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Simulation of a Synchronous Machine Model

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Abstract

A major shift in power generation is witnessed in todays power system due to the integration of renewables. The behavior of a synchronous machine has inspired a plethora of control strategies that aim to operate the grid in a reliable way.

To provide more understanding of power generators, this thesis presents a Simulink model of a realistic synchronous machine. We consider a 160 MVA synchronous machine, where some parameters were taken from a real machine as described in power system literature, and others were calculated accordingly. Initial conditions corresponding to steady state operation are calculated to run the simulations in steady state from the beginning. To make it even more realistic a governor controller an AVR and a PSS are modelled. The final simulations with test case scenarios show a typical behaviour of synchronous machines with a comparable size.
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List of Acronyms

SM    Synchronous Machine
AVR   Automated Voltage Regulator
PSS   Power System Stabilizer
EMF   Electromotive Force
TF    Transfer Function
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Chapter 1

Introduction

Since the industrial revolution man’s demand for electrical energy has increased steadily. This energy was traditionally provided by centralized power plants with synchronous machines as generators. In the last ten years roughly a shift in this power generation to more integration of renewable power resources into the grid can be witnessed. In figure 1.1 for example, the total installed solar power worldwide is pictured. The installed solar power rises exponentially. This rise still holds on, not only for solar power, but also for other renewable power resources such as wind for example. This shift in power generation also leads to more power electronics introduced into the grid. Those power electronic systems need to be controlled, which is mainly done by emulating synchronous machines. Replacing the heavy synchronous machines with power electronics leads to a significant loss of inertia in the total power system. Therefore the dynamics have changed, and they will change more and more as the shift is still ongoing. It is becoming more important than ever to understand the behavior of the synchronous machine and how the individual machine components are interfaced to the whole power system.

![Figure 1.1: World total solar power installations](image)

Our objective is to provide a foundation for power system dynamic analysis by simu-
CHAPTER 1. INTRODUCTION

In order to accurately model the typical behavior of SM systems and serve as a point of reference for deeper exploration of complex phenomena and applications in electric power engineering, such as the influence of power electronics on the overall system, a suitable SM model is developed.

Figure 1.2 provides a broad overview of the total dynamic power system, spanning from the power generation in the power plant to the consumption in the loads.

![Figure 1.2: Dynamic structure of the power system [1]](image)

The diagram is divided into two sections: one for electrical dynamics and one for mechanical dynamics. While the distinction is not as rigid as depicted, it provides a useful framework. A motor, for example, which exhibits highly mechanical dynamics, is included to illustrate the block diagram's accuracy in placing synchronous machines within the system.

This block diagram begins with the fuel source, which is burned in the boiler to produce steam. This steam powers the turbine, which drives the generator. Generators in power plants are predominantly synchronous machines. The synchronous machine converts mechanical power from the turbine into electrical power, which is then transmitted through the network to the loads. At the loads, power is consumed, completing the cycle and closing the block diagram of power distribution. All system components are controlled by an energy control center to ensure reliable operation.
The synchronous machine plays a main role in the whole system as it is the interface between the electrical and the mechanical world. A detailed understanding of the dynamics of the SM is therefore important. This thesis provides detailed model of the synchronous machine and simulations with realistic values for the machine parameters.

A detailed simulation of a synchronous machine is necessary to deeply understand its behavior in context to the overall system. It can be used for comparison of the behavior of the synchronous machine with different converter control strategies, such as the mentioned emulation of synchronous machines.

After some preliminaries the model of the synchronous machine, which is used for the simulations, will be introduced, followed by an introduction of some primary outer loop controllers. It will be explained how the model is implemented and how the parameters of the synchronous machine and its controllers were chosen. The final simulations and their interpretations will complete the thesis.
Chapter 2

Preliminaries

2.1 Notations

In this section some notations that are used throughout this thesis are introduced. That includes the root mean square (RMS) value. In Physics, the RMS current for example is the value of the direct current that dissipates power in a resistor. The corresponding formula for a continuous function \( f(t) \) defined over the interval \( T_1 \leq t \leq T_2 \) is

\[
\text{rms} = \sqrt{\frac{1}{T_2 - T_1} \int_{T_1}^{T_2} f(t)^2 \, dt} \quad (2.1)
\]

For a typical sine wave \( f(t) = A \sin(\omega t) \) for example the RMS value is \( \frac{A}{\sqrt{2}} \). Where \( A \) is the Amplitude and \( \omega \) the angular velocity.

Another notation that needs to be introduced is the norm of a vector. In this thesis only the \( L_2 \)-norm is used. It corresponds to the length of the vector. Mathematically this is

\[
|x|_2 = |x| = \sqrt{x_1^2 + x_2^2 + \ldots + x_n^2}. \quad (2.2)
\]

Where \( x = [x_1, x_2, \ldots, x_n]^T \) is a vector with \( n \) elements.

2.2 \( \alpha \beta \)-frame

The model of the synchronous machine which is used in this thesis is in \( \alpha \beta \)-frame. This is because the model should be used for comparison with some promising converter controllers which are implemented in \( \alpha \beta \)-frame. For a better understanding the \( \alpha \beta \)-frame is briefly introduced in this chapter and compared to the more familiar dq-frame. The
advantages of using the $\alpha\beta$-frame will be pointed out.

On the right side of Figure 2.1 the normal three phase $abc$-frame with its three phasors $a$, $b$ and $c$ is pictured. These phasors describe the rotation of the three phases on the left side of the figure. The phasors are placed 120° to each other in a balanced system, what we assume in our model. The $abc$-signals can be transformed into $\alpha\beta$-frame by multiplying the phasors with the transformation matrix $T_{\alpha\beta}$

$$T_{\alpha\beta} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}.$$  \hspace{1cm} (2.3)

After this transformation the coordinate system looks like shown in Figure 2.2. The two main components of the $\alpha\beta$-frame which are $U_\alpha$ and $U_\beta$ in this figure are highlighted in red. There is also a third component, which is zero in a balanced three phase system. That component is always zero in our model due to the balanced system we will always assume. The $\alpha\beta$-frame is a stationary frame. That means it stays aligned with the $abc$-frame.
In comparison to the \(\alpha\beta\)-frame there is a \(dq\)-frame, which is pictured in Figure 2.3. In the \(dq\)-frame there are, like in the \(\alpha\beta\)-frame, two main components named \(d\) and \(q\). In the \(dq\)-frame the third component is the same as in the \(\alpha\beta\)-frame, that means zero for a balanced system. The main difference compared to the \(\alpha\beta\)-frame is that the coordinate system of the \(dq\)-frame rotates with the angular velocity of the rotor \(\omega\). That simplifies equations by making rotating values such as the stator voltage constant.

The transformation from \(abc\)-frame to the \(dq\)-frame can be done by using the following transformation matrix \(T_{dq}(\gamma)\), where \(\gamma\) is the current angle of the rotating coordinate system of the \(dq\)-frame. It holds that \(\dot{\gamma} = \omega\).
\[ T_{dq(\gamma)} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos(\gamma) & \cos(\gamma - \frac{2\pi}{3}) & \cos(\gamma + \frac{2\pi}{3}) \\ \sin(\gamma) & \sin(\gamma - \frac{2\pi}{3}) & \sin(\gamma + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix}. \quad (2.4) \]

You can see that there is an angle \( \gamma \) needed in the transformation matrix. This is to describe the rotation of the coordinate system. That angle though, is a main drawback of the \( dq \)-frame.

There is also a direct transformation from \( dq \)-frame to the \( \alpha \beta \)-frame which can be described by the following rotation matrix \( R_{\gamma} \)

\[ R_{\gamma} = \begin{bmatrix} \cos(\gamma) & \sin(\gamma) & 0 \\ -\sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix}. \quad (2.5) \]

Also here you need to know the angle of the coordinate system. To avoid this angular dependency the synchronous machine model used in this thesis is in \( \alpha \beta \)-frame.
Chapter 3

Model of the Synchronous Machine

This chapter describes the physical structure as well as the mathematical model of the synchronous machine used for the simulations in this thesis. The synchronous machine model consists of four main parts which are the rotor, the stator, the excitation system and the outer loop controllers. Each part will be explained separately in a section.

The SM is called synchronous machine, because the rotor of the machine rotates synchronously with the frequency of the grid. That means for a synchronous generator in Europe for example 50 $Hz$. It can be used as a motor as well as a generator. In fact the synchronous machine is the most commonly used machine to generate power at power plants of all kinds, due to its ability to also supply the needed reactive power.

3.1 Rotor

The synchronous generator (also called alternator) consists of two main parts, the rotor and the stator, where the rotor is the mechanically rotating part of the machine. It is used to produce a magnetic field that rotates and induces a voltage in the surrounding windings of the stator. Permanent magnets can be used to create a constant magnetic field, but usually the magnetic field is not desired to be constant, because the output voltage and the provided reactive power can be controlled by the magnetic field strength. So, it is better to use a controllable excitation winding instead of a permanent magnet.

There are different forms of rotors. It can be round or it can be a so-called salient rotor, which has some indentations. The salient rotors have a different field distribution along the axes due to its asymmetry. The main advantage of salient rotors is to save material costs. Another property of a rotor is the number of pole pairs. That means how many magnetic pole pairs are created by the excitation windings. It determines the frequency with which the rotor rotates by dividing the grid frequency by the number of...
We will consider a round rotor with a single pole pair. Which means that the rotor frequency is the same as the frequency of the grid.

The rotor is in the center of the synchronous machine surrounded by the stator. In Figure 3.1 a schematic picture of a round rotor and its stator around is shown. To describe the rotation of this rotor we introduce two states. The rotating angle $\theta$ and its rotating frequency $\omega$. The letter $F$ in the figure describes the excitation winding. In the excitation winding the magnetic field that links the rotor with the stator is produced. This magnetic field is created by the excitation current $i_f$ flowing through the excitation windings. Therefore $i_f$ can be considered as an input into the machine. Another input is the mechanical power $P_m$ provided by the turbine. The counterpart to the mechanical power, acting as another input, is the electrical power $P_e$ drawn by the load.

![Figure 3.1: Rotor and Stator](image)

There is also a damper winding pictured in Figure 3.1 denoted by the letter $D$. The damper winding is there to provide damping to the natural electromechanical oscillations of the rotor. These oscillations namely induce a current in the damper winding that works against these parasitic oscillations. The last parameter to be introduced for understanding the rotor dynamics is the moment of inertia $M$. It is needed to describe the rotation of the rotor.

To link the rotor with the stator, we introduce the mutual inductance $L_m$ between the excitation windings and the stator windings. The mutual induction influences the internal voltage $E$, which is induced in the stator, linearly.

### 3.2 Assumptions

Before starting with the dynamic models of the rotor and the stator we summarize again the assumptions made in the model. We will assume to always be in a balanced
CHAPTER 3. MODEL OF THE SYNCHRONOUS MACHINE

3-phase system. The synchronous machine has a round rotor with a single pole pair. The excitation current $i_f$ can be assumed to be constant, which will be verified in section 3.6.

### 3.3 Dynamics of the Rotor

The dynamic model of the rotor can then be described with the following two equations, where the second one is the typical swing equation of a synchronous machine.

\[
\dot{\theta} = \omega \\
M^* \dot{\omega} = -D^* \omega + \tau_m - \tau_e
\]  

(3.1)  
(3.2)

where $M^*$ is the total moment of inertia of the rotor and $D^*$ is the damping constant; $\tau_m$ is the mechanical torque applied to the machine and $\tau_e$ is the electrical torque drawn by the load working against the mechanical torque.

We can now multiply equation (3.2) with the nominal frequency $\omega_0$ to describe the swing equation in terms of powers instead of torques. We multiply with the nominal frequency instead of the instantaneous frequency to simplify the dynamic equation, because the machine will work around the nominal frequency with only little deviations. The model now look as follows

\[
\dot{\theta} = \omega \\
M \dot{\omega} = -D \omega + P_m - P_e,
\]  

(3.3)  
(3.4)

where the coefficient $M = M^* \omega_0$ is the inertia constant and $D = D^* \omega_0$ the new damping coefficient. The mechanical power $P_m$ is given by the formula $P_m = \tau_m \omega_0$ and the same holds for the electrical power $P_e$ which is $P_e = \tau_e \omega_0$.

The electrical power drawn by the load can be rewritten as the current in the stator $i_{\alpha \beta}$ multiplied with the EMF voltage $E$ which is the mutual inductance $L_m$ multiplied with the excitation current $i_f$ and the frequency $\omega$.

\[
P_e = i_{\alpha \beta}^T L_m i_f \begin{bmatrix} -\sin(\theta) \\ \cos(\theta) \end{bmatrix}
\]  

(3.5)

Inserted in the rotor dynamic model (3.4) we get the final model of the mechanical rotor dynamics to be

\[
\dot{\theta} = \omega \\
M \dot{\omega} = -D \omega + P_m - i_{\alpha \beta}^T L_m i_f \begin{bmatrix} -\sin(\theta) \\ \cos(\theta) \end{bmatrix}.
\]  

(3.6)  
(3.7)
3.4 Stator

The second main component of a synchronous machine is the stator. It is placed around the rotor and like the name says it is static. There are usually three stator windings in an angle of $120^\circ$ from each other for the three phases of the machine output.

![Single phase equivalent circuit of stator winding](image)

Each of the stator windings can be described by the single phase equivalent circuit in Figure 3.2. The mutual inductance $L_m$ induces an internal voltage in the stator windings named $E$. This is the input into the stator circuit. The current running through the stator $i_{\alpha\beta}$ and the voltage at the output $v_{\alpha\beta}$ can be seen as the states of the stator circuit. The stator windings have a resistance $R$ and a self inductance $L_s$. At the output part of the equivalent circuit there is a shunt capacitor $C_{\text{out}}$ in parallel to an output conductance $G_{\text{out}}$ that acts as a load in this model.

3.5 Dynamics of the Stator

To describe the dynamics of the stator we take a look back into the equivalent circuit in Figure 3.2. For the dynamics of the stator circuit we need to understand the dynamics of the output capacitor $C_{\text{out}}$ first. We need to find the current going into the capacitor $i_C$. Based on the drawn currents in the equivalent circuit $i_c$ is $i_{\alpha\beta} - i_{\text{load}}$. We insert that in the capacitor dynamic model and get

$$C_{\text{out}} \dot{v}_{\alpha\beta} = -i_{\text{load}} + i_{\alpha\beta}$$

(3.8)

which is the first equation of our stator model.
CHAPTER 3. MODEL OF THE SYNCHRONOUS MACHINE

The second equation comes from the dynamics of the self inductions of the windings $L_s$. Here we need to find the voltage across this inductance $L_s$. It can simply be found with Kirchhoff’s voltage law. That results in

$$L_s \dot{i}_{\alpha\beta} = -Ri_{\alpha\beta} - v_{\alpha\beta} - E$$  \hspace{1cm} (3.9)

The induced EMF voltage $E$ depends on the frequency $\omega$, the mutual inductance $L_m$ and the excitation current $i_f$ and can be written as

$$E = \omega L_m i_f \begin{bmatrix} -\sin(\theta) \\ \cos(\theta) \end{bmatrix}.$$  \hspace{1cm} (3.10)

Therefore we can rewrite equation (3.9) as our final dynamic equation of the induction and combine it with the capacitor model to get the full model of the stator windings.

$$C_{out} \dot{v}_{\alpha\beta} = -i_{\text{load}} + i_{\alpha\beta}$$  \hspace{1cm} (3.11)

$$L_s \dot{i}_{\alpha\beta} = -Ri_{\alpha\beta} - v_{\alpha\beta} - \omega L_m i_f \begin{bmatrix} -\sin(\theta) \\ \cos(\theta) \end{bmatrix}$$  \hspace{1cm} (3.12)

### 3.6 Dynamic Model

To summarize the full dynamic model of the synchronous machine we combine the dynamic model of the rotor and the one of the stator. We therefore need the equations (3.6) and (3.7) for the rotor and equations (3.11) and (3.12) for the stator.

$$\dot{\theta} = \omega$$  \hspace{1cm} (3.13)

$$M \ddot{\omega} = -D\omega + P_m - i^T_{\alpha\beta}\omega L_m i_f \begin{bmatrix} -\sin(\theta) \\ \cos(\theta) \end{bmatrix}$$  \hspace{1cm} (3.14)

$$C_{out} \dot{v}_{\alpha\beta} = -i_{\text{load}} + i_{\alpha\beta}$$  \hspace{1cm} (3.15)

$$L_s \dot{i}_{\alpha\beta} = -Ri_{\alpha\beta} - v_{\alpha\beta} - \omega L_m i_f \begin{bmatrix} -\sin(\theta) \\ \cos(\theta) \end{bmatrix}$$  \hspace{1cm} (3.16)

### 3.7 Excitation System

Another important part to be looked at is the excitation system of the synchronous machine. It consists of a winding around the rotor and is responsible to create the controllable magnetic field for the interconnection between the rotor and the stator.
Figure 3.3: Equivalent circuit of the excitation system

The excitation system can be described by the equivalent circuit in Figure 3.3, where the excitation voltage \( V_f \) is the input into the circuit and the excitation current \( i_f \) is the defining state. The excitation winding has a resistance \( R_f \) and produces a flux linkage with the stator named \( \lambda_f \).

### 3.8 Dynamics of the Excitation System

The goal of this section is to simplify the excitation system behavior to a first order dynamic system. The calculations are based on a paper about "compositional transient stability analysis of multi-machine power networks" [5].

To fully describe the dynamics of the excitation system we will make use of the induction matrix \( L(\theta) \), which is defined as

\[
L(\theta) = \begin{bmatrix}
L_s & 0 & L_m \cos(\theta) \\
0 & L_s & L_m \sin(\theta) \\
L_m \cos(\theta) & L_m \sin(\theta) & L_f
\end{bmatrix},
\]

where \( L_s > 0 \) is the self inductance of the stator windings and \( L_m > 0 \) the mutual inductance between the rotor and the stator introduced above. And \( L_f \) is the self inductance of the excitation windings.

As described in the previous section, the excitation equivalent circuit can be described as in the equivalent circuit in Figure 3.3.

The flux linkage \( \lambda \) is defined in a matrix representation for all three components of the model as

\[
\begin{bmatrix}
\lambda_\alpha \\
\lambda_\beta \\
\lambda_f
\end{bmatrix} = \begin{bmatrix}
L_s & 0 & L_m \cos(\theta) \\
0 & L_s & L_m \sin(\theta) \\
L_m \cos(\theta) & L_m \sin(\theta) & L_f
\end{bmatrix} \begin{bmatrix}
i_\alpha \\
i_\beta \\
i_f
\end{bmatrix}
\]

(3.18)

To describe the dynamics of the excitation system we need to set up the voltage equation. That is
\[ \dot{X}_f = R_f i_f + V_f. \] (3.19)

By making use of the third column of equation (3.18) and taking the derivative of the flux linkage we can rewrite the voltage equation as

\[ L_f \dot{i}_f = L_m \omega \sin(\theta) i_\alpha - L_m \cos(\theta) \dot{i}_\alpha \]
\[ - L_m \omega \cos(\theta) i_\beta - L_m \sin(\theta) \dot{i}_\beta \]
\[ - R_f i_f + V_f \] (3.20)

This equation of the excitation system can be simplified if we now set an externally controlled excitation voltage \( V_f \) to be

\[ V_f = - L_m \omega \sin(\theta) i_\alpha + L_m \cos(\theta) \dot{i}_\alpha \]
\[ + L_m \omega \cos(\theta) i_\beta + L_m \sin(\theta) \dot{i}_\beta \]
\[ + R_f i_f + \alpha (i_f - i_f^*) \] (3.21)

Replacing the excitation voltage \( V_f \) in the equation (3.20) we can describe the excitation current with the following desired first order dynamics, where \( \alpha \) is the gain.

\[ L_f \dot{i}_f = \alpha (i_f - i_f^*) \] (3.22)

We now choose \( \alpha < 0 \) to be much larger than the time constant of the synchronous machine dynamics. We can then assume \( i_f \) to be constant. That simplifies our description of the dynamic models of the rotor and the stator.

### 3.9 Outer Loop Controllers

To have a controllable and reliable dynamics of the synchronous machine there are outer loop controllers introduced. For the power system it is important to have a stable frequency and voltage. So the controllers used in this model are acting for that purpose. You can see an overview of the used outer loop controllers in the following Figure 3.4.
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Figure 3.4: Overview of the outer loop controllers of the synchronous machine

At first, there is the governor controller. It changes the mechanical input to the machine by opening valves for example to let more steam into the turbine. By doing that, it regulates the droop of the machine to a desirable value. The second controller to be introduced is the Automated Voltage Regulator (AVR). Like the name says, it is there to keep the output voltage to a constant value. This can be achieved by changing the excitation current $i_f$, which has a direct impact on the magnetic field that induces the EMF voltage $E$. This regulation can create parasitic electromagnetic oscillations in the machine. To damp these oscillations another controller can be used. Namely it is the last one used in the model, which is the Power System Stabilizer (PSS). These oscillations can be measured in the frequency deviation $\Delta \omega$. And like the AVR it changes the excitation current $i_f$ to have an impact on the oscillations. By doing so it also changes the voltage output like the AVR. To not have a permanent voltage off-set the effect of the PSS wipes out after a certain time, when the system is stabilized.

For a better overview the full outer loop control can be described in the following matrix representation in equation (3.23). Here the different $K$’s represent the gains of the different controllers.

$$
\begin{bmatrix}
\Delta P_m \\
\Delta i_f
\end{bmatrix} =
\begin{bmatrix}
K_g & 0 \\
K_{PSS} & K_{AVR}
\end{bmatrix}
\begin{bmatrix}
\Delta \omega \\
\Delta V_{out}
\end{bmatrix}
$$

(3.23)

3.10 Dynamics of the Controllers

In the following sections the dynamic models of the controllers are introduced.

3.10.1 Governor Control

Figure 3.5 is the block diagram representation of the governor control model, which is used in the simulations. According to literature this is a typical way of implementing a
governor controller [6]. $K_g$ is the gain of the governor controller and $\tau_g$ a time constant.

\[
\frac{\Delta \omega}{\Delta P_m} = \frac{-K_g}{\tau_g s + 1}
\]

**Figure 3.5:** Transfer function of the governor control

To have a look how it works we take a look into the time domain representation of this governor controller. Which is

\[
\tau_g \Delta \dot{P}_m = -\Delta P_m - K_g \Delta \omega
\]  

(3.24)

We now assume that $\tau_g$ is set fast enough. So, that we can look on the steady state of the controller dynamics. We combine it with the swing equation from (3.4) and get

\[
M \Delta \dot{\omega} = -(D + K_g) \Delta \omega + P^* - P_e,
\]

(3.25)

where $P^*_m = P_m - \Delta P_m$

The governor gain $K_g$ adds up to the damping $D$ of the machine, which provides a dynamically controllable droop of the machine.

### 3.10.2 Automated Voltage Regulator

A typical transfer function for an AVR is the same as the one of the governor control according to literature [6]. Again $K_{AVR}$ is the AVR gain and $\tau_{AVR}$ a time constant. The block diagram can be seen in the Figure 3.6.

\[
\frac{\Delta V_{out}}{\Delta i_f} = \frac{-K_{AVR}}{\tau_{AVR} s + 1}
\]

**Figure 3.6:** Transfer function of the AVR

By changing the excitation current $i_f$ we change the magnetic field created by the excitation system. That impacts the magnitude of the induced EMF voltage $E$, which is linked to the output voltage $v_{\alpha\beta}$.

Figure 3.7 shows the bode plot of the used AVR as an example.
3.10.3 Power System Stabilizer

According to literature [6] the PSS is often modelled as a two stage lead compensator. The reason for using a lead compensator is to improve the phase margin around the frequency of the parasitic oscillations $\omega_m$.

Figure 3.8 shows the block diagram of the PSS and the transfer function that is modelled in the simulations.

Let us go through this step by step:

A change in $i_f$ refers to a change in the output voltage as the part about the AVR showed. The first term of the PSS transfer function is there to not have a permanent offset of the voltage induced by the PSS. It wipes out the effect of the PSS after a time lag $\tau_0$ when the system should be stabilized.

The second term of the transfer function models the two stage lead compensator. In the TF there are two time constants $\tau_1$ and $\tau_2$. These time constants can be calculated to damp the parasitic oscillations of the machine with frequency $\omega_m$. By using the following formulas

$$\tau_1 = \frac{1}{\omega_m \sqrt{a}}$$

$$\tau_2 = a \tau_1,$$
where $a$ is a value coming from the desired adding up phase margin we want to achieve around the parasitic oscillation frequency $\omega_m$. It can be calculated with the formula

$$a = \frac{1 + \sin(\phi_{\text{max}}/2)}{1 - \sin(\phi_{\text{max}}/2)}.$$  \hfill (3.28)

Here we can take half of the angle $\phi_{\text{max}}$ because it is a two stage lead compensator. In Figure 3.9 a bode diagram of a lead compensator with all its parameters is pictured.

Figure 3.9: Diagram of a lead compensator [4]
Chapter 4

Implementations

The synchronous machine model derived in the previous chapter was implemented in a Simulink model. After running properly in steady state the outer loop controllers based on the transfer functions from section 3.10 were added to the synchronous machine model in Simulink. These controllers were tuned for a good dynamic behavior of the machine model. The working model was than embedded in a Sim-Power System. In the Sim-Power System model it can be implemented similarly to the predefined Matlab version of the synchronous machine. In this environment several test cases could be implemented with predefined blocks.

This chapter mainly gives an overview about the values used for the various parameters of the synchronous machine model and the used controllers.

4.1 Parameters of the Synchronous Machine

The model should be as realistic as possible. That is why it is decided, that it should be in SI units instead of the normally used per unit values to be even more realistic. The choice of realistic parameters of the synchronous machine is crucial for good results of the final simulations. The values that were chosen are from an actual machine, given in an example of a book [6].

Some nominal values are set to be given. That is first of all the value for the frequency of the machine $\omega_0$ which is simply taken to be the grid frequency. That means 50 $Hz$ in Europe. So the resulting $\omega_0$ is

$$\omega_0 = 2\pi 50 s^{-1}$$

The nominal power $S$ of the machine is 160 $MVA$, which fits to our prerequisites. A power factor of the machine is given to be 0.85. Which leads to a nominal active power rating of 136 $MW$. The rated voltage is set to 15 $kV$, which is the phase to phase voltage. That leads to a nominal current of 6158.4 $A$. The resistance of the stator winding $R$ is also given in the example. It is $1.542 \times 10^{-3} \Omega$. 
4.1.1 Excitation System Parameters

The excitation system is very well described and therefore all the values were given in the example of the synchronous machine. The nominal excitation field current to achieve the necessary magnetic field is called \( i_f \). That excitation system is powered by a voltage source \( V_f \), which is externally controlled to set \( i_f \) constant like derived in chapter 3.6. The induction \( L_f \) of this system is also given and the same for the excitation windings resistance \( R_f \).

<table>
<thead>
<tr>
<th>Name ( i_f )</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_f )</td>
<td>375</td>
<td>V</td>
</tr>
<tr>
<td>( L_m )</td>
<td>2.189</td>
<td>H</td>
</tr>
<tr>
<td>( R_f )</td>
<td>0.371</td>
<td>Ω</td>
</tr>
</tbody>
</table>

Table 4.1: Excitation system parameter values

4.1.2 Inertia Constant

The Inertia constant \( H \) is given to be 1.765 \( \frac{kWs}{hp} \). One horsepower (hp) is rated to be 0.746 kW. So, we can easily calculate the value in seconds if we divide \( H \) by 0.746 kW. What determines \( H \) to be 2.37 seconds. From this value we can then calculate the actual moment of inertia \( M \) of the synchronous machine in \( [Ws^2] \). This is the form of the inertia that is used in the model of the rotor. We can find it with the following equation:

\[
H = \frac{E_{mech}}{S_n},
\]

where \( E_{mech} \) is the mechanical energy. That is \( E_{mech} = \frac{1}{2}J\omega^2 \).

Using this and the fact that \( M = \omega_0 J \) we get the following equation for the needed moment of inertia \( M \).

\[
M = \frac{2HS_n}{\omega_0} = 2.41 \times 10^6 Ws^2
\]

4.1.3 Damping

The damping coefficient of the synchronous machine is not measurable. That is why it is usually not given as an attribute in the machine descriptions. Therefore, it is difficult to find realistic values for the damping. We tried two different approaches to find a value for the damping parameter \( D \).

The first way was by making some assumptions. We defined a maximum frequency deviation \( \Delta\omega \) for a given power change \( \Delta P_n \) and the derivation of the frequency change.
\( \Delta \omega \) should not exceed a maximum value. So, for a power change of \( \Delta P_n = 1\% \) of the nominal power, we assume that \( \Delta \omega_{\text{max}} \) should not exceed 0.2 Hz with a change rate \( \Delta \dot{\omega}_{\text{max}} \) of maximum 0.2 Hz/s. To find the corresponding value for the damping \( D_1 \) we use the equation

\[
D_1 = \frac{\Delta P_n - J \Delta \dot{\omega}_{\text{max}}}{\Delta \omega_{\text{max}}} = 2.6 \times 10^6 \text{Ws} \quad (4.3)
\]

That is a high value for a machine of the size of our machine, so we tried another way to calculate the damping \( D \). In some literature a value of around 25 pu is often taken for the damping. To calculate the SI value of the damping \( D_2 \) we multiply with the base value of the power, which is just the nominal power \( S_n \) and divide through the base frequency \( \omega_0 \).

\[
D_2 = \frac{D_{\text{pu}} S_n}{\omega_0} = 4.053 \times 10^4 \text{Ws} \quad (4.4)
\]

This result is two orders of magnitude lower than the value of \( D_1 \). It seems to be more realistic and therefore we decided to use \( D_2 \) in the simulations for the damping \( D \).

4.1.4 Inductions

The synchronous machine parameters [6] are given in \( dq \)-frame. That holds especially for the values of the stator inductions. These values are given as \( L_d \) and \( L_q \). The values for \( L_d \) and \( L_q \) are similar, which means the rotor is nearly round.

The mutual induction \( L_m \) of the synchronous machine is difficult to measure exactly, so it is calculated from steady state equations. In nominal operation the induced voltage \( E \) can be assumed to have the same amplitude as the output voltage \( v_{\alpha\beta} \).

\[
|E| = \omega_0 L_m i_f = |v_{\alpha\beta}| \quad (4.5)
\]

Solving that for the mutual induction \( L_m \)

\[
L_m = \frac{|v_{\alpha\beta}|}{i_f \omega_0} = 51.56 \text{mH} \quad (4.6)
\]

The stator self induction \( L_s \) results out of solving the steady state calculations of equation 3.16.

\[
L_s |i_{\alpha\beta}| \omega_0 = \omega_0 L_m i_f \quad (4.7)
\]

\[
L_s = \frac{i_f L_m}{|i_{\alpha\beta}|} = 4.48 \text{mH} \quad (4.8)
\]
4.1.5 Output Impedance

The output of the machine is decided to be an output capacitor $C_{out}$ in parallel with a output conduction $G_{out}$. The purpose of the conductance is to consume the active power delivered by the mechanical input. The capacitors function is to balance the reactive power output and is designed for nominal output. For the nominal value of $G_{out}$ we just divide the rated output active power $P$ by the square of the corresponding output RMS voltage $v_{\alpha\beta,rms}$.

$$G_{out} = \frac{P}{(v_{\alpha\beta,rms})^2} = 0.6044S \tag{4.9}$$

For the output capacitance $C_{out}$ we must also consider the reactive power. Figure 4.1 shows the diagram of the powers of the machine. Where we can obviously see that $Q = \sqrt{S^2 - P^2}$. The output power consumed by the load can also be described by

$$S = P + jQ$$
$$= (v_{\alpha\beta,rms})^2(G_{out} + j\omega C_{out}) \tag{4.11}$$

From that we get $Q = (v_{\alpha\beta,rms})^2\omega C_{out}$, which is the imaginary part of $S$ in equation (4.11). Solving that equation now for the output capacitance $C_{out}$

$$C_{out} = \frac{Q}{(v_{\alpha\beta,rms})^2\omega} = \frac{\sqrt{S^2 - P^2}}{(v_{\alpha\beta,rms})^2\omega} = 1.192mF \tag{4.12}$$

4.1.6 Initial Conditions

To run the simulated synchronous machine in steady state from the beginning we need to determine initial conditions. Which are mainly the angle between the output voltage
$v_{\alpha\beta}$ and the EMF voltage $E$ named $\theta_0$ and the angle between the output voltage $v_{\alpha\beta}$ and the current $i_{\alpha\beta}$ named $\Phi_0$. In Figure 4.2 there are the phasor diagram of the currents and the voltages and their angles in the stator windings for one phase.

![Voltage and current phasor diagrams](image)

**Figure 4.2:** Voltage and current phasor diagrams

To find the angle between the currents $\Phi_0$ we will need to have a look on the currents $i_C$ and $i_{load}$.

\[
i_C = jv_{\alpha\beta}\omega C_{out} \tag{4.13}
\]
\[
i_{load} = v_{\alpha\beta}G_{out} \tag{4.14}
\]
\[
i_{\alpha\beta} = i_{load} + i_C \tag{4.15}
\]

From that we can find the angle $\Phi_0$ by taking the $\tan^{-1}$ of the quotient of the imaginary and the real part of $i_{\alpha\beta}$.

\[
\Phi_0 = \tan^{-1}\left(\frac{\text{Im}(i_{\alpha\beta})}{\text{Re}(i_{\alpha\beta})}\right) \tag{4.16}
\]
\[
= \tan^{-1}\left(\frac{\omega C_{out}}{G_{out}}\right) = 0.5194\text{rad} \tag{4.17}
\]

The angle between the voltages $\theta_0$ can be calculated similarly by setting up the voltage equation.

\[
E = v_{Ls} + v_R + v_{\alpha\beta} \tag{4.18}
\]
\[
= (j\omega L_s + R)i_{\alpha\beta} + v_{\alpha\beta} \tag{4.19}
\]
\[
= (j\omega L_s + R)(G_{out} + j\omega C_{out})v_{\alpha\beta} + v_{\alpha\beta} \tag{4.20}
\]
\[
= v_{\alpha\beta}(RG_{out} - \omega^2 L_s C_{out} + 1 + j(L_s G_{out} + C_{out} R)) \tag{4.21}
\]
Again using the $\tan^{-1}$ of the quotient of the imaginary and the real part of $E$ we get a value for the initial angle $\theta_0$

$$\theta_0 = \tan^{-1}\left( \frac{\text{Im}(E)}{\text{Re}(E)} \right)$$

$$= \tan^{-1}\left( \frac{\omega L_s G_{out} + \omega C_{out} R}{R G_{out} - \omega^2 L_s C_{out} + 1} \right) = 1.0309 \text{rad}$$

4.1.7 Overview

To give an overview about the values used in the simulation Table 4.2 provides a summary of all the parameter values derived in the sections above.

<table>
<thead>
<tr>
<th>Description</th>
<th>Name</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>S</td>
<td>160</td>
<td>MW</td>
</tr>
<tr>
<td>Rated Active Power</td>
<td>P</td>
<td>136</td>
<td>MW</td>
</tr>
<tr>
<td>Power Factor</td>
<td>$\text{pf}$</td>
<td>0.85</td>
<td>-</td>
</tr>
<tr>
<td>Nominal Output Voltage</td>
<td>V</td>
<td>15</td>
<td>kV</td>
</tr>
<tr>
<td>Nominal Output Current</td>
<td>I</td>
<td>6.16</td>
<td>kA</td>
</tr>
<tr>
<td>Nominal Frequency</td>
<td>$\omega_0$</td>
<td>$2\pi \times 50$</td>
<td>rad/s</td>
</tr>
<tr>
<td>Moment of Inertia</td>
<td>M</td>
<td>$2.41 \times 10^6$</td>
<td>Ws$^2$</td>
</tr>
<tr>
<td>Winding Resistance</td>
<td>R</td>
<td>$1.542 \times 10^{-3}$</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>Damping</td>
<td>D</td>
<td>$4.053 \times 10^4$</td>
<td>Ws</td>
</tr>
<tr>
<td>Mutual Inductance</td>
<td>$L_m$</td>
<td>$5.16 \times 10^{-2}$</td>
<td>H</td>
</tr>
<tr>
<td>Stator self Inductance</td>
<td>$L_s$</td>
<td>$4.5 \times 10^{-3}$</td>
<td>H</td>
</tr>
<tr>
<td>Output Capacitance</td>
<td>$C_{out}$</td>
<td>1.192</td>
<td>mF</td>
</tr>
<tr>
<td>Output Conductance</td>
<td>$G_{out}$</td>
<td>0.6044</td>
<td>S</td>
</tr>
<tr>
<td>Field Current</td>
<td>$i_f$</td>
<td>926</td>
<td>A</td>
</tr>
<tr>
<td>Field Winding Resistance</td>
<td>$R_f$</td>
<td>0.371</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>Field Winding Inductance</td>
<td>$L_f$</td>
<td>2.189</td>
<td>H</td>
</tr>
</tbody>
</table>

**Table 4.2:** Overview of the values used in the simulation

4.2 Parameters of the Controllers

This chapter provides an overview about the values that were used in the simulation for the controller gains and their time constants. The values for the initial guesses are taken from literature and were then tuned manually for a better dynamic behavior.
CHAPTER 4. IMPLEMENTATIONS

4.2.1 Governor

As a reminder the transfer function used in the simulation for the governor

\[ G_g(s) = \frac{-K_g}{\tau_g s + 1} \] (4.24)

A typical value for the time constant \( \tau_g \) of the governor control is around 0.05 s. Which is also used in the simulations later.

The gain was tuned to get the desired droop of 4 %, which is the standard value for the droop in Europe. That means that for a load change of 100 % for example the frequency of the machine should change by 4 %. By simulating a load step of 10 % the governor gain \( K_g \) was tuned in a way, that the frequency dropped by 0.4 %. That was the case for a \( K_g = 11.4 \times 10^6 \).

4.2.2 AVR

In chapter 3.10.2 the AVR transfer function was defined as

\[ G_{AVR}(s) = \frac{-K_{AVR}}{\tau_{AVR} s + 1} \] (4.25)

The values for the governor controller were taken from literature [6] and adapted to our synchronous machine. A typical value for the time constant therefore is 0.5 s. The gain \( K_{AVR} \) was tuned manually for a good behavior. The behavior was in the end reasonable for the gain value of \( K_{AVR} = 30 \).

4.2.3 PSS

In chapter 3.10.3 the transfer function of the power system stabilizer was defined as a two stage lead compensator like in the transfer function below

\[ G_{PSS}(s) = \frac{K_0 \tau_0 s}{\tau_0 s + 1} \left( \frac{\tau_1 s + 1}{\tau_2 s + 1} \right)^2 \] (4.26)

The time constants \( \tau_1 \) and \( \tau_2 \) can be calculated according to the formulas (3.26) and (3.27). First we have to find the frequency of the parasitic oscillations \( \omega_m \) that have to be damped. Measurements of the simulations resulted in a value of \( \omega_m = 370 \text{ rad/s} \). Then a value for \( a \), the coefficient used to calculate \( \tau_1 \) and \( \tau_2 \), had to be determined. \( a \) is determined to be

\[ a = \frac{1 + \sin(\phi_{max}/2)}{1 - \sin(\phi_{max}/2)} \] (4.27)

A reasonable value for \( a \) is 25. Solving equation (4.27) for the angle \( \phi_{max} \) results in an additional phase margin of 134.76°.
CHAPTER 4. IMPLEMENTATIONS

With $\omega_m$ and $a$ it is now possible to calculate the values for the time constants $\tau_1$ and $\tau_2$.

\[ \tau_1 = \frac{1}{\omega_m \sqrt{a}} = 0.000541 \quad (4.28) \]

\[ \tau_2 = a\tau_1 = 0.0135 \quad (4.29) \]

The values for the gain of the first term $K_0$ of the transfer function is chosen and tuned for a good behavior. Whereas the time lag $\tau_0$ is a reasonable value for the oscillations to be disappeared. So that the effect of the PSS can be wiped out. It is chosen to be 0.1.

4.2.4 Overview

Like for the overview of the parameters of the synchronous machine in chapter 4.1.7 the Table 4.3 provides an overview on the values used for the controllers of the machine.

<table>
<thead>
<tr>
<th>Description</th>
<th>Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Governor Gain</td>
<td>$K_g$</td>
<td>$1.1 \times 10^6$</td>
</tr>
<tr>
<td>Governor time const.</td>
<td>$\tau_g$</td>
<td>0.05</td>
</tr>
<tr>
<td>AVR Gain</td>
<td>$K_{AVR}$</td>
<td>30</td>
</tr>
<tr>
<td>AVR time const.</td>
<td>$\tau_{AVR}$</td>
<td>0.5</td>
</tr>
<tr>
<td>PSS Gain</td>
<td>$K_0$</td>
<td>500</td>
</tr>
<tr>
<td>PSS time const. 0</td>
<td>$\tau_0$</td>
<td>0.1</td>
</tr>
<tr>
<td>PSS time const. 1</td>
<td>$\tau_1$</td>
<td>0.0135</td>
</tr>
<tr>
<td>PSS time const. 2</td>
<td>$\tau_2$</td>
<td>0.000541</td>
</tr>
</tbody>
</table>

Table 4.3: Overview of the controller values used in the simulation
Chapter 5

Simulations

The simulations are done in the Sim-Power Systems add-on of Matlab. Three test cases were chosen to have a look at the dynamic behavior of the synchronous machine. The first case, a step in the load introduced by an additional load in parallel to the nominal load, was modelled. A step in the load is a typical behavior of a power grid for example if a plant somewhere fails and others have to take over the loads. The second case is a line opening of a single line for 4 cycles. This can occur if a failure is detected and a circuit breaker opens the line for safety reasons. The breaker usually closes again to look if the fault in the system is still there. It would open again if that would be the case. In our simulated case we assume the fault to be gone and the circuit breaker remains closed. This case can be simulated with the circuit breaker model. That is the green block in Figure 5.1.

![Figure 5.1: Sim-Power System implementation of the synchronous machine and the fault blocks](image)

The third case is a single line to ground fault on the line. That is the most common fault that happens in the power network. It occurs for example when a tree touches...
the line, or a lightning strikes a line and causes a flash over at a isolation point. It can be introduced by the predefined fault block. In Figure 5.1 it is shown how the implementation of the Simulink model of the synchronous machine on the very left side in a Sim-Power Systems model was done.

5.1 Case 1: Step in the load

The first case that was simulated was a step in the load. It is introduced as a second load connected in parallel to the nominal load. Note that in the Sim-Power System model the load is modelled as a resistor instead of the output conduction $G_{out}$ as it was in the Simulink model. The connector disconnects the load again after two seconds, which lets the machine go back to nominal operation.

![Figure 5.2: Powers, frequency and voltage response of a step in the load](image)

In the first graph of Figure 5.2 the electrical power $P_e$ drawn by the load steps up to a higher value after some oscillations due to the load change. The mechanical power $P_m$ inputted to the machine follows the curve of the electrical power due to the operation of the governor controller. The governor controls the droop of the machine and stabilizes the frequency $\omega$ at its new operating point. The governor is important in this case, because it wipes out the difference between the drawn power and the inputted power.
If it wasn’t operating, the electrical power output would remain much higher than the mechanical power, which would reduce the frequency over the full two seconds. In the third graph of this figure the voltage magnitude of the output voltage $v_{\alpha\beta}$ is plotted. The Automated Voltage Regulator is operating, as the voltage magnitude is kept at 15 kV even after the load has changed. The current which is drawn by the load has increased simultaneously, because the power consumption has grown and the voltage has remained the same. There are oscillations in the voltage magnitude at the time of the step, but they are reasonable for a load change of this size.

### 5.2 Case 2: Line opening

The second case that was simulated is the single line opening for four cycles.

![Figure 5.3: Line currents, powers and frequency response of a single line opening](image)

In the first graph of Figure 5.3 one line current is going to zero due to the opening. The other two are decreasing steadily due to the lack of power that is delivered to the loads. Therefore the electrical power in the second graph is going down to zero and starting to break down. It is oscillating quite heavily due to the imbalance in the system. The mechanical power is also starting to decrease, but it is too slow to loose a lot of its energy in that short time of the line opening.
The fault was cleared after four cycles. The machine keeps running and goes back to its nominal operating point at steady state. The frequency in the third graph rises, due to the deviation of the mechanical power and the electrical power. The machine accelerates, because the inputted power is higher than the drawn power. But obviously the frequency also goes back to nominal frequency at 1 pu shortly after the fault was cleared.

### 5.3 Case 3: Line to ground fault

The third case in this section describes a single line to ground fault. Like the line opening fault it clears after four cycles.

![Figure 5.4: Line voltages, powers and frequency response of a single line to ground fault](image)

In the top graph in Figure 5.4 one line voltage is going down to zero for the mentioned four cycles and clears afterwards. The electrical power starts oscillating heavily and starting to become unstable, because the AVR tries to keep the voltage constant and for that increases $i_f$. But after the fault was cleared the system goes back to nominal operation, just as it does in the line opening fault above. Also like in the second test case the governor control is to slow to follow up with the electrical power and it stays more or less constant, what produces a deviation in the power balance. But this time
the other way around. The drawn electrical power exceeds the mechanical power, what makes the synchronous machine decelerating. It can be well observed in the third graph of the frequency.
Chapter 6

Conclusion and Outlook

In this project, we provide a Simulink model of a realistic synchronous machine in $\alpha\beta$-frame. For that, the synchronous machine was studied in detail. As well as the classical way of modelling it. Realistic values for the parameters had to be found or calculated. After that, the initial conditions had to be determined for a flat start in steady state. The next step was to implement the mathematical model into a Simulink model. After working properly in steady state some outer loop controllers were added for a realistic dynamic behavior. The gains of the controllers had to be found and tuned. Then the Simulink model had to be embedded in a Sim-Power System grid model which was set up before. In the Sim-Power System model some test cases were added and simulations were done. The results from these test cases were interpreted. In the future one could run more test cases, for example a multi-machine case. A comparison with the Matlab version of the synchronous machine could also be done to verify our results. Or one could also compare the synchronous machine model with the behavior of some converter controllers.
Bibliography


