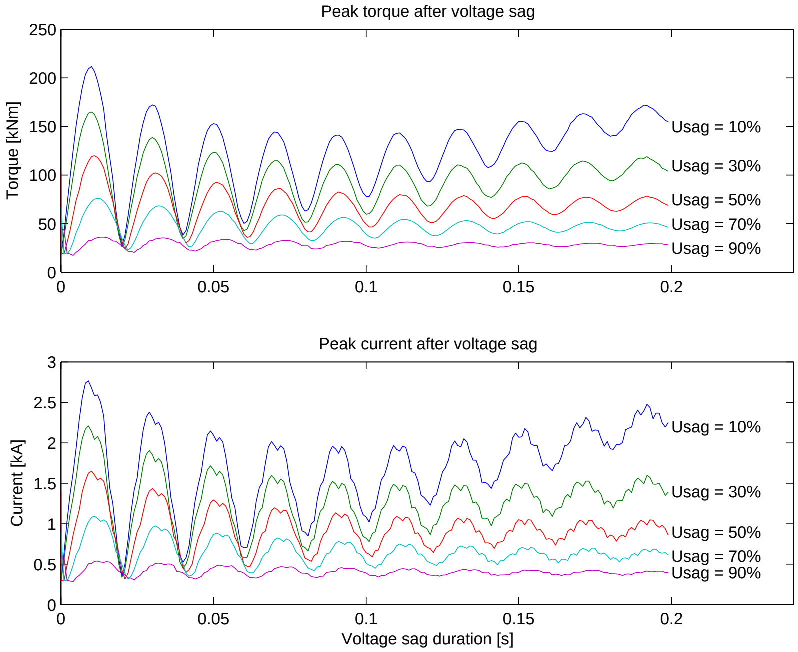


Figure 11: Peak torque and current after symmetrical three-phase voltage sags.

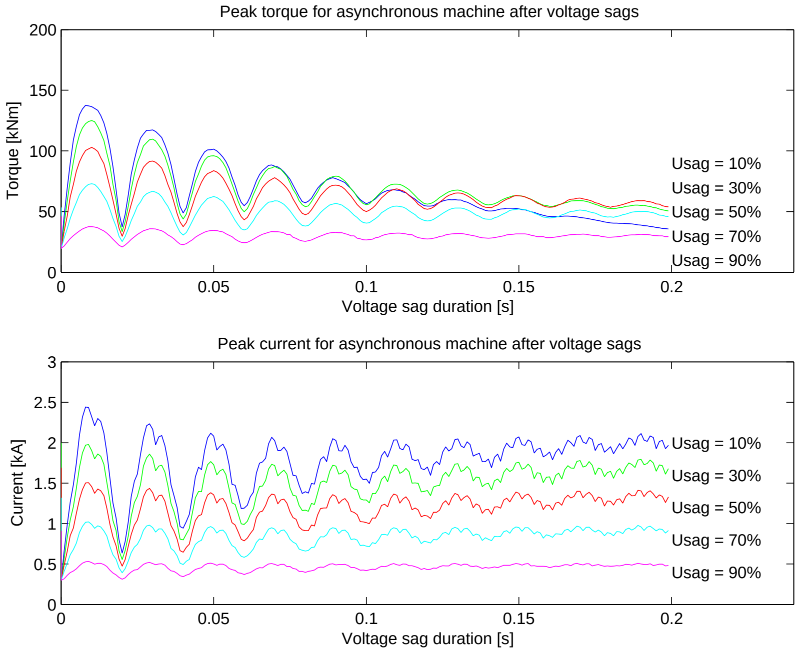


Figure 12: Peak torque and current after symmetrical three-phase voltage sags.

Chapter 4

Reduction of the effects of voltage sags

With the information given in Chapter 3 is it possible to predict which voltage sag durations that are less severe for the line-operated AC-machine. These voltage sag durations may be possible to achieve in the power grid. This chapter explains how.

4.1 Adjusting the duration of voltage sags

The durations of voltage sags caused by faults like lightning strikes to the power lines are set by protection equipment that disconnect power lines in the transmission and distribution system. There are a lot of types of faults and they generate different voltage sag types, like the three-phase, two-phase or single-phase faults. These types can also be different, there are for instance two-phase line-to-line fault and two-phase to neutral /ground fault. These will of course look different. This chapter will only focus on the symmetrical three-phase fault, which also can be line-to-line or line-to-ground faults. These are both classified to the voltage sag type A. The other fault types can be adopted to this concept as well, but in a bit different way. In this chapter, it is also assumed that the line frequency is 50 Hz.

The usual way of disconnecting faulted lines is to disconnect each one of the three phases separately, that is when each line has its zero-crossing current. The best way would of course be to disconnect all at the same time. Since the angle between the phases in a three-phase symmetrical system is 120°, the time between each zero-crossing is 20 ms / 6 = 3.33 ms (60°). If the fault is line-to-ground, the time to break all three phases is then $2 \cdot 3.33$ ms = 6.67 ms (120°). If the fault is line-to-line, the first phase is disconnected at its zero-crossing, the two other phases will then have zero-crossing at the same time, since it is the same current flowing in these lines, but in the opposite direction. In this case, the time between these two zero-crossings is only 5 ms (90°). Thus, the duration of the voltage sag is not obvious. There is a gap of a couple of millisecond, actually as much as 120°. Still, this is good enough to achieve a voltage sag duration that is less harmful for electrical machines. For the end-user, the breaking instants in the phases may not always be identifiable, since there might be one or more transformers (with different configurations such as Δ-Y) between the end user and the fault. However, it is possible to control the duration of the voltage sag. This can be done with an accuracy of 3.33 ms (60°), since it always is possible to wait for the next zero crossing. Thus, there are six instants per cycle that can be used to break the line to obtain a good voltage sag duration. The whole operation from the instant the breaker receives the signal to break takes maximum 10 ms, since the breaker could have to wait up to 3.33 ms for the first zero-crossing and another 6.67 ms to break the other two phases. This means that the signal should be sent 10 ms / 2 = 5 ms in advance, to obtain the correct voltage sag average duration. If the fault is instead line-to-line, the signal should be sent (3.33 ms + 5 ms) / 2 = 4.1 ms in advance. The protection equipment must also know all delays, which have to be very repetitive.

The concept of creating voltage sag durations that is not so bad includes the following steps to go through by the protection equipment. In this case it is assumed that it is possible to create a voltage sag duration that is 60 ms. If this for some reason is not possible (due to delays, etc) or if it is possible to do it faster, just add or subtract the mentioned numbers with any multiple of 20 ms.

1. When a voltage sag is detected, a timer must start (at $t = 0$). The time to detect must of course be included.
2. The type of fault should be detected within a cycle (20 ms), for instance that it is a three-phase fault.
3. Call the right procedure depending on the fault type.

If the type is a three-phase line-to-line fault:

4. Send signal at the instant $t = 56$ ms to breaker, to break as soon as possible. With this procedure, the duration of the voltage sag will be approximately 60 ms. For instance if the first zero-crossing is at $t = 58$ ms, then the next zero-crossing is 5 ms later, that is at $t = 63$. The average duration in this case is $t_{sag} = 60.5$ ms.

If the type is a three-phase line-to-ground fault:

4. Send signal at the instant $t = 55$ ms to breaker, to break as soon as possible. With this procedure, the duration of the voltage sag will be approximately 60 ms. For instance if the first zero-crossing is at $t = 58$ ms, then the next zero-crossing is 3.33 ms later, that is at $t = 61.33$, and the last zero-crossing is at $t = 64.67$ ms. The average duration in this case is $t_{sag} = 61.3$ ms.

Figure 13 and Figure 14 show two cases where the synchronous machine is subjected to a three-phase line-to-ground voltage sag to 10%. The duration differs with 10 ms, and it is obvious from the figures that the second case is better for the machine.

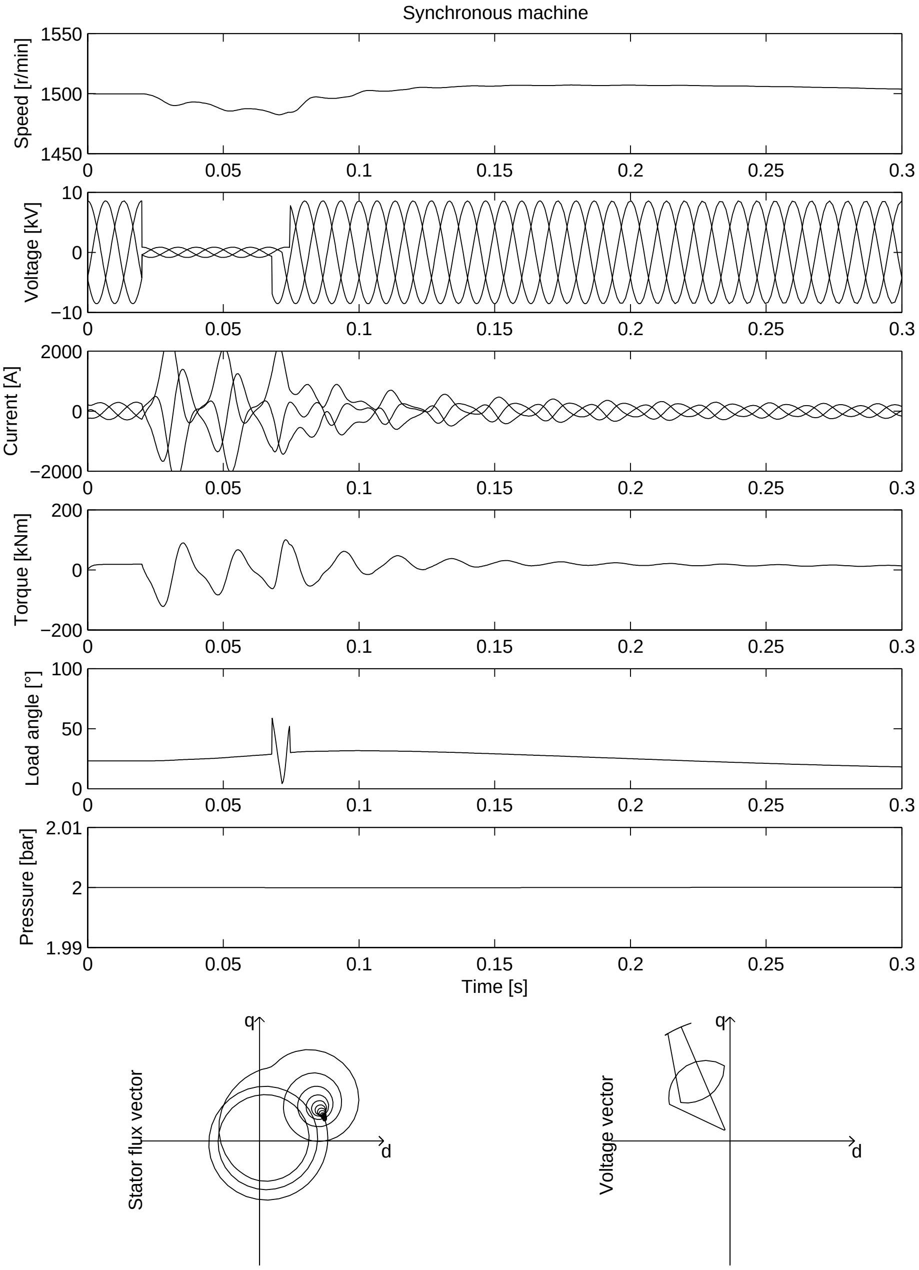


Figure 13: Shows speed, voltage, machine current, air-gap torque, load angle and pressure. Duration is 50 ms.

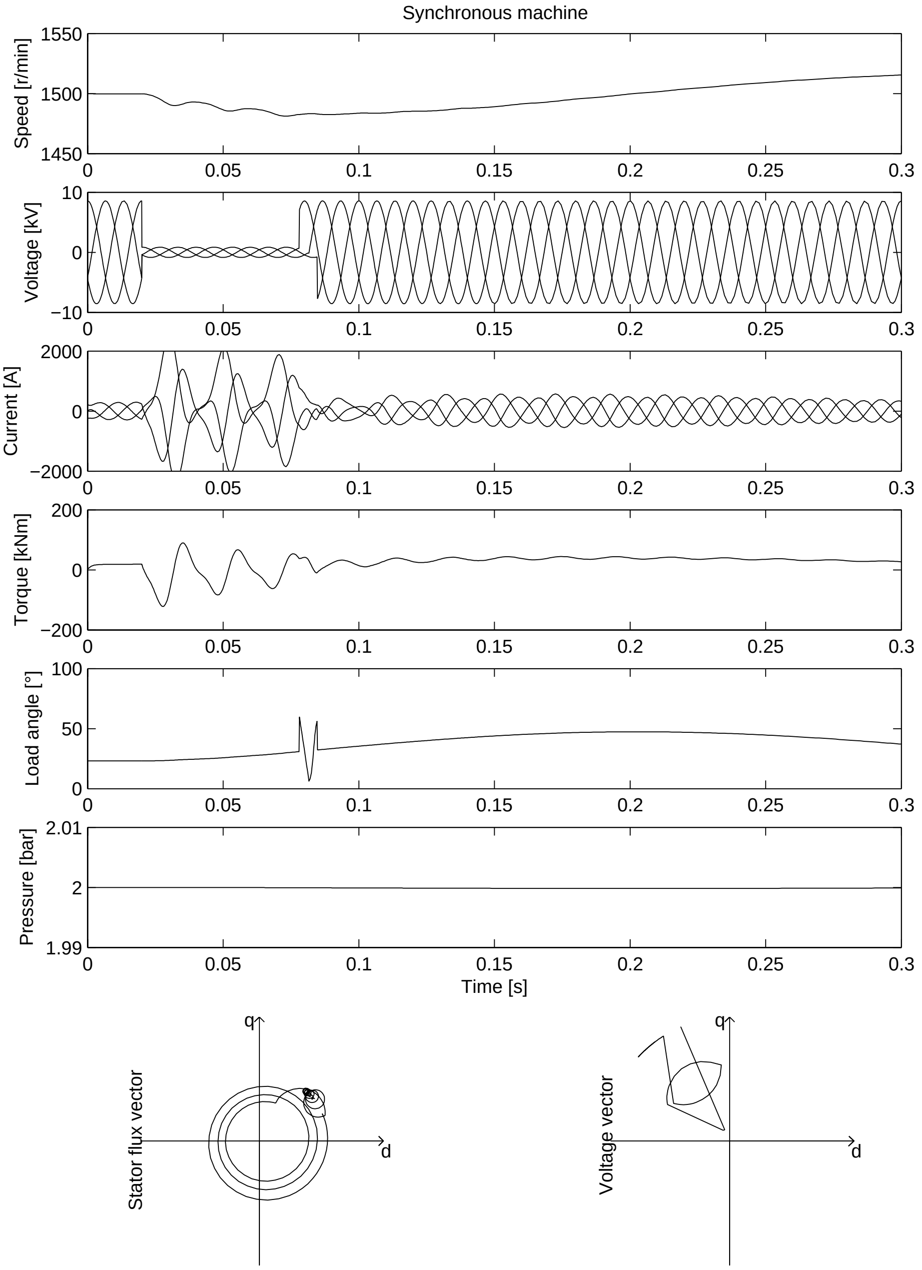


Figure 14: Shows speed, voltage, machine current, air-gap torque, load angle and pressure. Duration is 60 ms.

Chapter 5

Conclusions

This chapter summarises the conclusions of this doctoral thesis and suggests some future work. Conclusions are made on the electrical machine behaviour and the connected process due to the influence of voltage sags. Conclusions are also made on voltage sags in the power grid.

5.1 Conclusions related to the metals processes

The following conclusions are drawn for the three metals processes that are investigated:

- The hot rolling mill process is the most sensitive of the three studied metal processes. Depending on the rolling speed and the applied torque from the rolling pass, the stop time when the electrical machines are automatically shut off is between 10 ms and 72.0 s. Since the active rolling time is between 10% and 84% of the power on time, the risk that a voltage sag affects the process has the same value range.

- The cold rolling mill process stops within 0.50 s to 4.70 s, when the DC-machines are automatically shut off, depending on the rolling pass. For deep voltage sags it is very likely that the overcurrent protection breaks the circuit, causing the rolling mill to stop. Since the active rolling time during daytime is approximately 67%, the risk that a voltage sag occurring daytime affects the process is also 67%.

- The blast furnace blower that powers the process can today manage voltage sags to 60%. The protection equipment should be adjusted to fit the sensitiveness of the synchronous machine in order to reduce the number of unplanned shutdowns. The pressure in the pipeline is not affected much by voltage sags that the blast furnace blower can ride-through. If the blower is turned off, the overpressure in the pipeline will be zero within 15 - 30 s. All voltage sags will affect this process, since the power on time is 100%.

5.2 Conclusions related to AC-machines

The following conclusions can be drawn for line-operated asynchronous (induction) and synchronous machines that are subjected to voltage sags:

- Voltage sags may cause magnetic saturation. Saturation occurs after voltage sags, not during voltage sags. Saturation transfers the machine faster into steady state conditions.

- Deeper voltage sags generally cause higher torque and currents.

- The behaviour of the asynchronous machine during and after voltage sags is similar to the synchronous machine. The difference is mainly less peak torque after voltage sags due to decreasing rotor flux during the voltage sag in an asynchronous machine.

- The durations of voltage sags are as important as the voltage sag magnitude. Voltage sags that are whole cycles results in less torque and currents. Voltage sags that are half cycles (0.5, 1.5, 2,5 etc) result in high torque and currents. The worst peak torque and peak current takes place for a three- or a two-phase voltage interruption (no remaining voltage) when the voltage sag duration that is half a cycle.

- Tripping irregularities, which are that a machine sometimes trip for a certain voltage sag and sometimes not, can be explained by either that the load is different or that the voltage magnitude before the voltage sag is different. In these cases it is usually the overcurrent protection that trips the electrical machines.

- Overcurrent protection should be used to protect electrical machines from damages of too much current or torque.

- Undervoltage protection should be used in combinations with the right synchronism curve (for the current load and voltage sag type) to shut down synchronous machines when they will not be able to run up to synchronous speed anymore.

- The synchronism curve for synchronous machines depends on the load of the machine, the inertia of the machine and connected equipment, and the voltage sag type. The ability to ride-through voltage sags is reduced by higher load, lower inertia and if the voltage sag type is a three-phase voltage sag. The ability to ride-through voltage sags is increased by lower load, higher inertia and if the voltage sag type is a single-phase voltage sag.

5.3 Conclusions related to the power grid

The following conclusions can be drawn for voltage sags occurring in the transmission and distribution system.

- Voltage sags are in Sweden more frequent in the summer time. The duration is in general approximately 100 ms and the remaining voltage magnitude is in general 80% of nominal voltage. The number of voltage sags per year at a typical factory in Sweden is approximately 30.

- The protection equipment (in switchyards etc) that disconnects power lines sets the duration of the voltage sags when lines are disconnected. The duration can be set adequately to reduce problems (high stator flux, torque and current) in line-operated AC-machines. This does apply to synchronous and asynchronous machines and generators that are directly connected to the power grid.

5.4 Future work

Here are some suggestions of future work based on this thesis.

- Studies with a FEM-program (Finite Element Method) with time stepping of electrical machines subjected to voltage sags could be investigated. This could improve the accuracy, especially of the magnetically saturation. Studies could also be performed on real electrical machines.

- The effects of the suggested improvements of voltage sag duration control could be investigated in a larger power grid. It would be interesting to see the effects of this when interacting with transformers and other electrical machines.

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List of symbols

Symbol	**Quantity**	**Unit**
A	Area	m^2
C_f	Flow capacitance	mol/Pa
c	Arbitrary integer	-
e	Natural base (≈ 2.7182818…)	-
E	Excitation voltage	V
f	Frequency	Hz
F	Force	N
$H(t)$	Heaviside’s step function	-
I	Current	A
j	Imaginary unit ($j^2 = -1$)	-
J	Inertia	kgm^2
l	Length	m
k	Constant	Nm/s^2
L	Inductance	H
m	Mass	kg
M	Torque	Nm
n	Speed of machine	r/min
n	Amount of substance	mol
p	pole-pair	-
$p(t)$	Pressure	N/m^2
P	Power	W
q	Flow	mol/s
Q	Reaktive power	var
r	Radius	m
R	Resistance	Ω
R	Ideal gas constant (≈ 8.314…)	J/(mol·K)
R_f	Flow resistance	Pa·s/mol
s	Laplace’ symbol	rad
S	Apparent power	VA
t	Time	s
T	Temperature	K
T_a	Time-constant of armature winding	s
$u(t)$	Voltage (instant value)	V
U	Voltage (rms)	V
U_{ll}	Voltage (line-line)	V

$U^r(t)$	Voltage vector (instant value)	V
v	Speed	m/s
V	Volume	m^3
W	Energy	J
X	Reactance	Ω
Z	Impedance	Ω
Ψ	Flux	Wb
β	Voltage sag instant	rad
δ	Load angle	rad
η	Efficiency	-
φ	Angle between voltage and current	rad
Φ	Magnetic flux	Wb
μ	Friction coefficient	Nm/s
π	Constant (≈ 3.141592653589793…)	-
ρ	Density	kg/m^3
τ	Time-constant	s
ω	Angular frequency	rad/s

Publication 1

F. Carlsson and C. Sadarangani

Behaviour of synchronous machines subjected to voltage sags of type A, B and E

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Publication 2

F. Carlsson

Explanations to irregularities in the dependence between voltage sag magnitude and the tripping level for line-operated synchronous machines

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Publication 3

F. Carlsson

Saturation in Asynchronous Machines due to Voltage Sags

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Publication 4

F. Carlsson

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Publication 5

F. Carlsson

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Publication 6

F. Carlsson

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Publication 7

F. Carlsson, H. -P. Nee and C. Sadarangani

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