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Industrial Electrical Engineering and Automation

Analysis of synthetic inertia using wind turbines for frequency stability in power systems

Carl Herrlin Hasselblatt

Division of Industrial Electrical Engineering and Automation
Faculty of Engineering, Lund University

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Carl Herrlin Hasselblatt

LUNDS
UNIVERSITET
Lunds Tekniska Högskola

LTH School of Engineering at Campus Helsingborg
Industrial Electrical Engineering and Automation (IEA)

LTH School of Engineering
Lund University
Box 882
SE-251 08 Helsingborg
Sweden

LTH Ingenjörshögskolan vid Campus Helsingborg
Lunds universitet
Box 882
251 08 Helsingborg

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"It matters not what someone is born,
but what they grow to be."
– Albus Dumbledore

Abstract

With the large expansion of renewable energy sources such as wind- and solar, the stability and quality of electrical power can be affected. The transition towards large-scale wind power offers many opportunities to maintain stability by using power converters to create synthetic inertia. At request of Sweco Energy, this thesis shows the effect and importance of synthetic inertia used in wind power to maintain a stable frequency. The importance of stability in power systems was proved by creating a simulation model in DIgSILENT PowerFactory© where synthetic inertia played an important role in decreasing frequency deviations from disturbances in the power system. The simulation gives a representation of how synthetic inertia can affect real life power systems and how the future of green power sources come with more solutions than issues. Society is forever changing with large environmental goals to provide a brighter tomorrow for the coming generations, and the hope of this thesis is to come even closer to reaching these goals.

Keywords: Synthetic inertia, wind turbines, energy systems, electrical power

Sammanfattning

Med den omfattande expansionen av förnybara energikällor, så som vind- och solkraft kan stabiliteten och kvalitén av den elektriska energin i ett elsystem påverkas. Genom att skapa syntetisk svängmassa med hjälp av kraftelektronik kan vi förenkla övergången mot grönare alternativ för att behålla lamporna tända över hela världen. På förfrågan från Sweco Energy kommer den här uppsatsen visa vikten av syntetisk svängmassa från vindkraftverk för att upprätthålla en korrekt stabilitet i energisystemet. För att bevisa vikten av stabilitet i ett energisystem skapades en simuleringsmodell i DIgSILENT PowerFactory© där syntetisk svängmassa spelade en avgörande roll vid störningar i systemet. Simuleringen ger en representation av hur syntetisk svängmassa påverkar energisystem som används i samhället idag och hur framtida energiproduktion från förnybara källor kommer med fler lösningar än problem. Samhället genomgår konstant förändring där stora miljömål sätts upp för att skapa en ljusare morgondag för kommande generationer och förhoppningsvis kommer den här uppsatsen göra så att målen känns ännu närmre.

Nyckelord: Syntetisk svängmassa, vindkraftverk, energisystem, elkraft

Acknowledgements

Sweco Energy

I would like to thank Sweco Energy for making me feel like part of the team from the very beginning. Without all the encouragement, tips & tricks and answering all my hundreds (if not thousands) of questions this thesis would not be possible. Thank you Per, who gave me the chance to work together with Sweco and a special thanks goes to Mari, who always finds the time to help me along the way, even when impossible projects make unexpected turns.

Lund University

Thank you, Imran, who saved the simulation model before it was too late and pushing me learning more than I thought I was ready, and had the time for. Who needs sleep anyway?

Terminology

- **DIgSILENT PowerFactory**: Simulation software used to model power systems.
- **DSL**: DIgSILENT Simulation Language.
- **Photo-voltaic**: Technique used to extract electrical energy from solar cells.
- **BESS**: Battery energy storage systems
- **AC**: Alternating current
- **DC**: Direct current
- **Watt [W]**: Unit for electrical energy
- **Voltage [V]**: Unit for electrical force used to generate electrical power.
- **Watt-hours [Wh]**: Unit for how much electrical energy is consumed for one hour.
- **SG**: Synchronous generator.
- **EMF**: Electromagnetic force, creates a voltage through magnetic applications.
- **Inertia**: Can be compared to a delay or slowness in rotating masses.
- **ROCOF**: Rate of change of Frequency.
- **Nadir**: Lowest point.
- **Zenith**: Highest point.
- **P.U**: Per-unit, used to calculate changes of a given value.

Table of Contents

1 Introduction

The energy system in Sweden is undergoing constant change and with the development of large-scale electrical power production from wind turbines some challenges will follow. The energy system in Sweden relies its production on mainly hydro, nuclear and wind power where hydro and nuclear power uses generators with large rotating masses which create natural inertia. The Swedish energy system has a frequency of 50 hertz (Hz) which is related to the rotational speed of the generators. To maintain a frequency of 50 Hz, the large generators in nuclear and hydro power plants can use the inertia to compensate for various disturbances in the system which affect the frequency. This ability decreases with nuclear power being discontinued and large-scale wind power is being introduced. As a result, there is less total mass to maintain the frequency at an acceptable level during periods of unbalance in the system. However, the integration of wind power represents an opportunity to aid the power system by the usage of synthetic inertia. Synthetic inertia uses power electronics to help the energy system maintain the correct frequency in the event of disturbances in the system or increased consumption. This thesis will focus on the technology and theory of synthetic inertia generated from wind turbines. The thesis will also discuss how the increased power production from wind turbines can be used to sustain the correct frequency of 50 Hz and meet future needs of electrical energy in the Swedish energy system.

1.1 Background

Sweco is one of Sweden’s largest consulting companies with expertise in multiple sectors of society such as structural, industrial and energy engineering, transportation infrastructure and architectural designs. Sweco Energy focuses on maintaining expertise on all aspects in the energy sector and the challenges that lie ahead to meet customer expectations and solving society’s future energy problems. With a wide expertise in renewable energy, Sweco requests extended knowledge of how their customers can apply synthetic inertia to meet future needs of stable electrical power systems.

To meet the future challenges of intermittent energy sources, such as wind turbines and photo-voltaic cells, the use of synthetic inertia will play a crucial role in always maintaining a stable frequency. To motivate Sweco's request for extended knowledge of synthetic inertia the project will provide a simulation model where different scenarios will be used to emulate its function and role in a small-scale power system. In addition to the simulation model, a brochure with technical guidelines regarding synthetic inertia using wind turbines will be provided.

1.2 Purpose

The overall purpose of this thesis is to create an understanding of synthetic inertia and how it can contribute to stability in large scale power systems using intermittent power sources. The increase of intermittent power sources is argued to create instability and limitation of frequency control in the power system. By using simulations of wind turbines to create synthetic inertia in the power system and handle frequency deviations, this thesis hopes to show how the ongoing and future expansion of wind power can contribute to stability and high-quality power distribution while at the same time lower the environmental impact from large generators that uses fossil fuel to create electricity.

1.3 Goal

With the understanding of synthetic inertia and analysing a simulation of its contributions to the stability of large-scale power systems, the goal of this thesis is to contribute to Sweco's large technical expertise. By designing a pamphlet of information gathered from this thesis, the main contributions will be accessible to Sweco's employees to better understand how synthetic inertia can contribute as a solution to Sweco's customers working with renewable energy.

1.4 Problem

The following issues will be answered in this report:

- What factors and components contribute to creating synthetic inertia from wind turbines?
- How does synthetic inertia affect frequency deviation during disturbances in modern power systems?
- How can synthetic inertia contribute to large scale energy production to maintain a stable frequency?
- How can synthetic inertia be automatically controlled?

1.5 Motivation of thesis

The energy sector and its challenges are constantly changing. The enormous investments being made around the world on renewable energy creates new problems to be solved and lessons to be learned. This thesis will act as a scratch on the surface of the complexity of the energy system and pave the way for a career in the energy sector.

1.6 Restrictions

Creating the simulation model required some simplification and approximations based on previous work in similar projects performed by Sweco and Lund University. Synthetic inertia can also be used in solar power and battery energy storage systems (BESS). This project focuses exclusively on wind turbines since the project scale would increase significantly if solar and BESS would be included. The model created cannot be interpreted as a realistic model since the number of parameters has been significantly reduced due to the size of the project, for example, the project does not consider reactive power, which is one of the main components in realistic systems.

1.7 Previous work on similar subjects

With the wide expansion of intermittent power sources, the required knowledge, and methods to sustain a stable power system is of high demand from academic work and innovations from the private sector. This thesis was based on similar work conducted at Lund University in Sweden, Loughborough University in UK and University of Technology and Economics in Hungary.

2 Technical background

2.1 Electrical power systems

An electrical power system consists of three main areas of focus: production, transmission, and consumption. The consumed energy needs to be momentarily produced using different methods to create a rotating motion in electrical generators or converted power from photovoltaic cells. This energy then needs to be transported from the production plant to the energy consuming load. The rotating motion in the generators can be created by using large water streams, wind and steam heated from nuclear power cores or burned materials in power plants [1].

The rotating generators in the Swedish power system creates an alternating current (AC), which has a frequency of 50 Hz throughout the whole electrical power system. This means that if the production of power cannot sustain the consumption of power in the system, the frequency will deviate from 50 Hz. Deviations of ±0.1 Hz are acceptable in the Swedish and Nordic systems, several frequency reserves are maintained to sustain from large deviations if disturbances were to occur [2]. The frequency control reserves are further discussed in section 2.3. To show the importance of balance in the power system, the Swedish power system supplied a total of 552 TWh of electricity in 2018, the same year the total electrical power usage was 552 TWh, which states a well-balanced electrical system over the year [3].

2.2 Synchronous generator

The synchronous generator (SG) is widely used in power systems to generate electricity to the system. The reason for its popularity is because the SG can be used for both variable and fixed speed applications. An example of variable speed application is wind power, whereas hydro power is an example of fixed speed application.

The SG consists of a stator and a rotor, where the stator is a fixed armature surrounding the rotational mechanism of the rotor. Both stator and rotor have wire windings which are used to generate a voltage. The output voltage is taken from the stator. The generator uses electromagnetic induction to produce AC power. This electromagnetic induction applies an electromagnetic force (EMF) on the stator windings which then generates an alternating voltage in the stator outputted to the power system [4].

2.3 Generator governors

In power systems, large generators such as the ones used in hydro power, uses several control systems to ensure that the generator spins at the referenced speed. The governor in a generator is used to accelerate/decelerate the rotational speed by constantly measuring the frequency of the power system. If the load would increase, the rotational speed of the generator would accelerate, driving up the frequency, and vice versa if the load would decrease [5].

2.4 Inertia and swing equation

Hydro power and nuclear power consist of large generators that converts the generators rotational energy to electrical energy. Since the 1970s, Sweden's electrical power production has been dominated by nuclear- and hydro power but in early 2000, Sweden began to cut back nuclear power production by shutting down reactors leading to further development and expansion of wind power all over the country. The same year, 31% of the electrical power was produced from nuclear power, 43% was produced using hydro power, 16% produced using wind power and 9% using conventional thermal power [6]. With the use of large and heavy turbines in nuclear and hydro power plants, the inertia created acted as a stabilizer if the generation of energy halts. For example, if the rotational energy applied to the turbine were to be lowered, the natural inertia of the generator would supply the system with further generation of power since the generator would not immediately come to a full stop. The natural inertia generally has 10 – 60 seconds before the decreased production affects the system. In the aspect of electrical frequency, the inertia in the system can help reduce large deviation since the generators can maintain the rotation due to its large proportions. This means that the larger inertia a system has implemented, the less frequency deviation will be experienced during a sudden disturbance in the system [7].

Since the systems frequency is a measure of the power balance in the system, where consumed power requires the same amount of power momentarily produced, this can be described by

$$J\omega_n \frac{d\omega}{dt} = P_a = P_{mech} - P_{el} \tag{1}$$

where J [kgm^2] is the total inertia of the rotating mass, ω_n [rad/s] is the rotational speed of the generator and P_a, P_{mech} and P_{el} [W] is the accelerating, mechanical and electrical power, respectively. Equation (1) is known as Newtons equation for rotating masses, but also goes by another name called *the swing equation*, which determines the power output deviation where the derivate of the rotational speed of the generator is multiplied with the total inertia and nominal rotational speed of the generator [8]. The expression of the total inertia from equation (1) is defined by

$$J = \int r^2 dm \tag{2}$$

where r [cm] is the rotational radius and m [kg] is the mass of the generator. This can be used to also define the momentarily kinetic energy in the generators mass. It can be expressed as kinetic energy stored in the rotating body if the rotational speed would be lowered:

$$E_k = \frac{1}{2} J\omega^2 \tag{3}$$

This expression points out that the kinetic energy of the generator is dependent on the moment of inertia and speed. Since inertia itself is the resistance to the change of speed in a rotating body, a disturbance in the system would mean less power output from the generator. With a generator with a rated capacity for operation, the kinetic energy can be measured, and the inertia constant H can be defined as:

$$H = \frac{0.5 \cdot J \cdot {\omega_n}^2}{S_n} \tag{4}$$

where H is the inertia constant [J/VA] and S_n is the apparent power [VA] [9] [10].

2.5 Frequency control in energy systems

As mentioned in the introduction to this chapter, the frequency deviation is acceptable in the range of ±0.1 Hz form the nominal 50 Hz in the Swedish power system. Svenska Kraftnät (SVK) is responsible for maintaining a balance in the power system and do so by procuring services to ensure that the frequency does not deviate further than the acceptable range. The following services are to control the frequency if disturbances would occur in the system [1].

- Fast Frequency Reserve (FFR) is an automatic system service that handles the initial frequency deviations that can emerge from low rotational speeds in the systems generators. This power reserve contains a minimum of 0.1 MW and has a response time of 0.7 seconds if the frequency drops to 49.5 Hz [11].
- Frequency Containment Reserve (FCR) consists of three instalments where FCR-N is the main service and is in place to automatically maintain frequency deviations within 49.9 – 50.1 Hz and has a power capacity of 240 MW which could be fully activated within 3 minutes [12].

- Frequency Restoration Reserve (FRR) is divided into two instalments where Automatic FFR (aFFR) and Manual FFR (mFRR) are used. aFFR is used to automatically restore the frequency to 50 Hz in case of a disturbance in the system. The aFFR service can contribute 140 MW within 2 minutes [13]. mFFR does not have specific power contribution since the frequency reserve is activated manually by SVK within 15 minutes. mFFR's goal is to restore the frequency to 50 Hz [14].

2.6 Wind turbine

This thesis explains synthetic inertia in wind turbines, but first, a discussion about the fundamentals of energy generation using wind power is needed. Figure 2.1 shows the included components mentioned in this section. Wind energy is converted to electric energy using an aerodynamic force on the turbine rotor blades which causes them to rotate. The rotor connects to a gear box which controls the rotational speed of the generator which then generates electricity [15]. The generator is connected to a power electronic converter which converts the electricity to the required AC-standard of the grid where it is to be distributed. The converter in wind power is explained in detail in section 2.5. There are several types of wind turbines, the main differences are which generator is used to generate the electricity and how they are connected to the power grid using various converter technologies [16].

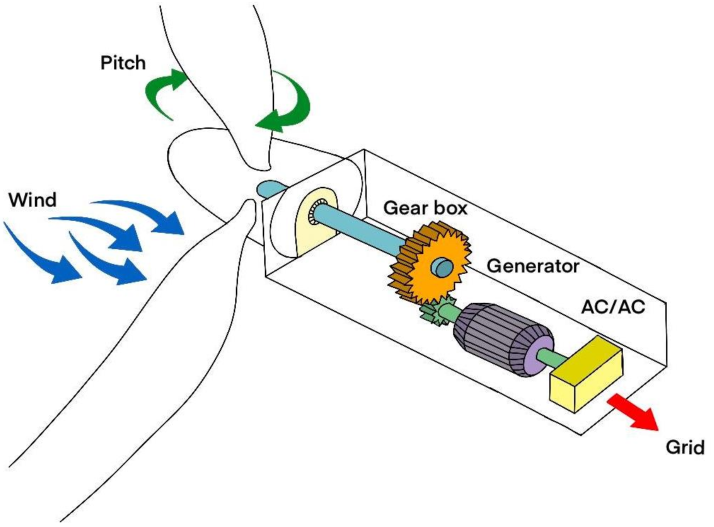

Figure 2.1: Basic wind power turbine. Pitch angle can be seen in top of figure. Wind power is transferred through the rest of the components where the AC/AC-converter can be controlled.

There are four different types of wind turbine generators in use today (SG was discussed in section 2.2). These four types of generators are listed below, followed by a brief explanation.

- Permanent magnet generator
- Synchronous generator
- Asynchronous generator
- Doubly fed induction generator

The induction generator is the oldest and cheapest one to use today, but in later developments and expansion of wind turbines, doubly fed induction generator is the most used.

Permanent magnet generator

The permanent magnet generator (PMG) is characterized by its direct contact to the grid. The generator itself consists of three wire-wound iron poles connected to a three-phase power supply. The rotor is a two-pole magnet, while the stator acts like a virtual rotating magnet which poles are connected to a different supply phase. This virtual rotating magnet causes the rotor to always be fully aligned. If this would not be the case and the rotor would be externally driven and restraining torque would be developed between the rotor and the stator.

Synchronous generator

The SG is explained in section 2.2. But worth mentioning is the function of controlling the generator's power factor by varying the magnetising current, which is valuable for supporting the grid voltage.

Induction Generator

Like the synchronous generator, the induction generator (IG) shares the same characteristics of its stator which is grid-connected. What differentiates the IG from SG is the rotor, which magnetic field is created by induction and lacks the windings or external connection but instead uses a ring of parallel conductors called a squirrel cage. Since the rotor lacks windings, the generator has a more solid construction making it a preferred choice for the first generation of wind turbines.

Doubly fed induction generator

As a development of the conventional IG, the doubly fed induction generator uses wire-wound instead of squirrel cage construction. The winding of the rotor is connected to a frequency converter, which is a highly appreciated feature since the rotor speed can be extended to ±30% to fit different purposes of the generator [17].

2.7 AC/AC converters in wind turbines

Power converters in wind turbines uses the AC voltage from the synchronous generator, which has variable frequency and converts this to voltage output with a stable frequency. The conversion is done by automatic controllers connected to the transistors in the converter which has the ability to change the switch-frequency and duty-cycle to alter the output voltage to the power grid. In more detail, the first three legs marked with small letters a, b and c in figure 2.2 use the AC voltage from the generator to create a DC voltage over the capacitor. This DC voltage is calculated by

$$V_{DC} = \frac{3\sqrt{2}}{\pi} \cdot V_{LL} \cdot \cos \alpha \tag{5}$$

where V_{LL} [V] can be simplified as the average voltage of each phase and cos α [rad] is the angle of measurement. The DC voltage created by the first three legs of the converter is then converted back to the desired AC voltage to the power grid [16].

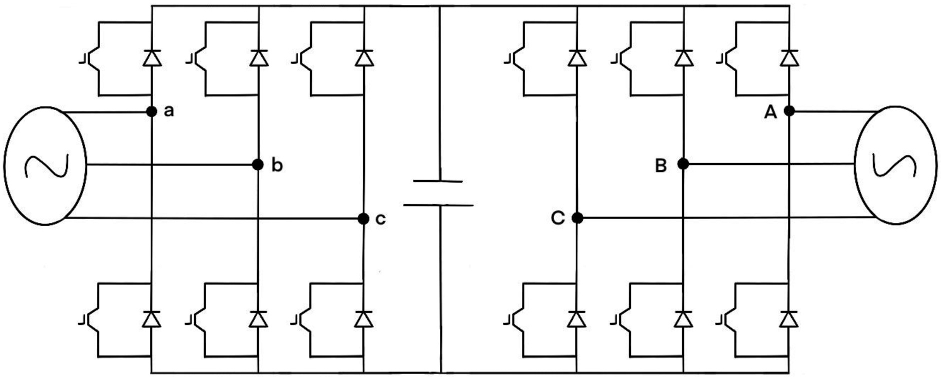

Figure 2.2: AC-AC converter circuit diagram which uses an AC-input showed on the left together with controllable transistors and diodes to control the AC-output showed on the right.

2.8 Synthetic inertia

In section 2.1, the importance of inertia from large generators in power systems was discussed and how inertia contributes to a stable frequency in case of large disturbances. The variable applied kinetic energy from wind power on the rotors of a wind turbine does not have the same characteristics as the continuous kinetic energy applied to large turbines in nuclear and hydro power and can therefore contribute only a small amount of inertia to the power system. Instead, wind turbines use different control techniques to change the angle of the rotor blades, together with power converts to generate synthetic inertia. Using these control techniques, the wind turbine can regulate the output power to some extent even if the wind speed varies.

In Sunne Kommun, Sweden, there are currently 13 wind turbines connected to the power grid which are used as frequency reserve with an installed capacity of 53 MW where 33 MW is used for frequency control. The way these wind turbines contribute to frequency control is to use a technique called pitching which changes the angels of the rotor blades to increase or decrease the kinetic energy applied to the rotor, thus making them suitable for frequency control [18]. Pitching of wind turbine rotors is shown in figure 2.1.

The control technique used in Sunne Kommun provides a fast power reserve by using the stored kinetic energy in the rotating masses as active power to the power system if needed. The increased electrical power output can be created by using pitching, which is regulated via a controller connected to the converter. The increased output power has the same characteristics as inertia from larger generators since the stored kinetic energy from the wind is used to maintain a steady power output [19].

2.9 Synthetic inertia controller

The technique used to control the power output from wind power turbines with synthetic inertia has several operational approaches where controllers respond to various trigger values. This thesis will focus on the approach for continuous operation of a wind turbine which is also implemented and modelled in PowerFactory, see figure 2.1. This approach uses the ROCOF to act as a trigger for the control which then produces a power deviation signal, ΔP. The power deviation signal is then multiplied by a doubled inertia constant. The power reference used in the converter is determined by the difference between the measured rotational speed, ω_{meas}, and reference rotational speed, ω_{ref}, creating $\Delta\omega$ which is then regulated using a PI-regulator. Using figure 2.3, the PIregulators function is to define and eliminate the measurement error between the referenced frequency and the measured frequency in the system. The power output that was multiplied by the inertia constant is then differentiated from the power signal output from the PI-regulated to create a signal called P_{ref} which is then added to the converter which adapts its power output accordingly [20] [21].

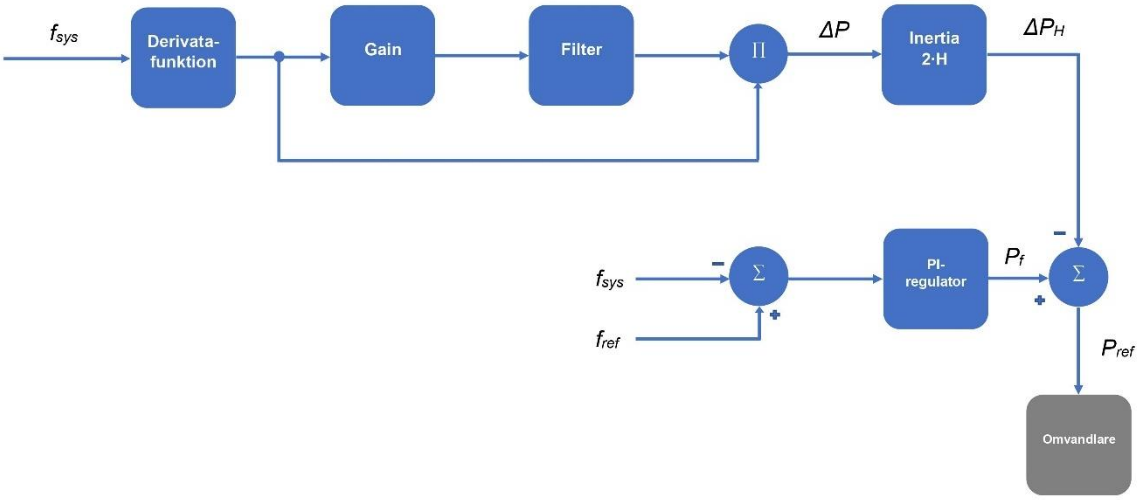

Figure 2.3: Synthetic inertia controller block diagram where the difference in power output is multiplied by a given inertia constant, see equation (3). The referenced power, P_{ref}, is then compared to P_f, which is measured using the PI-regulator.

The inertia controller is highly dependent on the ΔP-signal, seen in in figure 2.3, which is multiplied by the inertia constant. This is critical for the output power signal and explained by

$$\Delta P = 2H \times f_{sys} \times \frac{df_{sys}}{dt} \tag{6}$$

where f_{sys} is the frequency signal from the power system [21].

3 Method

The project was executed by creating a simulation model using DIgSILENT PowerFactory© with data, scientific work, articles, and information found on the Internet using the previously presented key words that outlines the thesis as search words. The knowledge acquired is presented in the thesis and used to create a comprehensive brochure with information regarding synthetic inertia which can be found in Appendix A. The information was used to create the simulation model to prove the function of synthetic inertia in a small-scale power system dived in to two cases. The first section simulates the frequency changes of the power system using only different values of inertia from wind power. The second section uses a more complex inertia controller to simulate how synthetic inertia can be controlled and regulated to meet different needs in the power system.

3.1 DIgSILENT PowerFactory©

DIgSILENT PowerFactory© is professionally used worldwide by power engineers to calculate and simulate specific models to study different scenarios. The reason for using DIgSILENT PowerFactory© in this thesis instead of similar simulation software is rooted in that DIgSILENT PowerFactory© is primarily used for power modelling and simulation. DIgSILENT PowerFactory© also contains a large library of components and models together with comprehensive user manuals. From here on DIgSILENT PowerFactory© will only be referred to as PowerFactory.

3.2 Test system

Figure 3.1 shows the power system model created in the study of synthetic inertia. PowerFactory provides several components to use in the graphical model of the system. With reference to the model in figure 3.1, the thicker lines represent busbars, which are used to connect loads, transformers, generators, and power lines. Each of the mentioned components can then be individually customized to suit the requirements of the model. For example, the inertia constant was changed in the wind power component, which in turn is a synchronous generator component with changed characteristics to suit a wind turbine. The transformer components used in the model has the built-in function to change the voltage levels from one side to the other, this is done by declaring what values should be used on the high voltage side (HV-side) and low voltage side (LV-side). The loads used in the model can be either dynamic or static where the dynamic load has a variable power value, while static has a fixed power value. Power lines in the model needs to be specified in the sense of length in kilometres and if the transmission line is overhead or cable underground since this changes the characteristics of the transferred power.

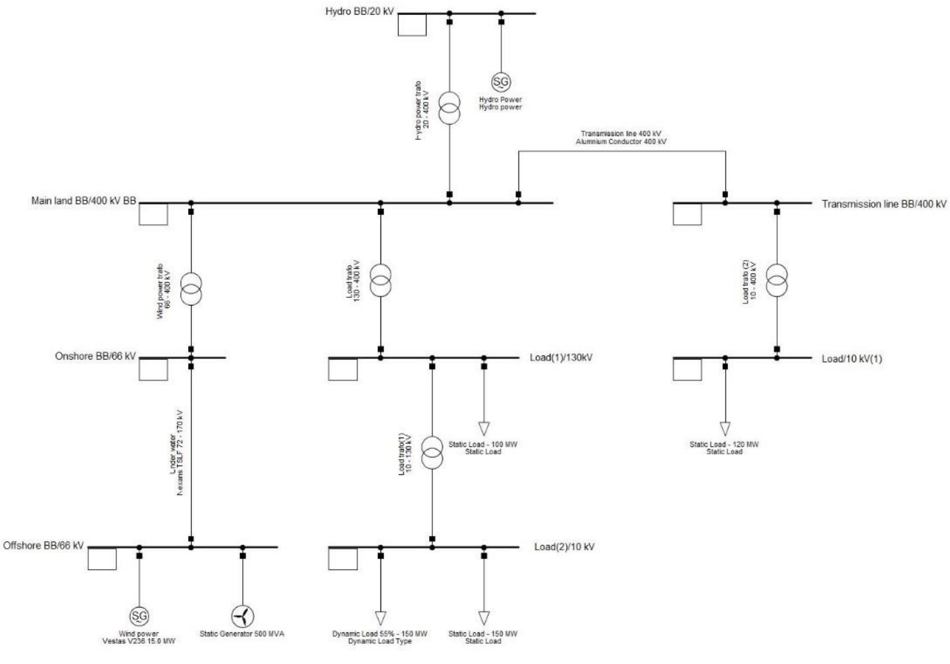

Figure 3.1: © DIgSILENT PowerFactory model used in the simulation. Hydro power generator is placed in the top part of the figure. Wind power generator and static generator is placed in the lower left part of the figure. Loads used in the simulation is placed in the bottom and right side of the figure.

To make the simulation as realistic as possible, synchronous generators are used to model both wind and hydro power where the latter component is equipped with a simple governor system model.

To create a governor, PowerFactory has the function of adding specific models to components placed in the power system model. The model used for the governor can be seen in figure 3.2. The governor model consists of several block diagrams used by the generator to react to the simulation scenarios discussed in section 3.3. The block diagram uses PowerFactory's own programming language called DSL, which is discussed further section 4.3. The governor implemented uses three input signals where the reference power (P_{ref}) from the system is the first, the second is the momentary speed of the generator (ω) and the third is the referenced speed of the generator (ω_{ref}). The difference in referenced speed and momentary speed is used to differentiate the value of the referenced power. The signal marked *yi* in figure 3.2 is then filtered and used as an input signal to the hydro power generator as a reference to increase or decrease power production.

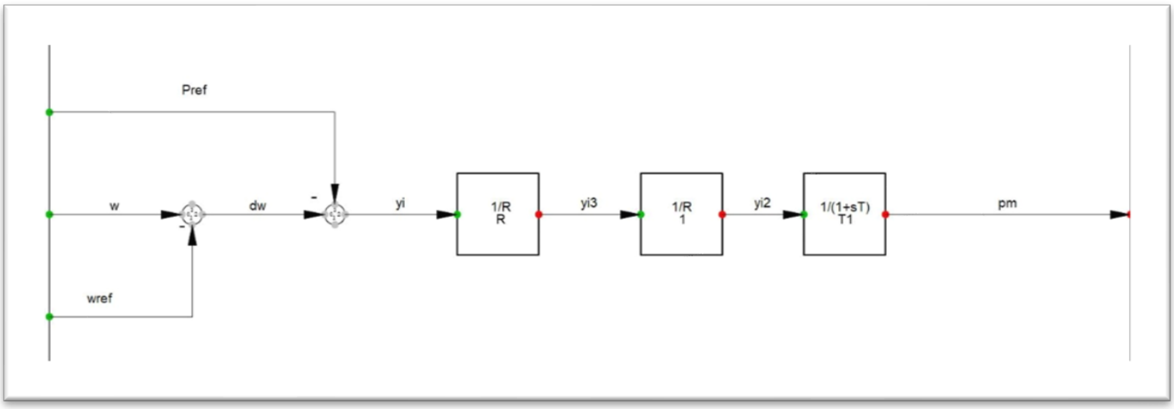

Figure 3.2: Governor model added to the hydro power generator component in the simulation model. Input signals P_{ref}, ω_{ref} and ω can be seen on the left-hand side and the output signal pm can be seen on the right-hand side.

The static generator component seen at the bottom of figure 3.1 was needed to apply the inertia controller model seen in figure 3.3. The values and properties of the controller can be changed to simulate several more aspects of synthetic inertia than the simpler approach where the inertia constant was changed in the wind power component type. This uses the same model type as with the governor model with the programming language DSL.

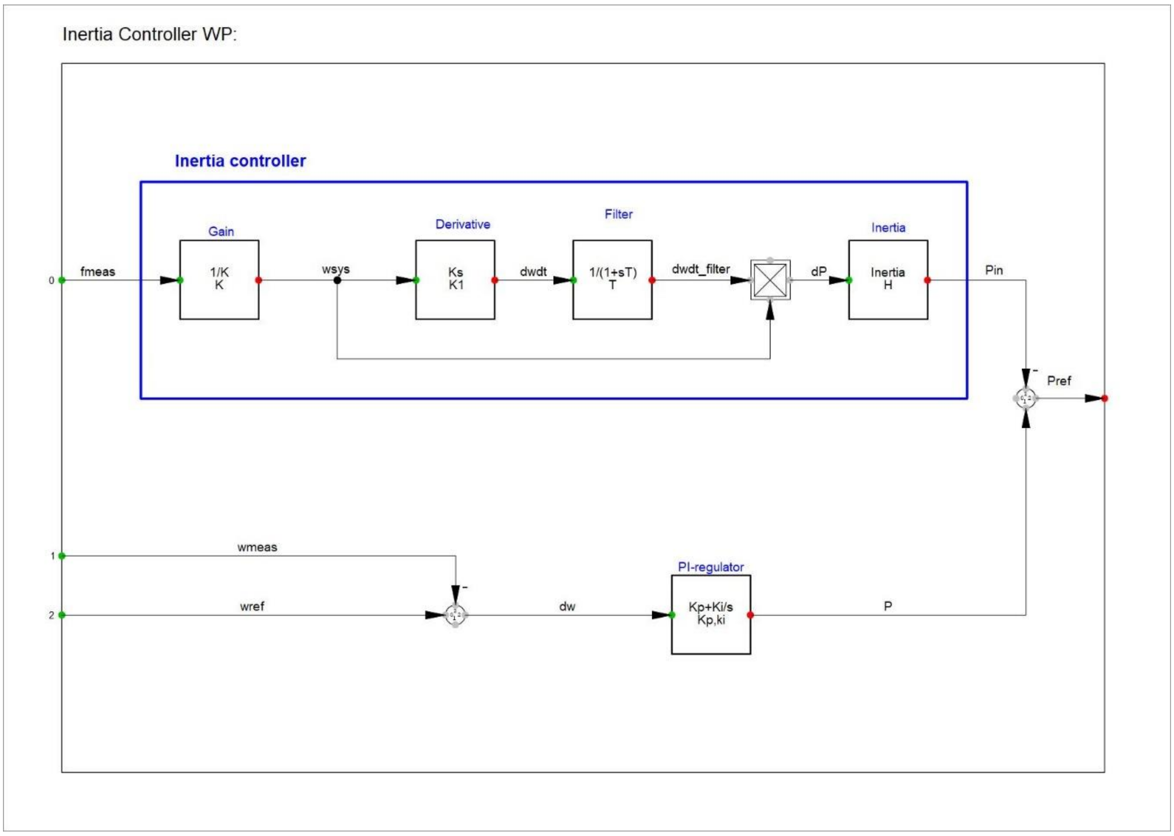

Figure 3.3: Block diagram of inertia controller based on the model from **[21]**. *Output power signal to converter can be seen to the far right and input signals* f_{meas}, ω_{meas}, P_{meas} *can be found to the far left.*

3.3 Simulation scenarios

The simulations in PowerFactory uses two kinds of simulation scenarios that are based on the following events:

- Synchronous Machine Event, where the generator in the hydro power component cannot maintain correct torque.
- Load increase from all loads component in the system model.

To simulate the scenario where hydro power cannot maintain a full power output, PowerFactory has a simulation function called Synchronous Machine Event where a generator's torque changes and the deviation in frequency can be observed. Using this function, the simulation was based on two separate events where the torque of hydropower was decreased by 0.05 per unit (p.u) and 0.2

p.u, respectively. Per unit is used to calculate variations in power systems and can be compared to a percentage of increase or decrease in variables. The second scenario examines the model’s behaviour in case of a load increase. To study this case a Load Event was simulated in PowerFactory where the selected loads can increase/decrease at a given time. The simulation model uses two types of loads, dynamic and static loads. To show the difference between various values, two separate load events were introduced using an increased load of 25% and 55%, respectively.

4 Analysis

The use of PowerFactory resulted in some deep dives in the user manual to discover the endless possibilities of the software. Previous work with similar topics from the author has been conducted in MATLAB, making one of the main issues of this thesis learning how to simulate in PowerFactory.

The following section will motivate the decisions and issues which arose during this project.

4.1 Simulation results

The results presented in this thesis are based on simulations of frequency deviations in a small-scale power system where the model was constructed using a software called PowerFactory. The results are presented in graphs using PowerFactory's built in functions where the deviations were shown in comparative formats with different inertia values.

4.2 PowerFactory versus MATLAB

As previously mentioned, the author has experience with MATLAB since previously work on similar work making MATLAB an obvious and easier choice to conduct the simulation. PowerFactory on the other hand has been used for many years by professionals working in the energy sector to conduct large and small-scale simulation. Sweco uses PowerFactory to simulate this kind of problems and since this thesis is requested from Sweco, PowerFactory was instead the preferred simulation software.

4.3 DIgSILENT Simulation Language

Since PowerFactory supplies a well written and comprehensive user manual for all aspects of the software getting started was not the main issue. Challenges emerged when creating the synthetic inertia controller discussed in section 2.7 and presented in figure 2.3. The controller is created using PowerFactory's own programming language called DSL where block diagrams were used to illustrate input and output signals to the controller. This is a highly advanced, graphical function in PowerFactory making the software capable of creating and simulating the overall components in a power system. Since the power of DSL also came with a lot of reading in the user manual, causing multiple simulations errors while creating the synthetic inertia controller, this phase of the thesis was the most time consuming.

5 Result

The presented simulation results consist of 8 separate simulations with different parameters. Using the already implemented inertia function in PowerFactory, the results presented uses four different inertia values to show how the frequency deviation is affected. The inertia constant values are 1, 3, 6 and 9 seconds. The inertia constant value can be described as a delay for the rotational energy to decrease significantly enough to affect the power output of the generator. The simulation consists of two separate scenarios presented in table 5.1.

Table 5.1: Description of the scenarios and cases.

Cases	Scenario 1 *Load Event*		Scenario 2 *Synchronous Machine Event*	
Case 1	+25%	No Governor	-0.05 p.u	No Governor
		With Governor		With Governor
Case 2	+55%	No Governor	-0.2 p.u	No Governor
		With Governor		With Governor

The following sections present the result in each scenario and case, starting with the worst-case scenario where the system does not include a governor system.

5.1 Scenario 1, Load Event

Scenario 1 shows the frequency deviation where the simulation was executed using a Load Event with an increased load of 25% presented in case 1 and an increased load of 55% presented in case 2. Both cases include results with and without the government system.

Case 1, no governor system

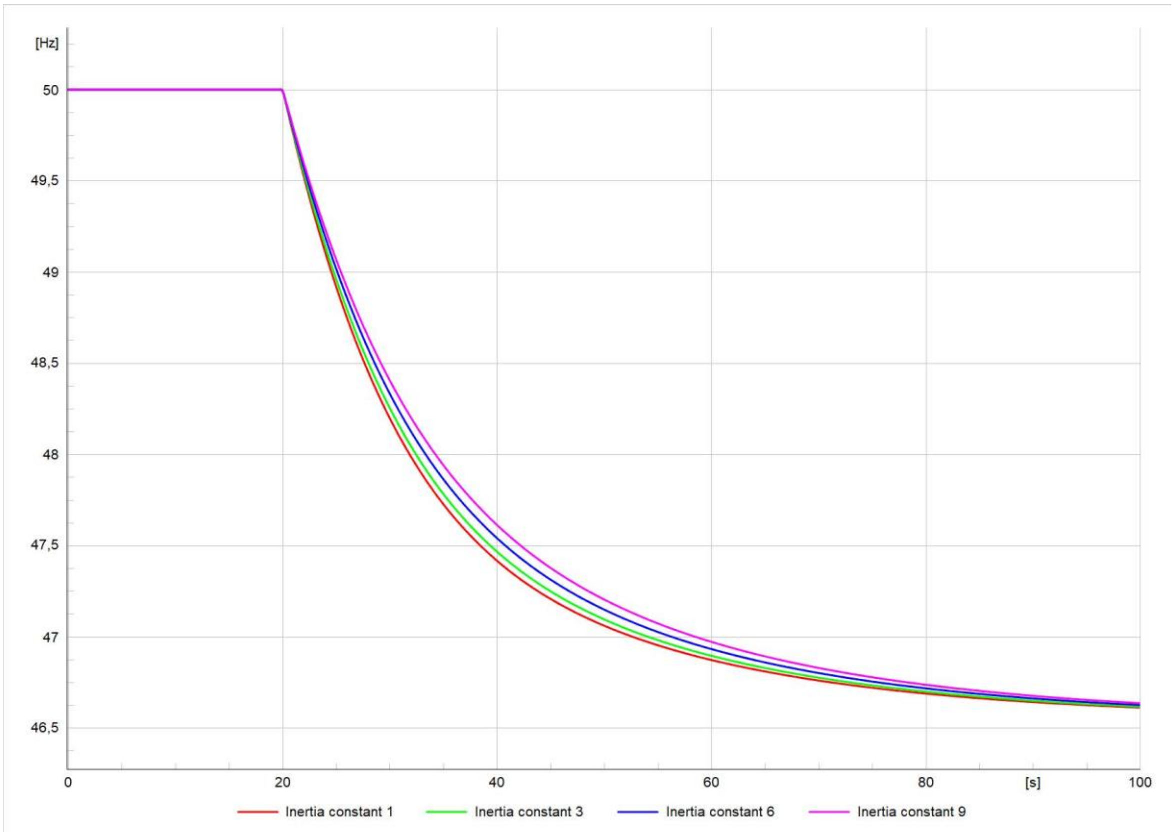

Figure 5.1: Simulation result shows frequency deviation during a load event where an increased total load of 25% were introduced to the system. This simulation does not contain governor controller.

Figure 5.1 shows how the frequency is rapidly declining to critical levels. By observing the inertia constant with the value 9 s, the simulation shows that the higher inertia is affected less than the rest of the values. The reason for the critical drop in frequency is explained by the lack of governor generator in the system, which purpose is to lower the frequency deviation by producing more electrical power. This result is somehow unrealistic since frequencies lower than 48 Hz would have critical impact on a real-life power system.

Case 1, using governor system

Figure 5.2 shows the frequency deviation from the simulation using a Load Event of 25% increase, this time using a governor system to maintain a stable frequency.

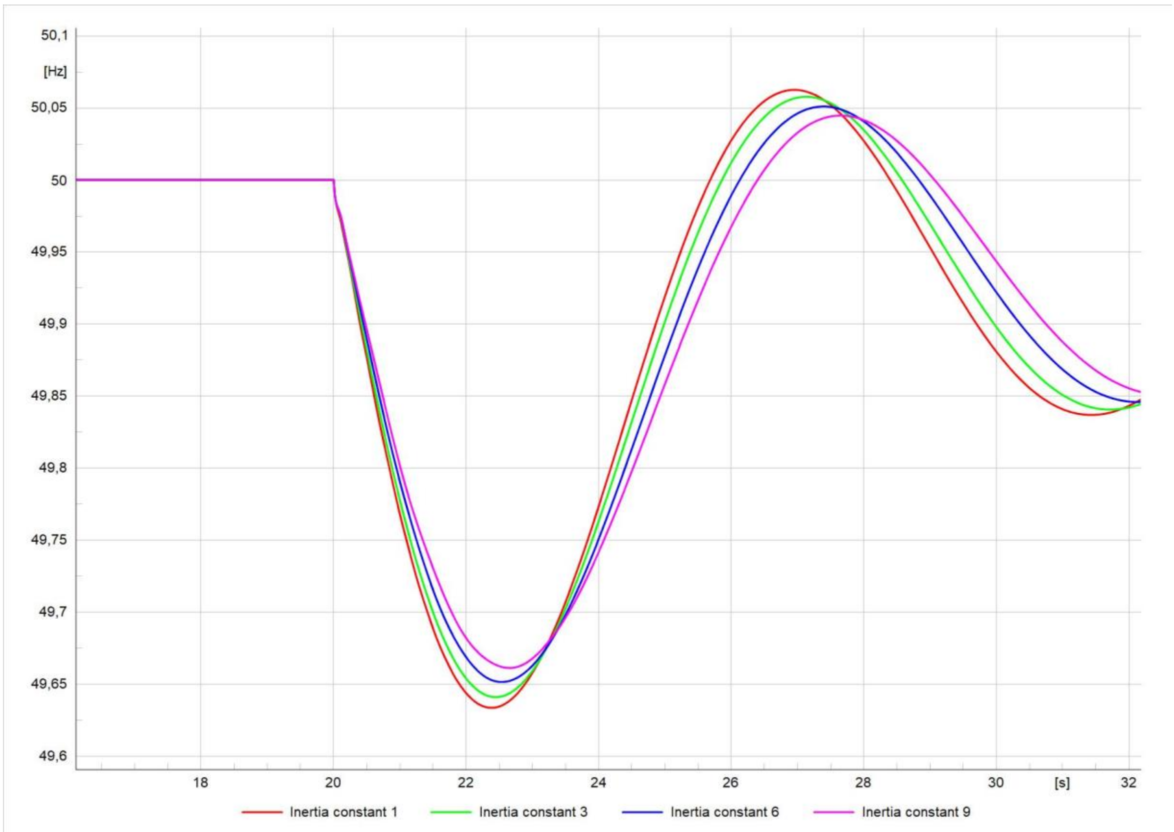

Figure 5.2: Simulation result shows frequency deviation during a load event where an increased total load of 25% were introduced to the system. This simulation contains governor controller.

Comparing the lower inertia value (1 s) to the higher inertia values (9 s), the result shows how the curve with inertia value 1 s both has a higher maximum and lower minimum value, note also a higher ROCOF than the curve which has the inertia value of 9.

Case 2, no governor system

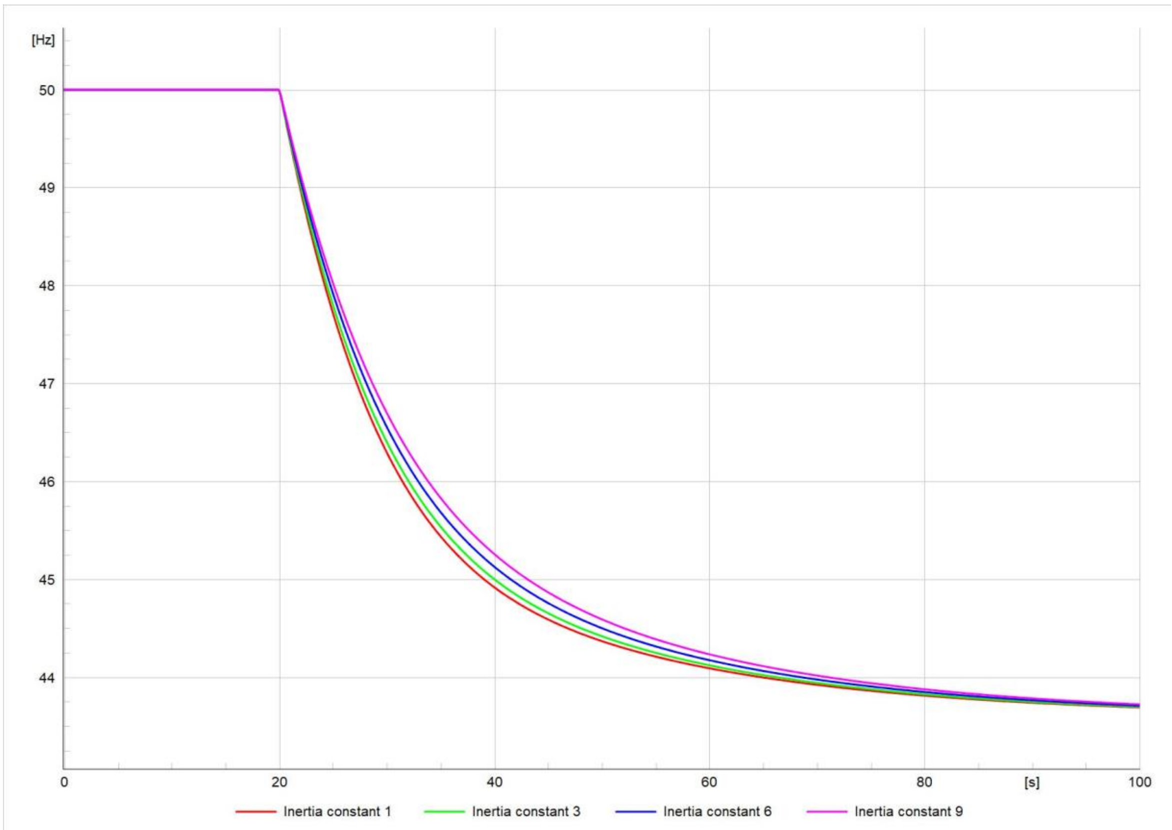

Figure 5.3: Simulation result shows frequency deviation during a load event where an increased total load of 55% were introduced to the system. This simulation does not contain governor controller.

The results presented in figure 5.3 is somewhat similar to the results presented in figure 5.2. The difference can be observed in the minimum frequency, which is below 44 Hz, this is a consequence of the load increase being more than doubled. The effects of the inertia values can also be seen in similarity to the results in figure 5.2, where the higher inertia values have a lower ROCOF, compared to the lower inertia values.

Case 2, using governor system

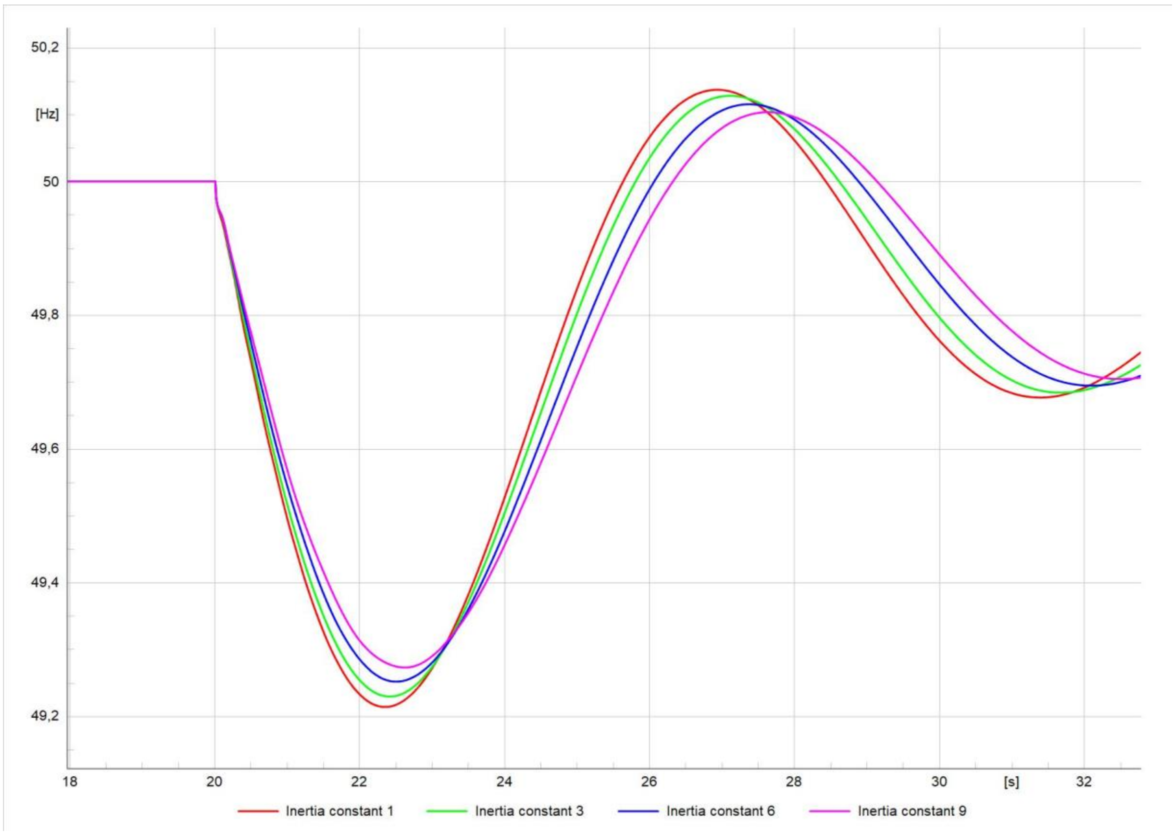

Figure 5.4: Simulation result shows frequency deviation during a load event where an increased total load of 55% were introduced to the system. This simulation contains governor controller.

Figure 5.4 uses the same parameters as the result in figure 5.2, with the difference of an even greater load increase. The result shown in figure 5.4 is characterized in that the maximum and minimum frequency, but also the ROCOF are increased overall, where the purple curve can be observed with significantly lower ROCOF.

5.2 Scenario 2, Synchronous Machine Event

Scenario 2 shows the frequency deviation where the simulation was executed using a Synchronous Machine E vent with a decreased torque value of -0.05 p.u presented in case 1 and a decreased torque value of -0.2 p.u presented in case 2. Both cases include results with and without the government system.

Case 1, no governor system

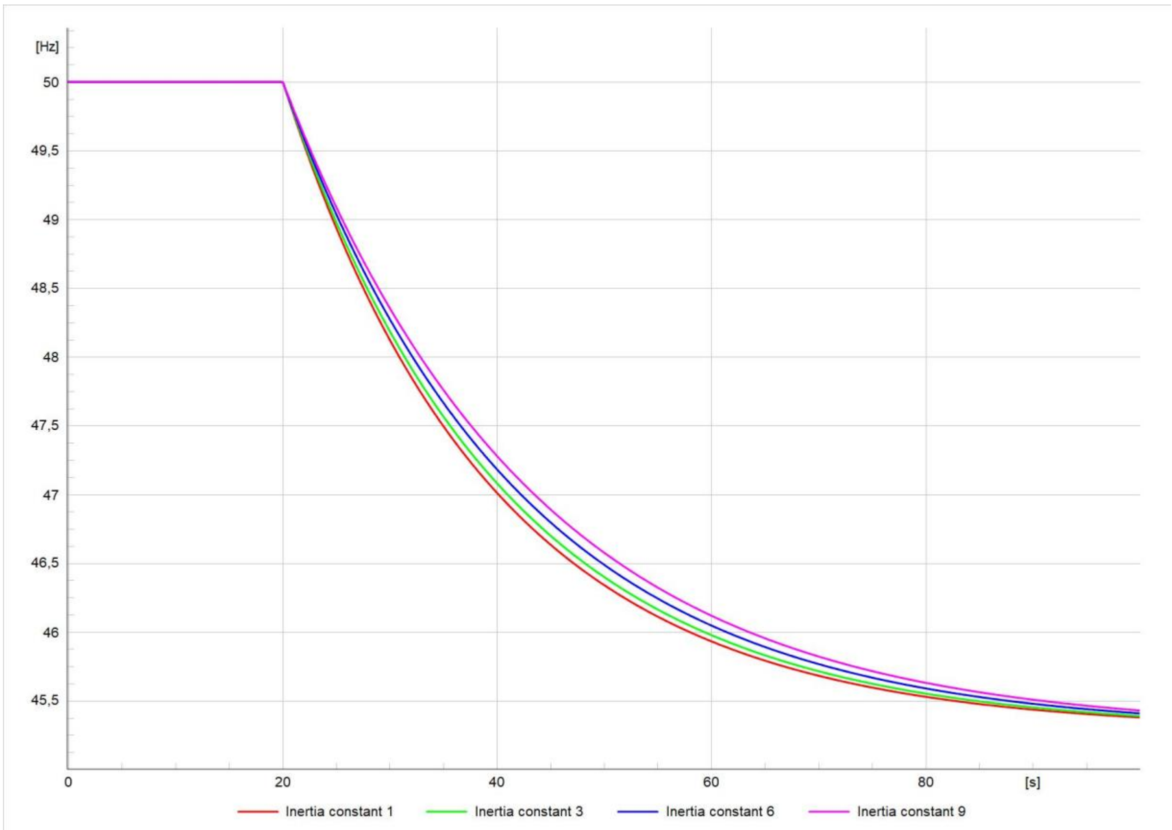

Figure 5.5: Simulation result shows frequency deviation during a synchronous machine event where a decreased torque value of -0.05 p.u in hydro power was introduced to the system. This simulation does not contains governor controller.

Similar to previous simulations without governor, the result in figure 5.5 shows even lower frequency minimum compared to the result in figures 5.1 and 5.3. The explanation for this is that the simulation is based on the hydro power being the largest generator and also governor. The result of lowering the torque in this generator, without having a governor system, generates a catastrophic ROCOF.

Case 1, using governor system

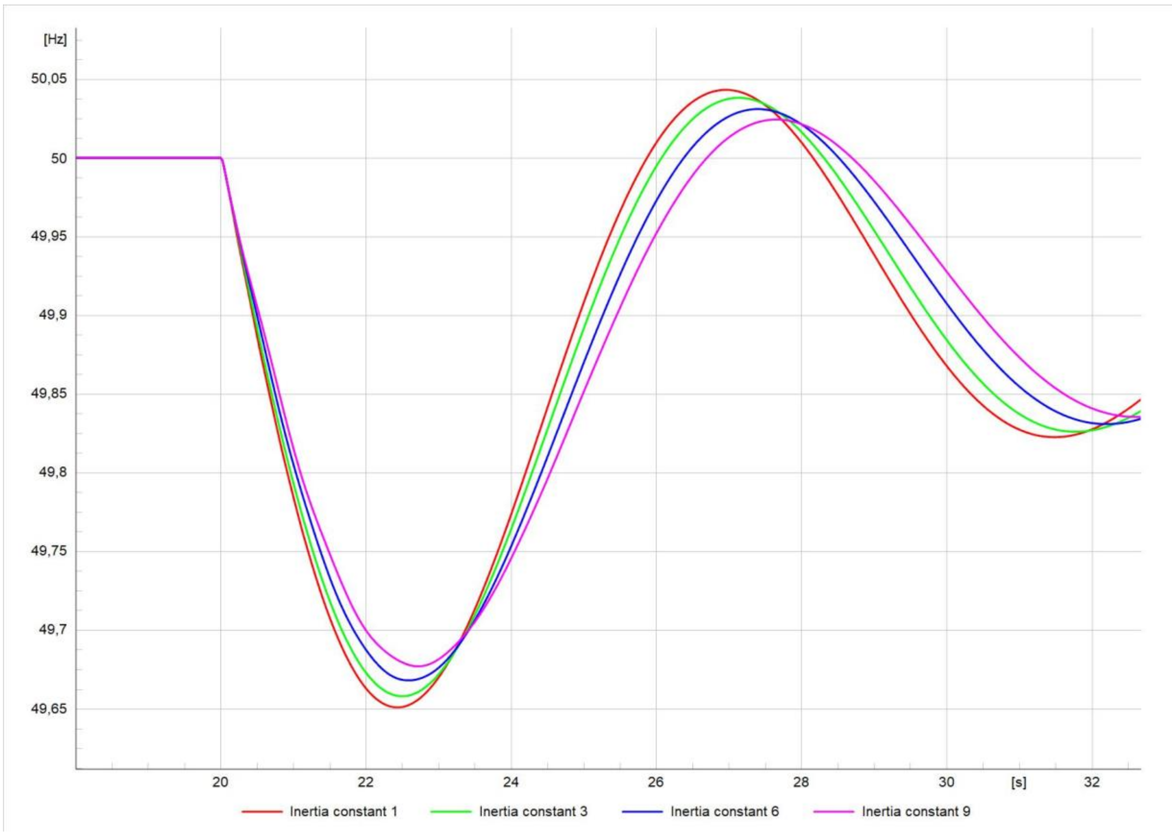

Figure 5.6: Simulation result shows frequency deviation during a synchronous machine event were a decreased torque value of -0.05 p.u in hydro power was introduced to the system. This simulation contains governor controller.

With a lowered torque value in hydro power, simulating less power generated, is presented in figure 5.6. Similar to previous results presented, the lower inertia value has a higher zenith/nadir and ROCOF, while the higher inertia value presents the opposite effect on the result.

Case 2, no governor system

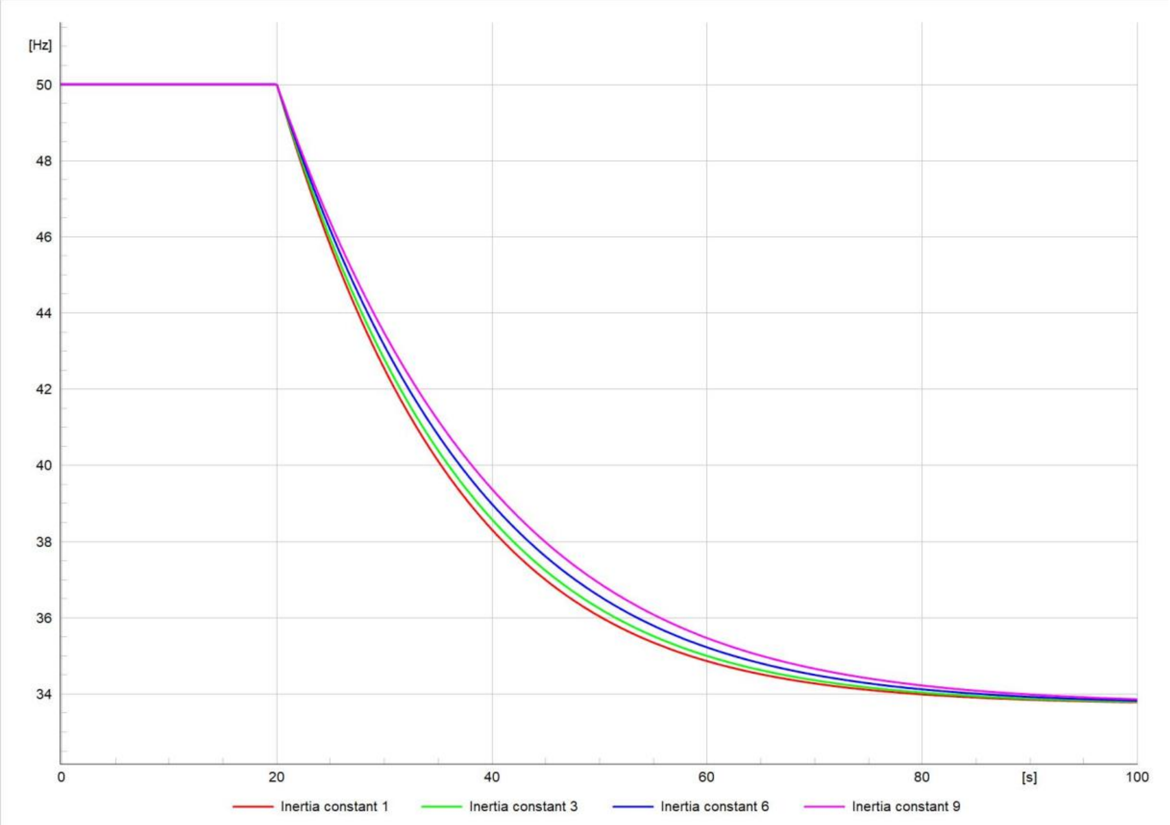

Figure 5.7: Simulation result shows frequency deviation during a synchronous machine event where a decreased torque value of -0.2 p.u in hydro power was introduced to the system. This simulation does not contains governor controller.

Figure 5.7 shows how the frequency is rapidly declining to critical levels because of the lack of governor system. Similar to previous results, by observing the inertia constant with the value 9, the simulation shows that the higher inertia is affected less than the rest of the values. This result is somehow unrealistic since frequencies lower than 48 Hz would have critical impact on a real-life power system.

Case 2, using governor system

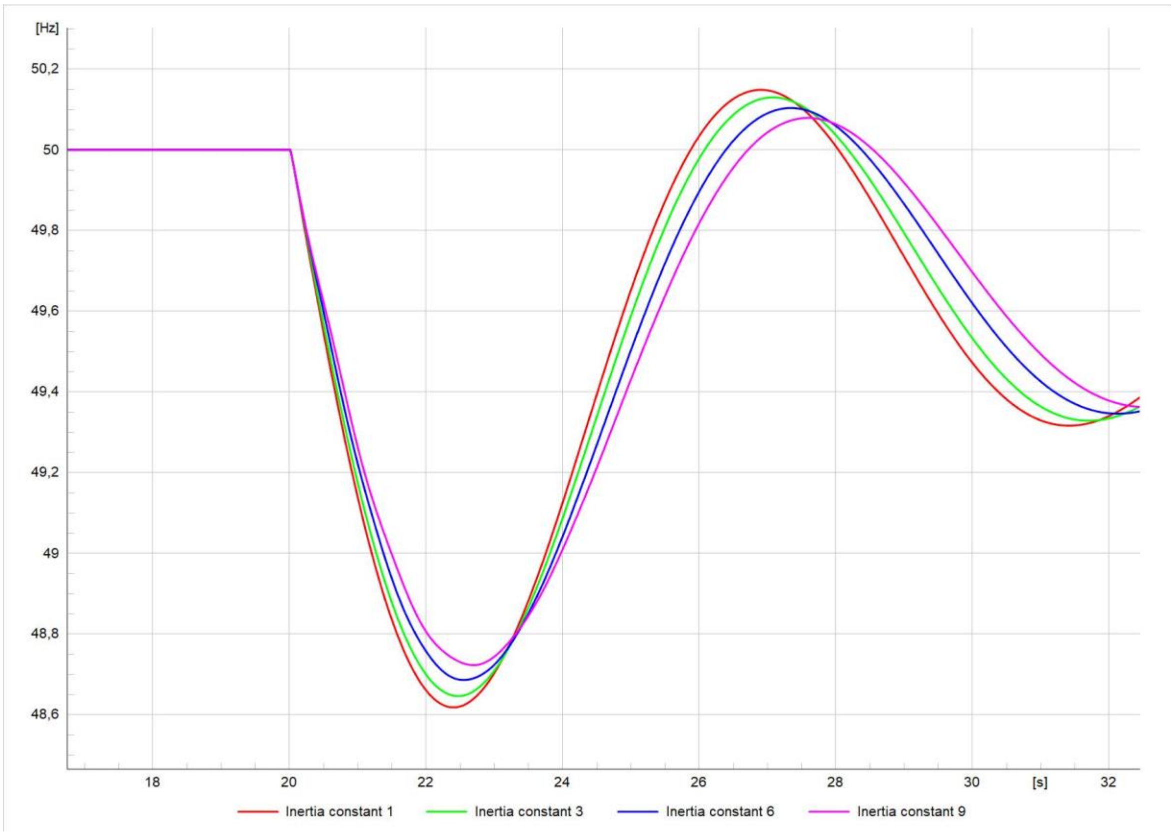

Figure 5.8: Simulation result shows frequency deviation during a synchronous machine event where a decreased torque value of -0.2 p.u in hydro power was introduced to the system. This simulation contains governor controller.

Figure 5.8 shows an even large decrease of torque in hydro power which affect the system in an even large scale. The frequency deviation points to similar results presented in previous simulations where lower inertia values give a higher zenith/nadir and ROCOF, whereas higher inertia has the opposite effect.

5.3 Result summary

The results presented in this chapter shows the simulations run in PowerFactory and how different time constants of inertia can affect the systems frequency deviations. With a higher value of inertia used by wind power in the system, there is a smaller deviation in the disturbances introduced in each scenario and case. This result is present in all simulations that was conducted, where the cases combining inertia control and governor frequency control from hydro power yields a clear visualization of how both the duration and magnitude of the frequency deviation is managed.

6 Conclusion

The results produced by the simulation model proves that a high amount of inertia contributes to lower rate of change of frequency, smaller frequency deviation and an overall more stable and robust power system. The factors contributing to creating synthetic inertia has been developed, tested, and are now used in many wind turbines around the world. Using automatic control systems for pitching to create synthetic inertia is helping the rapid growth of intermittent energy sources without causing issues related to previous concerns. To make the control of wind turbines fully automatic there are more work needed to be done when it comes to large scale wind power but since the rapid expansion of wind turbines has already started, the data and proof needed for its success is soon at hand with the data collected from inertia controllers applied and used for wind turbines. Together with the factors and components of synthetic inertia already being in place and the controllers connected to the converters making pitching and kinetic energy reserves available with just a signal. Synthetic inertia in large scale power systems can be used to maintain a stable frequency with these technologies already installed in Sunne kommun, Sweden where Svenska Kraftnät already procures the needed power to maintain a stable frequency. The result in the simulations prove that the higher amount of inertia added to the wind power inertia controller, the lower frequency deviations will occur in case of large power disturbances in modern power systems. In Sweden, a total of 17% of the electricity produced in 2021 was from wind power, where the majority of the remaining 83% of production came from hydro and nuclear power. Sweden has great possibilities to take a leading role for frequency containment from wind power. This statement aligns well with Sweden’s promise of being fully carbon neutral by 2045, which also includes energy production. This thesis hopes to give a calmer perception of the expansion of wind and solar power in the energy system and help move the development of energy production to a greener and cleaner future but doing so with a robust energy system, which lacks the need for large generators using burnt materials in case of deviations in the power system.

6.1 Future work

The DSL-model for synthetic inertia controller could not be finished during the project but hopes to be implemented in similar projects in the future. For now, the inertia controller in explained in detail since it is widely used in real life wind turbines all over the world.

To represent a better simulation of a real-world power system, more generation sources such as nuclear power could be introduced, together with photovoltaic cells, which shares the similar expansion and challenges as wind power. Further, the simulation can be expanded even more with the use of additional wind power farm, using different variables and wind speeds together with individual control units.

Future works also needs to include theoretical additions where a more complex perspective can be added to the power calculations in combination of the synthetic inertia controller to fully understand the power output of a wind turbine and how this affects the synthetic inertia created from wind turbines at a given moment. This would yield a better understanding of how the power can be increased or decreased as needed, together with certain delays in this power output.

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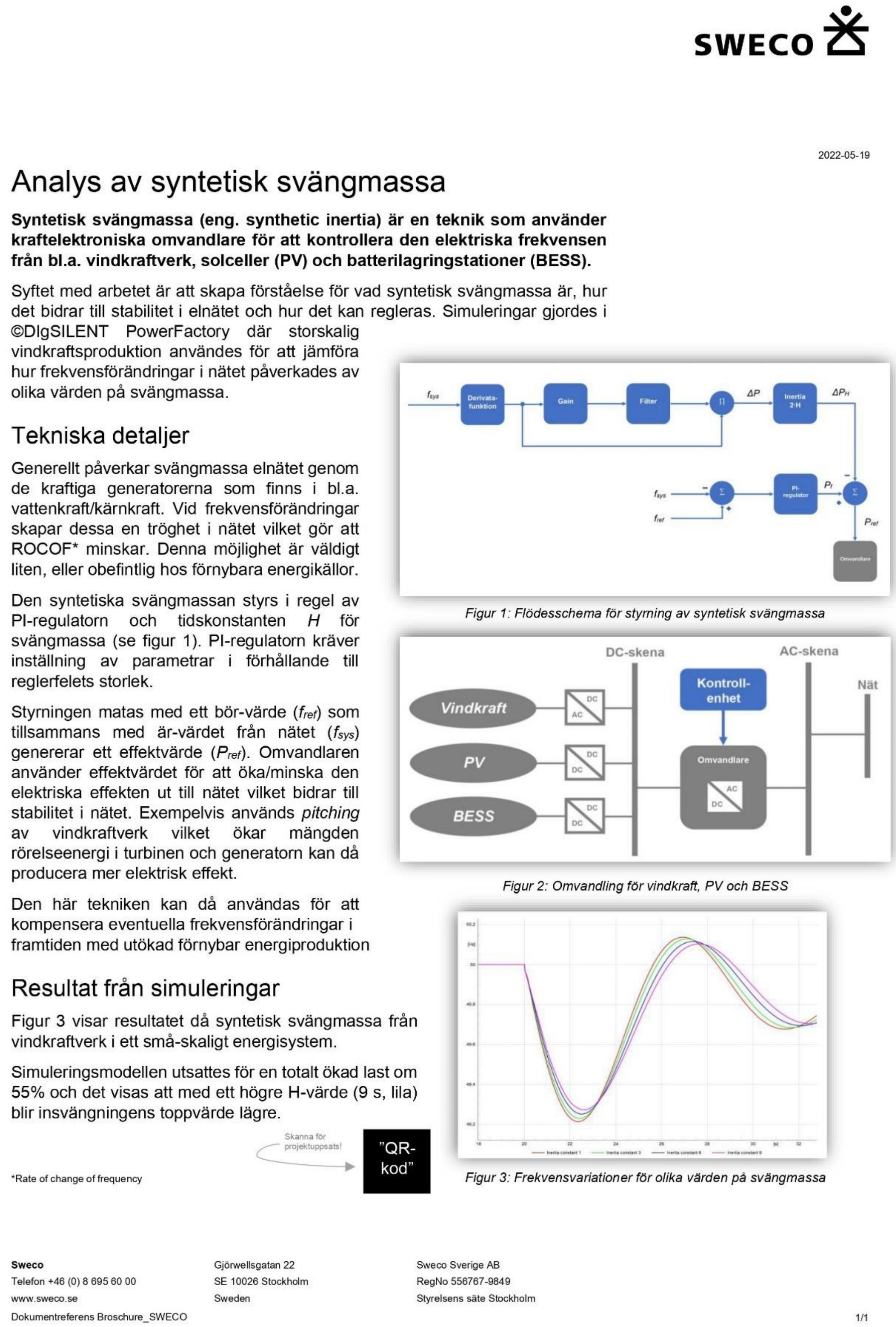
Appendix

Appendix A – Sweco brochure



SWECO

2022-05-19

Analys av syntetisk svängmassa

Syntetisk svängmassa (eng. synthetic inertia) är en teknik som använder kraftelektroniska omvandlare för att kontrollera den elektriska frekvensen från bl.a. vindkraftverk, solceller (PV) och batterilagringstationer (BESS).

Syftet med arbetet är att skapa förståelse för vad syntetisk svängmassa är, hur det bidrar till stabilitet i elnätet och hur det kan regleras. Simuleringar gjordes i ©DIgSILENT PowerFactory där storskalig vindkraftsproduktion användes för att jämföra hur frekvensförändringar i nätet påverkades av olika värden på svängmassa.

Tekniska detaljer

Generellt påverkar svängmassa elnätet genom de kraftiga generatorerna som finns i bl.a. vattenkraft/kärnkraft. Vid frekvensförändringar skapar dessa en tröghet i nätet vilket gör att ROCOF* minskar. Denna möjlighet är väldigt liten, eller obefintlig hos förnybara energikällor.

Den syntetiska svängmassan styrs i regel av PI-regulatorn och tidskonstanten *H* för svängmassa (se figur 1). PI-regulatorn kräver inställning av parametrar i förhållande till reglerfelets storlek.

Styrningen matas med ett bör-värde (f_{ref}) som tillsammans med är-värdet från nätet (f_{sys}) genererar ett effektvärde (P_{ref}). Omvandlaren använder effektvärdet för att öka/minska den elektriska effekten ut till nätet vilket bidrar till stabilitet i nätet. Exempelvis används *pitching* av vindkraftverk vilket ökar mängden rörelseenergi i turbinen och generatorn kan då producera mer elektrisk effekt.

Den här tekniken kan då användas för att kompensera eventuella frekvensförändringar i framtiden med utökad förnybar energiproduktion

Figur 1: Flödesschema för styrning av syntetisk svängmassa

Figur 2: Omvandling för vindkraft, PV och BESS

Resultat från simuleringar

Figur 3 visar resultatet då syntetisk svängmassa från vindkraftverk i ett små-skaligt energisystem.

Simuleringsmodellen utsattes för en totalt ökad last om 55% och det visas att med ett högre H-värde (9 s, lila) blir insvängningens toppvärde lägre.

Figur 3: Frekvensvariationer för olika värden på svängmassa

Skanna för projektuppsats!

”QR-kod”

*Rate of change of frequency

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Telefon +46 (0) 8 695 60 00
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Sweco Sverige AB
RegNo 556767-9849
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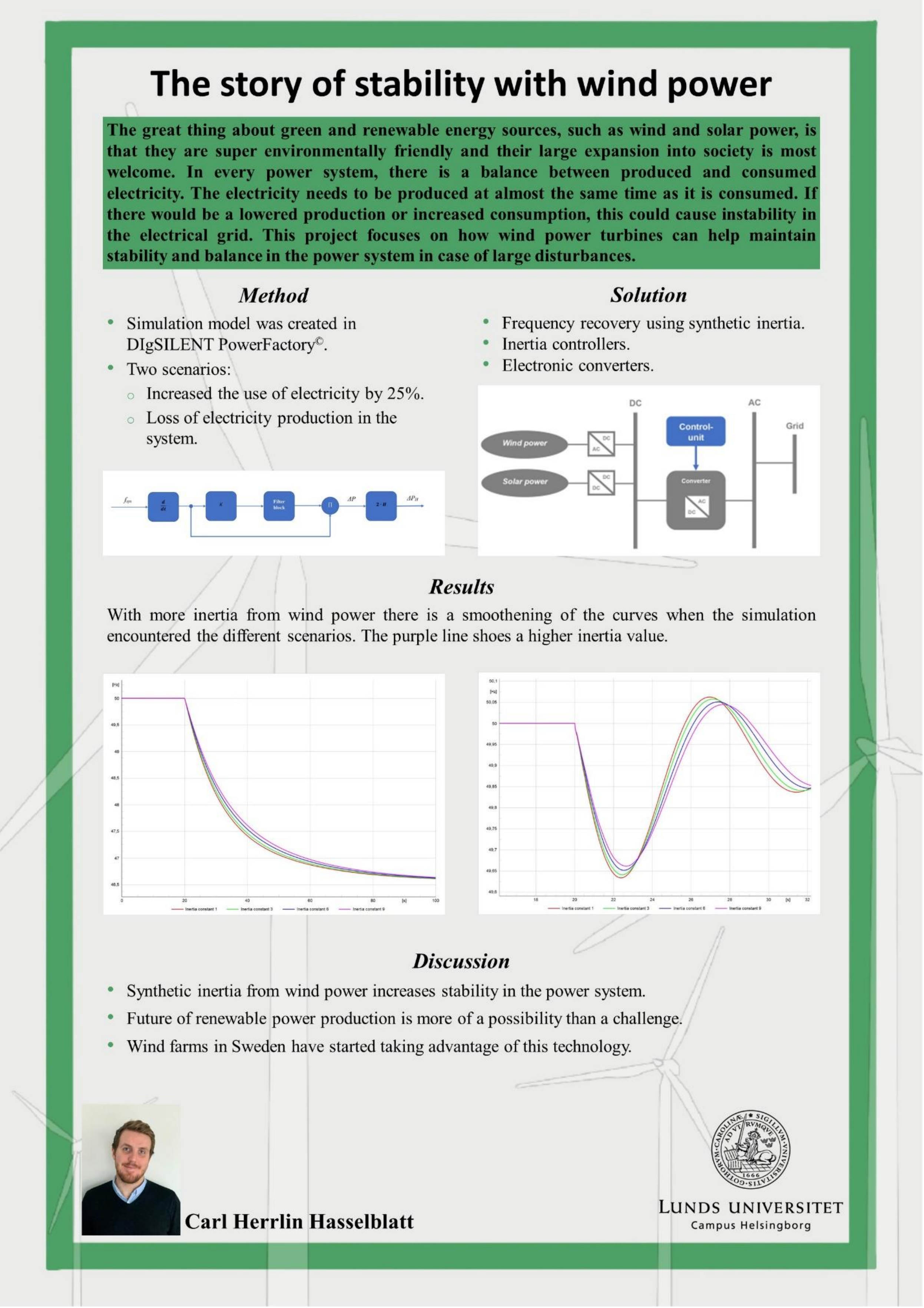
Appendix B – Thesis poster



The story of stability with wind power

The great thing about green and renewable energy sources, such as wind and solar power, is that they are super environmentally friendly and their large expansion into society is most welcome. In every power system, there is a balance between produced and consumed electricity. The electricity needs to be produced at almost the same time as it is consumed. If there would be a lowered production or increased consumption, this could cause instability in the electrical grid. This project focuses on how wind power turbines can help maintain stability and balance in the power system in case of large disturbances.

Method

- Simulation model was created in DIgSILENT PowerFactory©.
- Two scenarios:
  - Increased the use of electricity by 25%.
  - Loss of electricity production in the system.

Solution

- Frequency recovery using synthetic inertia.
- Inertia controllers.
- Electronic converters.

Results

With more inertia from wind power there is a smoothening of the curves when the simulation encountered the different scenarios. The purple line shoes a higher inertia value.

Discussion

- Synthetic inertia from wind power increases stability in the power system.
- Future of renewable power production is more of a possibility than a challenge.
- Wind farms in Sweden have started taking advantage of this technology.

Carl Herrlin Hasselblatt

LUNDS UNIVERSITET
Campus Helsingborg