Simulations of Rotating Brushless AC Excitation System with Controlled Thyristor Bridge Rectifier for Hydropower Generators

Peter Butros
Abstract

Simulations of Rotating Brushless AC Excitation System with Controlled Thyristor Bridge Rectifier for Hydropower Generators

Peter Butros

This thesis aims to simulate and find out more about the electrical dynamics of a six-phase exciter for hydropower generators. Because ordinary electric circuit-based simulation software only simulate three-phase electrical systems, a FEM-based software is used for the electrical dynamics simulations of the six-phase system. The objective is to analyse the pulsation behaviour of the rectified electrical output on the six-phase system and compare it to the three-phase system. The three-phase system is also simulated with filters with the aim of decreasing the amplitude of the pulsations on the electrical output.

It is expected that an upgraded system from a three-phase system to a six-phase system should double the pulsation frequency on the rectified electrical output. However, the result shows that the rectified electrical output of the six-phase system consists of pulsations with unexpected frequencies. The simulated RL-filter on the three-phase system shows only insignificantly small changes on the rectified electrical pulsation amplitude.
# Contents

1 Introduction 3  
1.1 Background 3  
1.2 Objective 4  

2 Theory 5  
2.1 The Synchronous Generator 5  
2.1.1 Active and Reactive Power 6  
2.2 Power System Stability 7  
2.2.1 Transient Stability 8  
2.2.2 Small-signal Stability 8  
2.2.3 Voltage Stability 8  
2.3 Voltage Regulation 9  
2.4 Excitation Systems 9  
2.4.1 Static AC Excitation Systems 9  
2.4.2 Rotating AC Excitation Systems 10  
2.5 Rectifiers 12  
2.5.1 Thyristors 12  
2.5.2 Six-Pulse Thyristor Rectification Bridge 13  
2.5.3 Twelve-Pulse Thyristor Rectification Bridge 15  
2.5.4 Harmonics Generated On the AC-side By the Rectification 16  
2.5.5 Harmonics Generated On the DC-side 16  
2.6 Filters 17  
2.6.1 RL-Filter Design 18
3 Method

3.1 Simulations Using FEM ............................. 20
3.2 Fast Fourier Transform .............................. 21
3.3 Simulation of the Three-Phase Excitation System .......... 21
3.4 Simulation of the Six-Phase Excitation System .......... 22
   3.4.1 Simulation Setup of the Six-Phase Excitation System .. 23
3.5 Simulation of the Three-Phase Excitation System with RL-Filters .... 23
   3.5.1 Simulation Setup of the Three-Phase Excitation System with RL-Filters . 25

4 Results and Discussions ............................... 27

4.1 Simulation Results of the Six-Phase Excitation System ........ 27
   4.1.1 Simulation of the Six-Phase Excitation System During No-Load Operation 27
   4.1.2 Simulation Using Exciter Model with 108 Slots During Load Operation . 28
   4.1.3 Simulation Using Exciter Model with 216 Slots .................. 31
4.2 Simulation Results of Three-Phase Excitation System with RL-Filters .... 35
   4.2.1 Simulation Without RL-Filters .......................... 35
   4.2.2 Simulation With RL-Filters ............................ 35

5 Conclusions ............................................. 37

6 Future Work ........................................... 38

6.1 Simulations of the Six-Phase Exciter With Two Separated Three-Phase Systems 38
6.2 Simulations of Other Types of Filter Designs .................. 38
1 Introduction

Since the introduction of the industrial era, hydropower has been one of the cornerstones in the energy system of the modern Swedish society. The combination of the mountainous north and the temperate climate with heavy precipitation have made it suitable for large scale hydropower stations in the country. In 2009, hydropower supplied the Swedish energy system with 65.3 TWh electricity. This corresponded to 48.8% of the total electricity production in Sweden that year and thus, hydropower continue to be the single most important electricity source in Sweden.[1]

The main advantages with hydropower is its ability to regulate for the power consumption in a matter of minutes [2]. Because of this, hydropower is used to balance the power consumption over the day and keep the transmission line frequency as constant as possible to 50 Hz. In addition to frequency compensation, hydropower stations are also used for the voltage stability regulation.

The voltage regulation is important to reduce the voltage disturbances caused for example by the load. A voltage disturbance on the transmission is an instability condition which may lead to system failure and collapse[4]. Dependent on the characteristics of the load and the active and reactive power consumption, the developed voltage disturbance on the transmitted power also have different characteristics. The stability condition regulation is usually assigned to the excitation system, with different results dependent of the excitation system dynamics.

Many different excitation system techniques are applied for the hydropower system generators. This thesis will discuss the brushless excitation technique, preferred because it is a clean and safe technique, but that is usually to slow to be able to regulate for the transient stability on the grid.

1.1 Background

VG Power AB, a generator manufacturer in Västerås, Sweden, have developed a new type of current controlled brushless excitation system for hydropower generators. The excitation system consists of an exciter where the poles are on the inside of the stator and the phase windings are found on the rotor, thus inducing an alternating current (AC) on the rotor-side of the air gap. The new method is to rectify the induced current using a thyristor rectification bridge consisting of six thyristors directly attached on the rotating axis. The rectifying bridge is controlled through a wireless bluetooth connection making it possible to instantly increase or reduce the excitation level of the main generator.

A pilot of the described excitation system is currently installed at Bergeforsen Hydropower Station near Sundsvall, Sweden. Tests that have been carried out on the excitation system shows that the system works well in operation. However, an unforeseen effect of the controlled rectifier is that it causes vibrations on the stator-side of the exciter. The vibrations are transferred to the upholding rack, making the vibrations both felt and heard.

According to the documented analysis made by VG Power AB [5, 6], the vibrations tend to grow and become disturbing with bigger trigger angle, used for the control of the rectification bridge, and with increased excitation level.
1.2 Objective

The purpose of this thesis is to understand the cause of the vibrations emerging on the excitation system. A general physical explanation of the current excitation system is vital to understand the cause of the vibrations. The objective is also to find a solution to reduce the vibrations. The analysis [5, 6] suggests that the existent excitation system develops a pulsation on the exciter air gap torque. It is also suggested that the pulsation is close to a resonance frequency of the exciter rack. A solution should be to increase the pulsation frequency of the air gap torque and thus mute any vibrations. This could be done, according to the analysis, by upgrading the current excitation system from a three-phase exciter with a six-pulse thyristor rectification bridge to a six-phase exciter with a twelve-pulse thyristor rectification bridge. The upgraded excitation system should have an air gap torque pulsation of double frequency, hopefully reducing the risk of triggering any resonance.

Before such a system is built, the developer wants to know more about the electrical dynamics in such a system. Ordinary electric circuit-based simulation software, such as Simulink and PSCAD, only supports simulations with three-phase machines. Instead, for this thesis a FEM-based software will be used to simulate the six-phase system.

An upgraded excitation system from a three-phase exciter to a six-phase exciter would require vast reconstructions that would be costly. If there is another solution to solve the problem which involves the current three-phase exciter, this solution should also be evaluated. Such a solution could be to install filters on the excitation system that effectively could reduce the magnitude of the pulsations of the air gap torque. Simulations on a filtered excitation system also needs to be carried out.
2 Theory

In order to know how to damp the arising vibrations it is important to thoroughly study the included components and how they interact to exactly describe how the vibrations arise in the first place. In this section, the included components, their function and how they interact with the excitation system will be explained.

2.1 The Synchronous Generator

The most common solution to convert kinetic energy to useful electricity is by exposing a conductor to a varying magnetic field which induces electric potential in the conductor. This is described by Faraday’s law where the induced voltage $e_i$ in the conductor is

$$e_i = \left(-\frac{d\psi}{dt}\right)$$

(2.1)

where $\psi$ is the instantaneous magnetic flux and $t$ is time. This is the simple main function that the generator has been developed around. The conductor windings where the electric potential is induced are placed on the stator, or the armature. The magnetic flux is developed on the rotor, which is surrounded by the stator, and rotated through an applied torque.

Figure 2.1: Synchronous three-phase generator with one pole-pair and a three-phase stator winding.

Figure 2.1 shows a simple generator where the rotor consist of only one pole-pair. Usually the synchronous generator of a hydropower station has more poles than only two to operate under synchronous speed, that is, at the speed at which the magnetic field created by the field coils rotates [7]. The electrical frequency, $f_{el}$, of such a generator is calculated as

$$f_{el} = \frac{P_n}{2} f_{mech}$$

(2.2)
where \( f_{\text{mech}} \) is the mechanical frequency \([\text{Hz}]\) and \( P_n \) is the number of poles in the machine. The synchronous speed \( n_s \) in revolutions per minute (rpm) is thus given as

\[
n_s = 120 \frac{f_{el}}{P_n}
\]  

(2.3)

### 2.1.1 Active and Reactive Power

A synchronous generator which is connected to a three-phase AC power grid will induce sinusoidal currents in each of the three phases, \( i_a, i_b \) and \( i_c \) that are symmetrically shifted 120 electrical degrees from each other.

\[
i_a = \hat{i} \cos(\omega t + \gamma)
\]

(2.4)

\[
i_b = \hat{i} \cos(\omega t - 120^\circ + \gamma)
\]

(2.5)

\[
i_c = \hat{i} \cos(\omega t - 240^\circ + \gamma)
\]

(2.6)

Here, \( \omega = 2\pi f_{el} \). [2]

In resemblance to the currents, the induced voltages, \( u_a, u_b \) and \( u_c \) can be written

\[
u_a = \hat{u} \cos(\omega t + \theta)
\]

(2.7)

\[
u_b = \hat{u} \cos(\omega t - 120^\circ + \theta)
\]

(2.8)

\[
u_c = \hat{u} \cos(\omega t - 240^\circ + \theta)
\]

(2.9)

Hence, the instantaneous power in each phase is given by

\[
p_i(t) = u_i i_i
\]

(2.10)

\[
= \hat{u} \hat{i} \cos(\omega t + \theta) \cos(\omega t + \gamma)
\]

(2.11)

\[
= \frac{1}{2} \hat{u} \hat{i} [\cos(\theta - \gamma) + \cos(2\omega t + \theta + \gamma)]
\]

(2.12)

where the angles \( \gamma \) and \( \theta \) represent the shifted angles of the voltage and current which occur when the grid is loaded. \( \varphi = \theta - \gamma \) would therefore represent the phase shift between the voltage and the current developed due to load properties. Inserted in the previous expression and evaluated even further, this would give an expression of the instantaneous power as

\[
p_i(t) = \frac{1}{2} \hat{u} \hat{i} \cos \varphi (1 + \cos 2(\omega t + \gamma)) + \frac{1}{2} \hat{u} \hat{i} \sin \varphi \sin 2(\omega t + \gamma)
\]

(2.13)

The expression of the instantaneous power consists of two separate functions of time. One of the time functions vary around the mean value \( \frac{1}{2} \hat{u} \hat{i} \cos \varphi \), and the other function around the mean value 0. Hence, it is convenient to define the apparent power \( |S| \) as

\[
|S| = \frac{1}{2} \hat{u} \hat{i}
\]

(2.14)

the active power \( P \) as

\[
P = \frac{1}{2} \hat{u} \hat{i} \cos \varphi = |S| \cos \varphi
\]

(2.15)
and the reactive power $Q$ as

$$Q = \frac{1}{2}ui \sin \varphi = |S| \sin \varphi \quad (2.16)$$

The relationship between the different powers is shown in Figure 2.2.

The total power consumption consists both of active and reactive power. The different type of load components on the grid will introduce a phase shift between the voltage and the current, which in turn determines the consumption ratio between the active and reactive power. It is however important to have in mind that only the active power component does any work.

Usually, the main objective of any power grid is to transmit as much active power as possible. An increase of the reactive power will not only lower the transmission capacity of the transmission lines, but also increase the losses [2]. Hence, reactive power compensation is important to increase the capacity of the existing transmission lines on the grid and to minimize the losses.

There are many techniques available to compensate for the reactive power consumption. The preferred method to regulate for the active and reactive power production and consumption is to control the excitation level of generators [4]. In general, overexcitation will produce reactive power while underexcitation will absorb reactive power. To further explain the control of the excitation level, it is necessary to have an understanding of the excitation system, its characteristics and its ability to control the field current.

### 2.2 Power System Stability

There are mainly three types of stability problems that have to be taken into consideration regarding power generation by a synchronous generator. The three stability problems depends on imbalances between either the active power or the reactive power distribution and consumption on the grid. If the imbalances are too great or these conditions are kept to long, it could eventually develop distribution failure and a system collapse. Here, the three types of stability problems are described [4].
2.2.1 Transient Stability

The transient stability problem is also called rotor-angle stability, because of the rotor-angle acceleration behaviour due to active power imbalances. The transient stability problem is derived from the Equation of motion of the machine rotor of the synchronous generator, driven by a prime mover, as

\[ J \frac{\partial^2 \delta}{\partial t^2} = T_m - T_e \]  \hspace{1cm} (2.17)

where \( J \) is the total moment of inertia of the rotor mass, \( T_m \) is the mechanical torque supplied by the prime mover, \( T_e \) is the electrical torque output, or the air gap torque, of the generator and \( \delta \) is the angular position of the rotor.

To keep the synchronous speed of the generator, the mechanical torque \( T_m \) has to equal to the electrical torque \( T_e \). Any difference between them would lead to an acceleration of the rotor angle. Due to the stiffness of the huge mass rotor, the rotor angle acceleration cannot react as fast as the change of the electrical torque. This is the main transient stability problem which could put the generator from its synchronous condition and cause a system collapse.

2.2.2 Small-signal Stability

Small-signal disturbances develops for example due to small incremental changes on the system load or because of sub-synchronous mismatching of the rotating component. The small-signal approach is based on the assumption that the dynamic behaviour of a power system can be linearized in the neighborhood of an operating point of interest. Such an assumption has two important consequences. It allows for the use of powerful linear analysis methods that are well suited for the study of large systems such as a power system. It also limits the area of the analysis to the region where the linear approximation is valid.

In many cases, such an assumption is not valid for a stressed power system. The non-linear terms in this case cannot be neglected and a linear analysis technique might not provide an accurate picture of the system modal characteristics. If the difference between the non-linear and the linearized power system becomes to large, this could impose a break of the synchronous condition.

2.2.3 Voltage Stability

Dependent on the excitation system used, the voltage regulator ability to maintain a constant voltage condition could be different. A power distribution system reaches an instability condition when for example increase in load demand or change in system condition causes an uncontrollable drop in voltage, which eventually develops to distribution failure and system collapse. The main reason for such an uncontrollable drop in voltage is an increase of reactive power demand.
2.3 Voltage Regulation

The voltage regulation is usually assigned to the excitation system. By continuously adjusting the excitation of the main generator, it is possible to adjust the reactive power production to meet the reactive power demand. Usually, a voltage regulator is used for this purpose. The voltage regulator keeps the generated voltage at a constant level during load operation by either increasing or decreasing the excitation level. Using such a regulator would help preserve a sustainable voltage stability condition.

Other stability problems are usually also being regulated by the excitation system. Depending on the dynamics of the excitation system, the regulation of the transient and small-signal stability are handled by some excitation systems more successful than others. For example, ordinary brushless excitation systems inherit a time constant due to the inductance of their own coil winding. For the transient and small-signal disturbances, voltage regulation with an inherited time constant could be ineffective.

The time constant of the voltage regulator, inherited by the excitation system, is therefore crucial. It is important that it is as small as possible for the voltage regulator to work effective.

2.4 Excitation Systems

The basic function of any excitation system is to provide direct current (DC) to the field winding of the synchronous generator. Whereas there still exists DC excitation systems that are in use today, the excitation systems are usually of AC type. Thus, it is necessary to rectify the output of the excitation system from AC to DC to be able to use it as field current for the main generator. In addition, the excitation system is also given the function to automatically adjust the DC field current to control the excitation level.

The different types of excitation systems are mainly categorised as DC excitation systems, AC excitation systems and Static excitation systems [4]. The AC excitation systems are of interest in this thesis, since the studied excitation system is of that kind. The other types of excitation systems will thus not be considered.

The AC excitation system utilises an AC generator as the system exciter. The AC generator, or the exciter, usually sits on top of the shaft of the main generator. Dependent on how the rectification of the exciter output from AC to DC is handled, the AC excitation systems are divided in two different sub-categories. These sub-categories are; Stationary AC excitation systems and Rotating AC excitation systems.

2.4.1 Static AC Excitation Systems

For the static AC excitation system, the AC current is induced in a stationary winding. There, the AC output of the exciter is rectified to DC input of the main generator field winding. This means that the field current needs to pass from a stationary to a rotating reference system. This is mainly done through the use of carbon brushes that are in contact with slip rings on
the rotating axis, as can be seen in Figure 2.3. While this solution is common, the carbon brushes in contact with the slip rings will produce a carbon dust due to the contact friction. The continuously created carbon dust will cause problems, both concerning health issues and directly on the machine. For instance, the carbon dust will be collected beneath the insulation which causes short circuits between the terminals and the slip rings. A sudden short circuit during operation will lead to major malfunction and could even make the excitation system blow up. Therefore, a continuous maintenance of the excitation system is necessary to avoid malfunctions.

![Figure 2.3](image)

**Figure 2.3:** Slip rings of excitation system used for the G1 generator at Bergeforsen Hydropower Station. These slip rings are only used for measurement signals.

### 2.4.2 Rotating AC Excitation Systems

A way to avoid the use of carbon brushes and slip rings is to use a rotating AC excitation system. It is best described as an inside-out synchronous generator where the poles are found on the stator and the three-phase winding is found on the rotor. This way, the current and voltage will be induced on the right side of the exciter air gap, directly in the rotating reference system, which will remove the need of carbon brushes and slip rings. Figure 2.4 illustrates the design of the rotating AC excitation system considered in this thesis. Such a system is referred to as a *Brushless excitation system*. The brushless excitation system has been around for some time, though it usually uses a rotating passive diode bridge for AC to DC rectification. The new rotating AC excitation system technology, that has been developed by VG Power AB, uses instead a rotating thyristor bridge rectifier that is controlled through a bluetooth connection.
Physically, the AC exciter behaves as an ordinary synchronous generator. This means for example that the induced current and voltage, and thus also the generated power, will have the same characteristics as described in section 2.1. Also the behaviour of the air gap torque will be the same. The air gap torque, \( T_e \), is the proportional generated power as

\[
T_e = \frac{P_{\text{tot}}}{\omega_{\text{mech}}}
\]  

Here, \( P_{\text{tot}} \) is the total power transferred across the air gap, while \( \omega_{\text{mech}} \) is the mechanical angular velocity of the rotor. Since the angular velocity of the excitation system rotor and the main shaft are the same, and the inertia of the exciter is negligible compared to the inertia of the generator, it does not have any time-dependent influence on the air gap torque, \( T_e \). However, \( T_e \) is directly proportional to the variation of the transferred power, \( P_{\text{tot}} \).

From equation 2.13 it is obvious that \( P_{\text{tot}} \) is directly proportional to the current times the voltage, \( u_i \), of each phase. This gives a dependence of the induced current and voltage to the air gap torque as

\[
T_e \propto P \propto u_i
\]

For a synchronous generator connected to an AC grid, this dependency is usually not any problem. The three-phase grid is so strong that the induced current and voltage will be sinusodial and not distorted by the load [4]. However, this is not the case of the rotating excitation system. Instead, the sinusodial output current passes a rectifier before it is delivered to the main generator field winding. The rectifier will distort the induced voltage and current from the excitation system and thus directly influence the air gap torque.
2.5 Rectifiers

The main property of a rectification component is to only allow a load current to flow in one direction. This usually means that when the current load through the component is positive, it is allowed to flow. But when the current load becomes negative, the rectification component will block the current from flowing. The simplest component used as a rectifier is the diode, which is illustrated in Figure 2.5. However, the diode does not have the ability to control the throughput, which for the excitation system is crucial as explained in part 2.4. Instead a controllable diode, a thyristor, is used for the rectification in this application.

![Figure 2.5: A single diode used to rectify AC to DC.](image)

2.5.1 Thyristors

The thyristor is a semiconductor and works much like a diode [8]. The main difference is its ability to control the throughput. This is done by letting the thyristor block the incoming current, even under positive load, until the thyristor gets “triggered”. The switching action of the thyristor from the non-conducting to the conducting state can be used to control the power in a circuit. Figure 2.6 shows the symbol used for the thyristor.

The semiconductor characteristics of the thyristor does not allow the positive current load to flow until a smaller triggering current conducts through the thyristor gate. The triggering can thus be controlled by deciding when during the positive load current the thyristor will conduct. By delaying the triggering current in relation to the incoming current, the output current will be lower compared to the case where all the incoming positive current load passes through the rectifier [9]. The delaying of the triggering current is decided by the trigger angle, or firing angle, $\alpha$ as

$$\alpha \leq \omega t \leq 90^\circ$$  \hspace{1cm} (2.20)

Hence, $\alpha$ is controllable from the angle $0^\circ$ to $90^\circ$ where $\alpha = 0^\circ$ means that there is no triggering delay and the thyristor will conduct all the incoming current, while $\alpha = 90^\circ$ means that the triggering angle will be delayed the entire period of positive current load and thus not conduct at all.

In general, the thyristor will conduct the incoming current as long as it is exposed to a positive current load, which occurs when $\alpha \leq 180^\circ$. But for the case when $90^\circ \leq \alpha \leq 180^\circ$ the thyristor acts as an inverter instead of a rectifier. For the thyristor application in this thesis, only the rectification ability is interesting. Any other ability of the thyristor is not being considered.
Figure 2.6: The thyristor symbol. The difference compared to the diode is the controllable characteristics of the thyristor. The thyristor will not allow any current to flow until it gets “triggered” by a small control current through its gate.

Figure 2.7: The six-pulse thyristor rectification bridge. To every incoming AC-line there are two antiparallel thyristors connected. Together, the thyristor connections make up a full-wave bridge circuit.

2.5.2 Six-Pulse Thyristor Rectification Bridge

To make use of the entire AC period, two antiparallel thyristors are connected to each phase. In this case, the two thyristors will have a separate positive current load per each half period of the incoming current. With this thyristor connection it is possible to control the entire incoming AC period, both when the current load is positive and when it is negative. For an ordinary three-phase system, it is therefore common to use two antiparallel thyristors per each phase connected in a so called six-pulse bridge, as is seen in Figure 2.7. This type of setup is called full-wave bridge circuit [9].

The control of a three-phase AC circuit is much the same as with the single phase AC circuit. In the case of a three-phase system connected to the described six-pulse bridge, the thyristors will fire with an interval of $\frac{\pi}{3}$. The output average DC voltage, $V_{dc}$, of such a rectifying system can
thus be integrated at any interval of $\frac{\pi}{3}$. Including the triggering angle $\alpha$, the integral will be

$$V_{dc} = \frac{3}{\pi} \alpha \int_{\alpha}^{\alpha + \frac{\pi}{3}} V_{LL} \, d\omega t$$  \hspace{1cm} (2.21)$$

Substituting the line-to-line AC voltage, $V_{LL}$, with the AC RMS voltage value gives the result

$$V_{dc} = \frac{3}{\pi} \alpha \int_{\alpha}^{\alpha + \frac{\pi}{3}} \sqrt{3} V_{peak} \cos(\omega t - 30) \, d\omega t$$  \hspace{1cm} (2.22)$$

$$= \frac{3\sqrt{3}}{\pi} V_{peak} \cos \alpha$$  \hspace{1cm} (2.23)$$

Given in terms of the line-to-line voltage, $V_{LL} = \sqrt{\frac{2}{3}} V_{peak}$, the result would be

$$V_{dc} = \frac{3\sqrt{3}}{\pi} V_{LL} \cos \alpha$$  \hspace{1cm} (2.24)$$

By changing the trigger angle $\alpha$ from $0^\circ$ to $90^\circ$, the output DC voltage, $V_{dc}$, can thus be controlled from the maximum value $\frac{3\sqrt{3}}{\pi} V_{LL}$ to 0. However, the derivation of the output DC voltage is under assumption that the six-pulse thyristor bridge fire with an interval of $\frac{\pi}{3}$. This is true only if the incoming current load behaves as a perfect sinusodial wave, which is the ideal case of any symmetric three-phase system [4].
Figure 2.8: The twelve-pulse thyristor rectification bridge. Here, two six-pulse thyristor bridges are connected in series. At the AC-side, two different three-phase systems must be connected, one for every including six-pulse bridge. The output voltage is gathered by connecting the highest and the lowest pin on the DC-side of the rectification bridge. The middle pin on the DC-side is only used for measurements.

### 2.5.3 Twelve-Pulse Thyristor Rectification Bridge

Connecting two six-pulse bridges together creates a twelve-pulse thyristor rectification bridge. Depending on how the connection between the six-pulse bridges are made, either in parallel or in series, will give the twelve-pulse rectification bridge different properties. Connecting two six-pulse bridges in series under no-load operation will double the output voltage compared to a single six-pulse bridge DC output. An example of a twelve-pulse rectification bridge can be seen in Figure 2.8. The twelve-pulse rectification bridge demands two three-phase connections, one for every six-pulse bridge it consists of. The two incoming three-phase systems could either have the same source or be entirely separated from two different sources. Depending on how the
incoming three-phase systems relates to each other, the twelve-pulse rectification bridge behaves differently, as is explained in 2.5.4.

2.5.4 Harmonics Generated On the AC-side By the Rectification

An embedded property of the rectification is that it causes harmonics on both AC and DC sides [4]. A six-pulse thyristor bridge connected to a three-phase AC system will generate an alternating current with a Fourier expansion as

\[
i_{ac} = \frac{2\sqrt{3}}{\pi} I (\sin \omega t - \frac{1}{5} \sin 5\omega t - \frac{1}{7} \sin 7\omega t + \frac{1}{11} \sin 11\omega t + \frac{1}{13} \sin 13\omega t + \ldots) \quad (2.25)
\]

The AC harmonics will thus be on the order of \(6n \pm 1\) where \(n\) is any positive number.

The harmonics generated by a twelve-pulse thyristor bridge, dependent on how the incoming three-phase systems are related to each other, will act differently. If, for instance, the two incoming AC-systems are shifted \(30^\circ\) electrical degrees from each other, the even orders of the harmonics will be cancelled. Such a system, with two three-phase systems shifted \(30^\circ\) electrical degrees from each other connected to a twelve-pulse thyristor bridge, will produce harmonics with a Fourier expansion as

\[
i_{ac} = \frac{2\sqrt{3}}{\pi} 2I (\sin \omega t + \frac{1}{11} \sin 11\omega t + \frac{1}{13} \sin 13\omega t + \frac{1}{23} \sin 23\omega t + \frac{1}{25} \sin 25\omega t + \ldots) \quad (2.26)
\]

The AC harmonics for such a twelve-pulse thyristor bridge will thus be on the order of \(12n \pm 1\). It is also important to notice that theoretically the harmonics decreases in magnitude with increasing order. The \(h^{th}\) order harmonic will decrease in magnitude by \(\frac{1}{h}\) times the fundamental [4].

2.5.5 Harmonics Generated On the DC-side

Using the same reasoning for the DC side of the rectification, it can be shown that the harmonics of the six-pulse thyristor bridge will be on the order of \(6n\) (6\(^{th}\), 12\(^{th}\), 18\(^{th}\) etc.). For the twelve-pulse thyristor bridge the DC-side harmonics will be on the order of \(12n\) (12\(^{th}\), 24\(^{th}\), 36\(^{th}\) etc.). This is mainly due to the firing of the thyristors which for the six-pulse thyristor bridge occurs in an interval of \(\frac{\pi}{3}\), while for the twelve-pulse bridge occurs in an interval of \(\frac{\pi}{6}\). Hence, for any ideal six-phase rectification system, with incoming voltages as is seen in Figure 2.9, the twelve-pulse rectification system will double the frequency of the harmonics compared to a six-pulse rectification system.

As was done by VG Power AB, which is described in the analysis documents [5, 6], it can also be shown that the air gap torque of the exciter has harmonics of the order of \(6n\) and \(12n\).
2.6 Filters

As has been mentioned, an upgrade from the original three-phase excitation system to a six-phase excitation system would require a vast reconstruction. If there are other solutions to solve the problem by using the existing exciter, it would be interesting. One solution could be to use filters to reduce the harmonics generated by the rectifier, which hopefully would reduce the harmonics of the air gap torque of the exciter.

It is a common practice to filter the harmonics generated by rectifiers in other applications [4]. For example, thyristors are used to rectify electricity on the grid for a HVDC-link. This would generate harmonics on the grid that would affect nearby components. To minimize the potential of acoustic feedback with any of the nearby grid components, which could be hazardous, these harmonics are successfully filtered. A similar filter technique for this particular application could possibly reduce the introduced harmonics on the air gap torque of the three-phase exciter.

There are many types of filter designs, both passive and active, suitable for different kinds of applications [11]. Any filter design could also have several order setups to be tuned for any specific frequency. For this application, several conditions must be considered for any filter design, where the size of the filter is the most restrictive parameter. Any filter adapted to this application must be placed between the exciter output and the main generator, which means directly on the shaft in the rotating reference system. Hence, the filter should be as simple and small as possible. Therefore, a first order lowpass-filter of passive components is chosen in this thesis.

Figure 2.9: Ideal line-to-line voltages of two three-phase AC systems shifted 30° electrical degrees from each other.
2.6.1 RL-Filter Design

In part 2.5.4 it was stated that the harmonics affecting the exciter air gap torque was on the order of $6n$ ($6^{th}$, $12^{th}$, $18^{th}$ etc.). It was also explained that the magnitude of the harmonics would decrease by $\frac{1}{h}$ times the fundamental, where $h$ is the order of the harmonics. This makes the first order harmonics, $n = 1$, the most crucial to the air gap torque pulsations. Using a rearranged form of equation 2.3 it is possible to determine the frequency of the induced voltages and currents of the exciter, $f_e$, as

$$f_e = \frac{n P_n}{120} \quad (2.27)$$

The harmonics should therefore have the frequency

$$f_n = 6nf_e \quad (2.28)$$

A sufficient filter design should damp the harmonic frequencies higher than the fundamental frequency, which could be done by using a lowpass filter. Such a filter could be designed by using the coil of the main generator as the inductor of the filter and connecting a resistor to the phase lines, creating an RL-filter. The idea with the RL-filter, simply an inductor, $L$, connected in parallel with a resistor, $R$, is to allow the flow of current of the fundamental frequency, but hinder the higher frequencies to pass. Instead, the higher current frequencies are passed through the resistor, leaving the system as heat. The suggested RL-filter design is shown in Figure 2.10.

To tune the RL-filter to the fundamental frequency of the system, the transfer function $G(s)$ of the system needs to be identified.

Using the system impedances from Figure 2.10, the ratio between the input and output voltages is found as

$$V_{in} = \frac{(Z_R + Z_L)}{Z_R} \cdot V_{out} \quad (2.29)$$

This gives the transfer function, $G(s)$, as

$$G(s) = \frac{V_{out}}{V_{in}} = \frac{Z_R}{Z_R + Z_L} \quad (2.30)$$
Using Laplace transform, in the $s$-domain the impedance $Z_R = R$ and $Z_L(s) = Ls$ [12]. The transfer function of the RL-filter system for each phase would be

$$G(s) = \frac{R}{R + Ls} \quad (2.31)$$

While the inductance of the filter is already known, determined by the coil winding of the main generator, the resistance has to be determined. Remembering that $\omega = 2\pi f$, the resistance can be determined as it is known that the impedance of the field winding increases for higher frequencies as follows

$$Z_L = j\omega L \quad (2.32)$$

Where $L$ is the inductance of the main generator.

Currents with higher frequencies than a certain frequency called the cut-off frequency, will pass through the parallel connected resistor instead of flowing into the main generator. To choose the right resistance for the resistor, the impedances absolute value are put equal

$$|Z_R| = |Z_L| \quad (2.33)$$

which leads to

$$R = \omega L \quad (2.34)$$

As $L$ is already known, the resistance $R$ is determined by the freely chosen cut-off frequency, $\omega = 2\pi f_c$. 
3 Method

It is concluded that the harmonics generated by the rectification bridge is directly transferred to the air gap torque. While the rotor side of the excitation system, directly attached to the main shaft, can be considered as strong and will not move due to the oscillating air gap torque, this cannot be said for the stator side of the excitation system. Measurements have confirmed that the pulsation frequency is between two calculated mechanical resonance frequencies on 84 Hz and 140 Hz respectively [6]. Hence, there is no risk of triggering any of the mechanical resonance frequencies. But the pulsation frequency is close enough to make the exciter to vibrate. One acceptable solution to damp the arising vibrations is to change the pulsation frequencies of the air gap torque oscillation far away from the range of the mechanical resonance frequencies of the stator upholding rack. Another solution would be to filter the crucial harmonics and damp the vibrations that way.

In this thesis, two different solution methods are tested. The first method is to simulate an upgrade of the system from a three-phase exciter to a six-phase exciter using the twelve-pulse rectification bridge. The second method is to simulate the current excitation system connected with RL-filters.

3.1 Simulations Using FEM

The simulations are carried out using a Finite Element Method (FEM) based software package. FEM is a technique used to numerically approximate solutions of partial differential equations. The equations can be numerically integrated using one of different computational procedures such as Euler’s Method or Runge-Kutta. All computational procedures have their own advantages and disadvantages ranging from slow or fast computation time to good or bad approximative solution.[13]

FEM is usually used to solve partial differential equations for complicated bodies or for flowing or changing domains. For these simulations, FEM is used to approximate solutions of the changing electromagnetic field of the exciter model, defined by the set of partial differential equations making up the Maxwell’s equations.

For this application the software developed by ANSYS MAXWELL®14.0 is used for the FEM exciter modelling and analysis. Euler’s Method is used as the computational procedure for this time-consuming process.
(a) Exciter with 18 poles and 108 slots. This would be 2 slots per pole and phase for the three-phase exciter while it is 1 slot per pole and phase for the six-phase exciter.

(b) Exciter with 18 poles and 216 slots. This would be 4 slots per pole and phase for the three-phase exciter while it is 2 slot per pole and phase for the six-phase exciter. Due to the dimension properties, it is not possible to fit all the 216 slots of the original size in the machine. There is not enough of space. Therefore, a minor change is made for the 216 slots exciter model. The slots body width, in the 216 slots exciter model, are reduced to about half of the size of the original slots.

Figure 3.1: The 2 different FEM-models used as exciters. The same models are used both for the three-phase excitation system and the six-phase excitation system. The only difference is the definition of the winding setup.

An important comment is that the simulation models of the exciter shown in Figure 3.1 are made to look like a “normal” rotating excitation system, that is where the poles are found on the rotor and the phase windings are found on the stator. However, this type of modelling are not affecting the behaviour of the air gap torque, which is of interest in this thesis. A “normal” excitation system setup is preferred because of the much shorter simulation setup-time. It is however assumed that the air gap torque of the real excitation system behaves as its simulated counterpart.

3.2 Fast Fourier Transform

The analysis of the currents and voltages and their harmonic components are extracted by using Fast Fourier Transform (FFT) which is an algorithm to approximate the Discrete Fourier Transform of any signal. The FFT transforms any signal from its time domain to the frequency domain. By using FFT in this thesis it is thus possible to extract the amplitude and frequencies of the harmonic components making up the signal, such as the currents, voltages and air gap torque of the exciter.

3.3 Simulation of the Three-Phase Excitation System

The three-phase excitation system is a setup of the original excitation system. It is used as a reference behaviour for the six-phase excitation system setup. The same setup is used for both of the FEM-models shown in Figure 3.1. The load parameters here consists of an inductor with the inductance $1\, H$ and a resistor with the resistance $0.17\, \Omega$. The setup of the three-phase excitation
system, used as a reference system, is shown in Figure 3.2. The upgraded six-phase excitation system setup is shown in Figure 3.3.

Figure 3.2: The three-phase excitation system, modelled after the current system installed on the G1 generator in Bergeforsen Hydropower Station.

3.4 Simulation of the Six-Phase Excitation System

As was described in section 2.5.4, the upgraded system with the twelve-pulse rectification bridge will double the air gap torque oscillation frequency of the excitation system. As was also discussed, it is required that the upgraded six-phase exciter induces two identical sinusodial three-phase connections shifted $30^\circ$ electrical degrees from each other.

The installed excitation system of the G1 generator in Bergeforsen Hydropower Station has 18 poles and 162 slots. For the current three-phase construction, this gives three slots per pole and phase. The output current and voltage of such a system are sinusodial enough for the rectification to behave as expected. An upgrade to six phases on the same exciter will reduce the amount of slots per pole and phase to 1.5. For the upgraded exciter, *zone width alteration* is used to alternate the number of slots per pole and phase between 1 and 2. Simulations will be carried out to see how the characteristics of the induced currents and voltages of the upgraded six-phase system would affect the switching of the rectification bridge, and how this would affect the air gap torque of the exciter.

As was described in section 2.5.3 regarding the twelve-pulse thyristor rectification bridge, it gets different properties depending on how it is connected, either in parallel or in series. In general, the voltage output is doubled with a series connection compared to the output of the six-pulse rectification while the current output is lower. In the same way, the current output doubles with parallel connection and the voltage gets lower. For this application, the main focus is put on the parallel connected twelve-pulse rectification bridge. The main reason is that the real exciter has its twelve-pulse rectification bridge connected in parallel due to space issues. There is simply not enough of space to have the rectifier connected in series. However, the best setup would be to
have the rectifier connected in series. This way, the current output would be lower and any heat losses would therefore decrease.

3.4.1 Simulation Setup of the Six-Phase Excitation System

The simulations of the six-phase excitation system are made both using FEM and electric circuit software. Figure 3.1 shows the geometry of the exciter models. Induced voltage and air gap torque is obtained from the electromagnetic field solution by means of FEM. The FEM-model of the exciter is connected to the electric circuit software where the connections to the main generator, with all the including components, has been modelled. A FEM-model of the three-phase exciter connected to a similar electric circuit is also made to compare the systems. The softwares used for the simulations are Maxwell® 14.0 for the FEM exciter modelling and Simplorer® 9.0 for the electrical circuit modelling. The trigger angle $\alpha$ of the thyristor bridges is chosen to be $25^\circ$.

The exciter is modeled both with 108 slots and 216 slots. This way it is possible to see the behaviour of the six-phase exciter both when it has 1 slot per pole and phase and when it has 2 slots per pole and phase and compare that to its corresponding three-phase exciter. To identify the behaviour of the induced voltages of the modelled exciters, no-load operations is also simulated.

Figure 3.3: The six-phase excitation system. As can be seen, the twelve-pulse thyristor bridge is connected in parallel. Such a setup is preferred for space issues of the real excitation system.

3.5 Simulation of the Three-Phase Excitation System with RL-Filters

The current three-phase exciter rotates, as was described in part 2.4.2, on the same shaft as the main generator. As the angular velocity, $\omega_{\text{mech}}$, is the same for all parts on the shaft, this also determines the rotating speed of the excitation system. In Bergeforsen Hydropower Station, the
excitation system rotates at the speed of 115.38 rpm. Using equation 2.27 with the rotational speed in mind, it is possible to find the excitation system induced voltage frequency as

\[ f_e = \frac{115.38 \cdot 18}{120} = 17.307 \text{ Hz} \]  

(3.1)

Combining this with equation 2.28, the first order harmonics affecting the air gap torque of the exciter, \( n = 1 \), has the frequency

\[ f_1 = 6 \cdot 1 \cdot 17.307 = 103.8 \text{ Hz} \]  

(3.2)

This have been confirmed by studies performed by VG Power AB [5]. The purpose of the introduced filter would thus be to pass the low frequencies to the main generator, but hinder the higher frequencies to flow. The filter should therefore be tuned so that the cut-off frequency lies between 17.307 Hz and 103.8 Hz. While the inductor, \( L \), of the filter is a known value of the coil inductance of the main generator, the cut-off frequency can only be determined by choosing a resistance for the resistor, \( R \). In this application, \( L = 1 \) H. Choosing the cut-off frequency as \( f_c = 20 \) Hz, and using equation 2.34, the resistance value, \( R \), is found to be

\[ R = 2\pi f_c L = 2\pi \cdot 20 \cdot 1 \approx 125 \Omega \]  

(3.3)

Inserting \( R \) and \( L \) in equation 2.31, the transfer function, \( G(s) \), becomes

\[ G(s) = \frac{125}{125 + s} \]  

(3.4)

In Figure 3.4 is shown the bode diagram of the transfer function \( G(s) \).
Figure 3.4: Bode diagram of the transfer function, $G_s$. Highlighted are the cut-off frequency, $f_c = 20$ Hz and the first harmonic frequency, $f_1 = 103.8$ Hz.

### 3.5.1 Simulation Setup of the Three-Phase Excitation System with RL-Filters

As for the RL-filter simulations, there is no need for any FEM-modelling of the exciter since it is a conventional three-phase synchronous machine. Such a component already exists in the electric circuit software and have been used for these simulations. The main reason for this is that while running a simulation with the FEM-software, the simulations range between 10-20 hours. With the electrical circuit software the simulations are reduced to a couple of seconds. The simulation setup of the three-phase excitation system with RL-filters is shown in Figure 3.5.

The system is simulated running with the thyristor bridge firing angle $\alpha = 25^\circ$ both with and without filters. This is compared to the filtered system to see if the filters affect the air gap torque.
Figure 3.5: Three-phase excitation system with RL-filter simulation setup. The setup is modelled to simulate the real behaviour of the excitation system as close as possible. With the filters removed, this model can be compared with the FEM-based three-phase system described in section 3.3.
4 Results and Discussions

4.1 Simulation Results of the Six-Phase Excitation System

The results are grouped in three parts. The first part consists of the results of the six-phase setup simulations under no-load operation. This is to see the characteristics of the induced voltages of the two six-phase exciters used, the first with 1 slot per pole and phase, the other with 2 slots per pole and phase. In section 2, the results of the six-phase exciter with 108 slots is compared to its corresponding three-phase setup simulations. Section 3 consists of the same comparisons between the six-phase exciter and the three-phase exciter, only in this case the exciters are modelled with 216 slots. The simulations of section 2 and 3 are made with the trigger angle $\alpha = 25^\circ$.

4.1.1 Simulation of the Six-Phase Excitation System During No-Load Operation

It is possible to rearrange the phase windings of the exciter from a three-phase system to a six-phase system. The exciter model used was rearranged in such a way that it induces two Y-connected three-phase systems with coinciding grounded points. The no-load operation in Figure 4.1 and 4.2 shows the two induced three-phase systems of the six-phase exciter shifted $30^\circ$ electrical from each other, the first three-phase system consisting of phases named A, B and C, and the second three-phase system consisting of phases named X, Y and Z. However, it is also possible to see that the induced voltages of the exciter differs significantly from the sinusodial behaviour of the ideal case. This is true both for the 108 slots and 216 slots exciter models.

![Figure 4.1: Induced voltage during no-load operation of the six-phase excitation system using the 108 slots exciter model (1 slot per pole and phase). Here, phase A is highlighted in red and phase X is highlighted in black.](image)
4.1.2 Simulation Using Exciter Model with 108 Slots During Load Operation

Figure 4.3 shows the induced AC line-to-line voltage characteristics of the three-phase excitation system during load operation. The typical cuts through the voltage emerges every time a thyristor is triggered and allows current to flow.
A plot of the air gap torque of the three-phase exciter with 108 slots during load operation is shown in Figure 4.4. Analysing the air gap torque using FFT, as is shown in Figure 4.5, it is settled that the air gap torque behaves as expected. Harmonics of the $6^{th}$, $12^{th}$, $18^{th}$ orders etc are visible. It is also clear that the amplitudes of the higher order harmonics are suppressed.

The characteristics of the induced voltages of the six-phase exciter, with 108 slots which would mean 1 slot per pole and phase as illustrated in Figure 4.6, will change the polarities of the thyristors more often than every $\frac{\pi}{3}$ of a period. The $6^{th}$ order harmonics, which are cancelled in the ideal case twelve-pulse rectification bridge, will appear because of this.
Figure 4.6: Induced AC line-to-line voltage of the six-phase excitation system, with a simulated 108 slots exciter, under operation. Highlighted in red is the voltage of phase A and in black the voltage of phase X.

In Figure 4.8, using 1 slot per pole and phase, it can be seen that even if the 12th order harmonics is the dominant one, there is still a significant harmonic of the 6th order present on the air gap torque, seen in Figure 4.7.

Figure 4.7: Air gap torque of the six-phase excitation system setup with 108 slots exciter.
4.1.3 Simulation Using Exciter Model with 216 Slots

Using the double amount of slots, it is expected that the induced voltages of the exciters appear more sinusoidal. In Figure 4.9 the induced AC line-to-line voltages of the three-phase excitation system using the exciter of 216 slots is presented. The cuts through the voltages, that emerges every time a thyristor is triggered, has a greater impact here than in the 108 exciter case.

In Figure 4.10 the air gap torque of the 216 slots three-phase exciter during operation is presented. The FFT of the air gap torque in Figure 4.11 shows that the air gap torque pulsations consist
of the $6^{th}$, $12^{th}$, $18^{th}$ etc. order harmonics as expected. Compared to the pulsation of the three-phase exciter with 108 slots, these harmonics are much lower in amplitude and do not affect the fundamental as much.

![Figure 4.10: air gap torque of the three-phase excitation system setup with 216 slots exciter.](image)

![Figure 4.11: FFT of the air gap torque of the three-phase excitation system setup with 216 slots exciter.](image)

Using the six-phase exciter with 216-slots, the induced AC line-to-line voltage during operation is shown in Figure 4.12. Here, the line-to-line voltages, which are applied across the thyristors, change polarity in an unexpected way near the peaks.
Figure 4.12: Induced AC line-to-line voltage of the six-phase excitation system, with a simulated 216 slots exciter, under operation. Highlighted in red is the voltage of phase A and in black the voltage of phase X.

In Figure 4.13 the air gap torque pulsations using two slots per pole and phase for the six-phase exciter is presented. Evaluating the plot using FFT, as seen in Figure 4.14, will still see a significant 6\(^{th}\) order harmonic present on the air gap torque pulsations.

Figure 4.13: Air gap torque of the six-phase excitation system setup with 216 slots exciter.
Figure 4.14: FFT analyse of the air gap torque of the **six-phase excitation system** setup with **216 slots exciter**.

Table 4.1: Compilation of the magnitude of the air gap torque pulsations simulating the FEM exciter models in different cases.

<table>
<thead>
<tr>
<th>Exciter model</th>
<th>Fundamental order [kNm]</th>
<th>6(^{th}) order [kNm]</th>
<th>12(^{th}) order [kNm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-Phase, 108 slots</td>
<td>14.2</td>
<td>6.8 (47.9%)</td>
<td>2.1 (14.8%)</td>
</tr>
<tr>
<td>Three-Phase, 216 slots</td>
<td>9.8</td>
<td>3.1 (31.6%)</td>
<td>1.3 (13.2%)</td>
</tr>
<tr>
<td>Six-Phase, 108 slots</td>
<td>2.4</td>
<td>0.9 (37.5%)</td>
<td>2.2 (91.7%)</td>
</tr>
<tr>
<td>Six-Phase, 216 slots</td>
<td>5.3</td>
<td>1.9 (35.8%)</td>
<td>0.5 (9.4%)</td>
</tr>
</tbody>
</table>

Table 4.1 is showing the simulation results of the magnitude of the air gap torque pulsations simulated using the FEM exciter models in different cases. Comparing the 108 slots three-phase and six-phase generators it is shown that the six-phase generator effectively reduces the 6\(^{th}\) order harmonic from 47.9 % to 37.5% of the fundamental. However, it was expected and theoretically derived that the 6\(^{th}\) order harmonic of the six-phase model, with 108 slots, would be reduced to 0. As was expected, the 12\(^{th}\) order harmonics dominates among the harmonics of the six-phase (108 slots) exciter model.

For the six-phase exciter model with 216 slots, the results turned out somewhat unexpected. Here the 6\(^{th}\) order harmonic, which should be reduced to 0 or at least very small, still dominates. It is possible that the doubled amount of slots, which forced a reduced slot width in the model, heavily affect the results due to, for example, increased mutual inductance.
4.2 Simulation Results of Three-Phase Excitation System with RL-Filters

The results of the RL-filter simulations are grouped in two parts. The first part consists of simulation results of system setup without any RL-filters. The second part consists of simulations using the same system, but with the RL-filters. To see how the filters behave compared to the filterless system, both simulations are carried out with the trigger angle $\alpha = 25^\circ$.

4.2.1 Simulation Without RL-Filters

To find out if the filtered system affects the air gap torque pulsations at all, a comparison is made with FFT of the air gap torque of the filterless excitation system, shown in Figure 4.15.

![FFT of the air gap torque of the three-phase excitation system without RL-filters](image)

Figure 4.15: FFT of the air gap torque of the three-phase excitation system without RL-filters.

4.2.2 Simulation With RL-Filters

The introduced lowpass filters are expected to filter any harmonics with a frequency higher than the cut-off frequency $f_c = 20$ Hz. A part of the current component will be converted to heat in the resistor.
In Figure 4.16, a plot of the FFT analyse of the air gap torque of the filtered excitation system is shown. It is possible to see that the $6^{th}$ order harmonic is still present in the air gap torque pulsation.

Table 4.2: Compilation of the magnitude of the air gap torque pulsations simulating the three-phase exciter system circuit models both with and without RL-filters.

<table>
<thead>
<tr>
<th>Circuit model</th>
<th>Fundamental order [kNm]</th>
<th>$6^{th}$ order [kNm]</th>
<th>$12^{th}$ order [kNm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without filter</td>
<td>1.44</td>
<td>0.2 (13.9%)</td>
<td>0</td>
</tr>
<tr>
<td>With filter</td>
<td>1.55</td>
<td>0.2 (12.9%)</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.2 is showing the resulting magnitudes of the air gap torque pulsations simulating the three-phase exciter system models both with and without the proposed RL-filters. Here it is possible to see that the RL-filtered model reduces the $6^{th}$ order harmonic by 1% compared to the system without any filter.

What is interesting here is that the filtered system is not reducing the $6^{th}$ order harmonic itself, which by magnitude is kept at the same level, 0.2 kNm, as the simulated circuit model without any filters. Instead, the fundamental order, or the DC component, is increased from 1.44 kNm to 1.55 kNm, an increase of the DC component by 7.6%. Because of this, the reliability of the results is somewhat unclear.
5 Conclusions

It has been confirmed that an upgraded excitation system with a twelve-pulse thyristor rectification bridge instead of a six-pulse thyristor rectification bridge doubles the frequencies of the generated harmonics. However, as can be seen in Figure 4.8 and Figure 4.14, the results did not turn out as was expected.

In section 2.5.4, it was established that there are two conditions for the upgraded rectification bridge to double the frequencies of the generated harmonics. The two three-phase AC-systems should be shifted $30^\circ$ electrical degrees should have as close appearance to sinusoidal waves as possible. These conditions are important to satisfy to be sure that the firing of the twelve-pulse thyristor bridge occurs in an interval of $\frac{\pi}{6}$.

Rearranging the phase windings of the current exciter model to a six-phase exciter system is possible. However, the simulation results have shown that the characteristics of the induced voltages of such a phase rearrangement, namely having two Y-connected three-phase systems with coinciding ground points, would not behave as sinusoidal waves for neither having one slot per pole and phase or two slots per pole and phase. This in turn is affecting the switching of the thyristor rectification bridge. The 6th order harmonic, cancelled in the ideal rectification case, will still have a great influence on the air gap torque pulsations using these arrangements.

However, it is still theoretically possible to double the frequencies of the generated harmonics of the rectification bridge by using a six-phase excitation system. This would however still require better sinusoidal characteristics of the induced voltages of the exciter. It is possible that the two Y-connected three-phase systems of the exciter are affecting each other since they share the same ground point. This could be the reason why the induced voltages have such a distorted characteristics.

The suggested first order lowpass RL-filter is good enough to reduce the AC-side harmonics generated by the rectification bridge. However, as can be seen in the results, the amplitude of the 6th order harmonic of the air gap torque pulsations reduces insignificantly due to the filtering. The simulation results indicates that such a lowpass RL-filter, designed to reduce any high-order frequencies on the AC-side, will only slightly affect the air gap torque pulsations. Comparison between the air gap torque analysis using the filtered and the filterless excitation system, seen in Figure 4.16 and Figure 4.15, shows that there is just an insignificant reduction of the fundamental pulsation using the suggested RL-filter.
6 Future Work

From the work done with this thesis, many important lessons can be learned. Working with a six-phase exciter connected to a rotating twelve-pulse rectification bridge has, as far as the author knows, rarely been evaluated in the past. Hence, this is still an uncovered field in many ways, where the interplay between the two Y-connected three-phase systems, in the viewpoint of the author, are the most interesting to evaluate. Below follows work that needs further evaluation.

6.1 Simulations of the Six-Phase Exciter With Two Separated Three-Phase Systems

As was explained in this thesis, the phase winding arrangements of the six-phase exciter consisted of two three-phase systems shifted 30° electrical from each other but with a coinciding ground point. It is possible that the voltage drop of one three-phase system, caused by the switching of the rectification bridge, is affecting the induced voltages of the other three-phase system. It is therefore suggested that future simulations on a similar six-phase exciter separate the two three-phase system ground points to be sure that there are no connection between them.

6.2 Simulations of Other Types of Filter Designs

It was concluded, a first-order lowpass RL-filter just insignificantly affect the air gap torque pulsations of the exciter. However, other filter designs could be more appropriate to use for this application. As the exciter air gap torque is directly proportional to the instantaneous power consumption, an appropriate filter design should be built to hinder the DC-side harmonics from being consumed at all. Therefore, further investigations using a RC-filter design on the DC-side are suggested.
References


