Load following in a Swedish nuclear power plant

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LUND UNIVERSITY

2020

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June 2020

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Picture on front page: Transmission lines. Photo by Jacob Bjurenfalk

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Preface

This thesis has been taking place during the spring semester of 2020. The project comes from the nuclear company OKG AB in Oskarshamn which is part of the energy concern Uniper, where also parts of the work were performed.

I would like to thank my supervisors at OKG AB with their special knowledge and feedback. Especially thanks to Mikael Olsson who contributed with a lot of feedback and knowledge about the nuclear process and thesis writing, and Mikael Petersson who contributed with helpful knowledge about the simulations.

I also would like to thank my supervisor at LTH, Mats Galbe, who contributed with help for practical matters about the thesis process and feedback for my report.

Additionally, I would like to thank Thomas Probert at OKG AB for the help with transportation to the company and all the interesting conversations we had.

Lastly, I would like to thank the tea machine at OKG for contributing with hot and calming tea in the moments when everything felt hopeless.

Sammanfattning

Sveriges energisystem står inför en stor omställning där andelen el från väderberoende energikällor, så kallade intermittenta, som sol och vindenergi för en allt större del i den totala elproduktionen samtidigt som elproduktionen från stabila energikällor som kärnkraft minskar. Länge har kärnkraften fungerat som baslast och vattenkraften som reglerkraft, men i takt med det förändrande energisystemet kommer befintliga kärnkraftverk att i framtiden behöva övergå till att vara mer flexibla i sin drift och köra lastfölning. Syftet med detta arbete har varit att undersöka möjligheterna för kärnkraftsreaktorn "Oskarshamn 3" att i framtida scenarion köra lastföljning, samt hur reaktorn skulle kunna stödja nätet vid ett eventuellt bortfall av frekvens eller spänning. Scenarion då lasten på elnätet är låg är under nätter, helgdagar och sommarmånader. För att undersöka möjligheterna har kärnkraftprocessen simulerats i simuleringsprogrammet APROS 6.07, där scenariot att sänka effekten under natten varit relevant.

Då utrustningen i kärnkraftverket är optimerad för att köra konstant på maximal tillåten effekt, kommer en sänkning leda till ökad risk för slitage och skador i vissa delar av utrustningen. Komponenter som kan komma att skadas av reducerad effekt är bland annat turbiner, pumpar, ventiler och rör. Mekanismer för skadorna är till exempel erosion-korrosion, utmattning, vibrationer och slitage. I härden finns det begränsningar på hur snabbt och lågt som den termiska effekten kan sänkas eller höjas innan problem med xenonförgiftning och PCI uppstår. Lägsta effektnivå som simulerades var vid 95 %, där 129.1 % är den maximala effekten. Simuleringen gjordes på effektnivåerna 95 %, 100 %, 109 % och 120 %. Från resultatet påvisades en stabil ned- och uppgång i den utlevererade eleffekten från generatorn. En ökad användning av pumpar och ventiler påvisades, vilket kan ge en ökad risk för slitage.

Vidare utvecklades och simulerades även hur kärnkraftverket skulle kunna möta en snabb frekvensminskning från 50 Hz till 49 Hz på elnätet genom att momentant sänka trycket i reaktorn med några bar för att få ut mer ånga till turbinerna, med en så kallad PSPA-enhet (Pressure Set Point Assessment). Från simuleringen konstaterades det att vid en sänkning av nätfrekvensen ökade generatoreffekten för samtliga simuleringar. PSPA-enheten användes också för att undersöka hur generatoreffekten momentant kan öka vid en större spänningsstörning på elnätet genom att sänka trycket i reaktorn.

Summary

The energy system in Sweden is currently under a great transformation, where the part of weather dependent energy sources, so called intermittent sources, like solar and wind power will get greater share in the total production of electricity while the production from stable energy sources like nuclear power is decreasing. For a long time, the nuclear power have been operating at baseload and the hydropower as flexible, though, due to the change in the current power system, nuclear power plants may need to transit to flexible operation and apply load following. The aim with this master thesis has been to investigate the possibilities for the nuclear reactor "Oskarshamn 3" to apply load following for future scenarios and to see how the reactor could support the power grid when there is a potential disturbance in the frequency or the voltage. The scenarios where the load is low on the power grid are nights, weekends and during the summer months. To investigate the possibilities, the nuclear process have been simulated in the program APROS 6.07, where scenarios to decrease the power during the night have been chosen.

Since the equipment in the nuclear power plant is optimized to operate at maximum allowed thermal power, a decrease will most likely lead to increased risks of wear and tear and damages in some parts of the equipment. Components that may become vulnerable with the power decreased are for instance turbines, pumps, valves and pipes. The mechanisms for the damages are for example erosion-corrosion, fatigue, vibrations and wear. In the reactor core, there are also limitations for the rate of how quickly the power decrease and increase can be performed and how low the power can be reduced before problems with xenon poisoning and PCI occur. The lowest simulated power level was at 95 %, where 129.1 % is the maximum power level. The simulations were performed at the power levels 95 %, 100 %, 109 % and 120 %. It could be concluded that the power change gave a stable decrease and increase of the electrical power from the generator. An increased usage of the pumps and valves was shown, which will give an added risk of wear and tear.

Furthermore, simulations about how the power plant could cope with a rapid frequency change from 50 Hz to 49 Hz on the power grid by quickly reducing the power in the reactor with a few bar were performed, with a unit in the control structure called the PSPA-unit (Pressure Set Point Assessment). The simulations showed that the generator power increased when frequency dropped for all simulations. PSPA-unit was also used to investigate how the generator power momently could increase when a larger voltage disturbance on the power grid occurs.

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1 Introduction

The electricity production in Sweden has for a long period of time mainly come from the energy sources hydro- and nuclear power. However, in the last decade, energy from renewable sources like wind power are getting a greater share in the total energy production, which can be seen in *figure 1*.

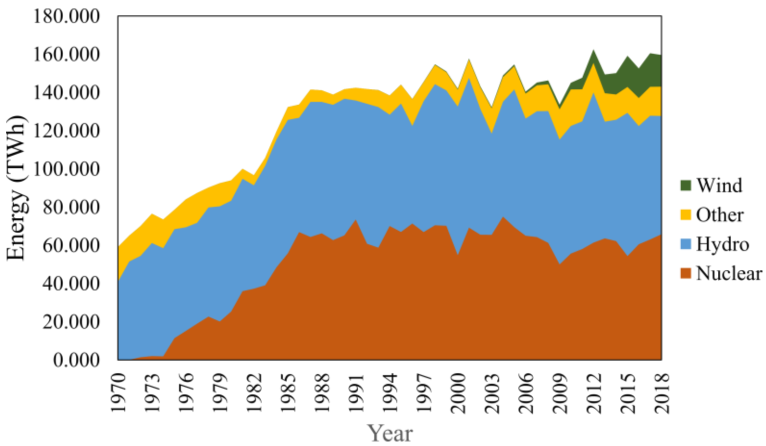


Figure 1: *The yearly production of electricity between 1970 and 2018* ***[1]***

Wind power is considered to be an intermittent energy source, meaning there is fluctuations between high and low energy production due to variations in weather. These fluctuations may give an unbalance in the power grid due to mismatches between the production and consumption of energy. To maintain the grid balance, other energy sources like hydropower and coal power can operate flexible to regulate their energy production to meet the load (energy demand). [2] [3] In Sweden, all nuclear power plants are currently operating in baseload, meaning they are constantly operating at their maximum rated thermal power and maximum rated electrical output. One of the reasons for operation in baseload is that nuclear power plants are considered to have high fixed costs and low variable costs, which make them beneficial to operate at maximum power output. Other reasons are that the operation is simpler, the current design is optimized for baseload at maximum power and that it is easier to predict the plant age and therefore meet the safety margins. [3] [4]

Load following with regards to nuclear power means that the nuclear power plants are operating flexible and change their power output for meeting the load on the power grid, either planed or by automatic control signals. This operational mode is already used today in other European countries, like France and Germany. In France, nuclear power has a share of around 75 % of the total electricity production, which makes it necessary to apply load following when the consumption of electricity is low, such as during weekends. [3]

1.1 Aim

For future energy production, it may be necessary for the Swedish nuclear power plants to start operating in a more flexible manner, employing load following. This master thesis will investigate the possibilities of transition from baseload to load following operation for the Swedish nuclear reactor "Oskarshamn 3" (O3) owned by the nuclear company *OKG AB*. Different scenarios of load following will be simulated, and physical and operational parameters will be analysed and discussed in regards of how they will affect the process. In addition, problems that may occur will be discussed, and in what way they could make an impact on the existing equipment.

1.2 Predisposition

First, there will be an introduction to the thesis. Thereafter in chapter 2, a literature review about the nuclear process is presented. In chapter 3, the methods that are used will be described. For chapter 4, there will be an explanation about the Swedish power system, the contribution with nuclear power and possible scenarios for employing load following. In chapter 5, the impacts and limitation for load following on the nuclear processes will be given presented together with the simulations that will be performed. The simulation results will be given in chapter 6 and the discussion in chapter 7. Lastly, in chapter 8, the conclusion for the work will be presented.

1.3 Demarcation

The thesis will not cover the economical aspect of load following. Neither will extensive calculations of the reactor core or the impact of specific components be performed. The aspects of safety and particular safety system in regards of load following will neither be discussed. This thesis will not give any confidential information from *OKG AB.*

2 Nuclear process

The nuclear process may be divided in two different sections, where the *nuclear reactor* generates the thermal energy for the nuclear reactions and the *turbine island* generates electricity from the produced thermal energy.

2.1 Nuclear physics

To understand how the nuclear reactor can produce thermal energy from radioactive materials, the fundamentals of nuclear physics will be given.

The atom nucleus consists of two different elementary particles, protons and neutrons, called nucleons, where electrons circulate around the nucleons. The total mass of the nucleons constitutes the atomic mass number which is the sum of all neutron and protons. The number of protons determines the element of the atom, while the number of neutrons may vary. Different numbers of neutrons for the element are called isotopes. Examples of simple isotopes are the ones of hydrogen, ^{2}H and ^{3}H, which consist of one respectively two additional neutrons from the more commonly occurring ^{1}H with only one proton. The atom structure of deuterium, ^{2}H , can be seen in *figure 2*. [5]

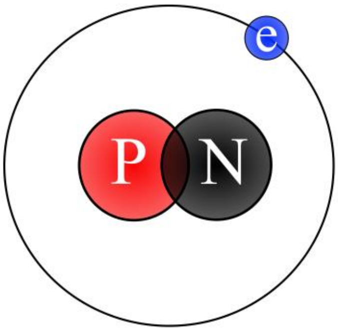


Figure 2*: The structure of ^{2}H (deuterium), where P is the proton, N is the neutron and e is the electron*

Many isotopes are unstable in nature and will therefore decay after some time. These isotopes are called radioisotopes. Radioisotopes can even though they are unstable, be found naturally in nature where there usually is a ratio between the different isotopes of the same element. [5]

The radioactive decay is the spontaneous transformation of the nucleus. The decay is usually denoted as the *half-life*, which is the time it takes for half the number of atoms in a sample to decay. When an atom decays, it will move from one quantum state to another, where there will be an energy difference between the two states. This energy will be released, yielding electromagnetic radiation and kinetic energy as products. The radioactive decay can be divided in three different categories, *alpha-decay*, *beta-decay* and *gamma-decay*, depending on their characteristics.

For the *alpha-decay*, a helium atom is emitted from the original atom; thus, the product of the decay will be two atoms with the sum equal to the original atom. The *beta-decay* is a bit more complex compared to *alpha-decay* since it can either be electron emission or positron emission. In the electron emission, a neutron is converted to a proton with an electron or beta-particle emitted together with an anti-neutrino. In the positron emission, a proton is converted to a neutron and a positron and a neutrino. With regards to beta-decay, electron capture (EC) can also take place, where an atom captures an electron from its inner orbital and changes a proton to a neutron, meanwhile an electron neutrino is emitted. When either alpha or beta decay have occurred, the nucleus of the atom will be in an excited state. When the atom goes from the excited state to its ground state, energy is released as either *gamma-rays* or internal energy conversion. [6]

In the nuclear reactor, *fission* is the mayor nuclear reaction that takes place. Briefly described, an atom is hit by a neutron and thus divided into two smaller atoms. During the split, energy and a couple of free neutrons are released. The free neutrons then hit new atoms and thus a chain reaction takes place. In commercial nuclear reactors, the isotope uranium-235 (^{235}U) is commonly used as fuel for the fission process together with the natural occurring uranium-238 (^{238}U) that does not split when absorbing a neutron. In nature, the uranium ore contains a concentration of 0.7 % ^{235}U and when used as a fuel in nuclear reactors, it must be enriched to around 3-5 %. In *figure 3*, an example of the fission of ^{235}U is shown. [7]

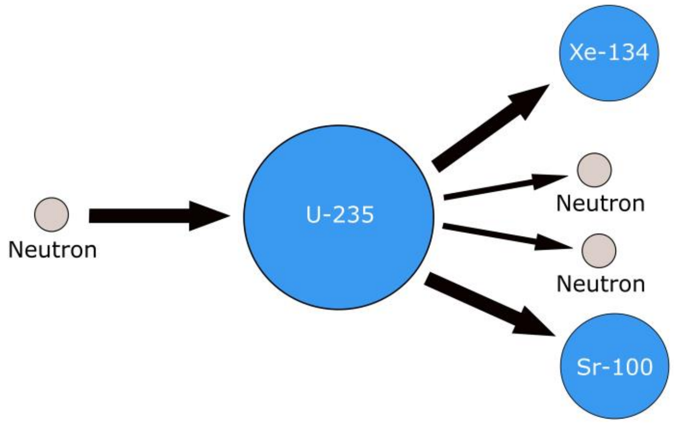


Figure 3: *Fission of Uranium-235 where Xe-134, Sr-100 and two neutrons are the fission products*

For the fission reaction to occur, a neutron needs to be absorbed by the atom's nucleus. Neutrons are neutrally charged particles and therefore it is relatively easy for them to diffuse into the nucleus since there are no coulombic forces from the atom. Different isotopes of an element have different probabilities of absorbing a neutron which is measured as the *neutron absorption cross-section.* The cross-section varies a lot between different nuclides, where elements like boron and gadolinium have a large cross-section and carbon have a small cross-section. As an example, the natural occurring isotope uranium-238 that are found in the nuclear fuel, turns into plutonium-239 when a neutron is absorbed.

[8] The isotopes of plutonium can then be used as a fissile fuel in the reactor. [9] Usually the neutrons that are formed under the fission reaction have too high kinetic energy to be able to get fully absorbed by other uranium nucleus. Therefore, a moderator is used for slowing down the neutrons, where heavy water, normal water or graphite are most used. [7]

2.2 Nuclear reactor

In Europe, the most common type of nuclear reactors in use today are *light-water reactors, LWRs*, where the two most common types are either the *boiling water reactor, BWR*, or *the pressurised water reactor, PWR*. Since "Oskarshamn 3" is a BWR, the focus in this thesis will only be on this reactor type.

Simply described, the process that follows in the reactor is that the fission reaction occurs between the *fuel rods*, where thermal energy will be released to the water circulating between them. The water circulates with the help of the *main recirculation pumps*. The *control rods* and the *main recirculation pumps* are used for achieving control of the fission reaction and the steam that is produced dries in the *steam separator* and *steam dryer* before it enters the turbine island. *Figure 4* shows how the reactor of a BWR looks like with its main components. [10]

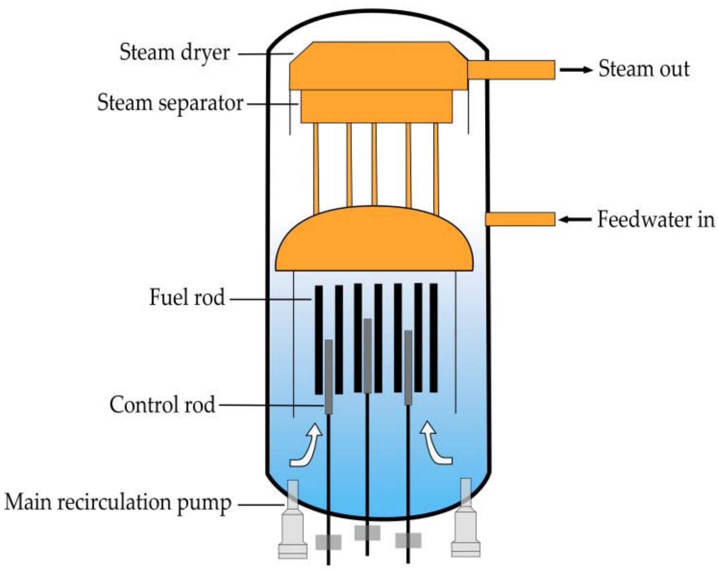


Figure 4: *Simplified drawing of a BWR with its main components*

"Oskarshamn 3" is of the model BWR75, built by ASEA-ATOM and put in operation the year 1985. When initially built, the thermal power was set to a maximum of around 3020 MW, with a generated net power of 1050 MW. During the years, there have been upgrades to the current reactor and turbine island; thus, the maximum thermal power today is 3900 MW with a maximum generated net power of 1400 MW to the grid. [10] Due to the upgrade of the reactor and turbine island, the maximum thermal power in percentage is more than 100 %. When operating at full rated thermal power, it operates at 129.1 %, where the power in the reactor is measured as the *average power range monitor, APRM*. [11]

The nuclear fuel consists of small cylinders containing uranium dioxide, which have ceramic properties and high melting temperature. These small cylinders are stacked on each other in long pipes called *fuel rods*. The fuel rods are usually made of zirconium alloy which is stable against corrosion, a poor neutron absorber and has a high mechanical strength. The fuel rods are then bundled together to form a fuel assembly. Between both the assemblies and each individual fuel rod, there are channels for water to flow between. The water works both as a moderator to slow down the neutrons and as a coolant. [12]

During the fission chain reaction, the number of free neutrons continuously increases. To have control of the process, the number of free neutrons need to be in balance. For the determination of the neutron balance, the multiplication number, k, is used, which gives the net value of neutrons produced in one cycle. When the reactor has neutron balance, the ratio between produced and consumed neutrons should be equal to one, $k=1$, which also mean that the system is critical. When the ratio is greater than one, $k>1$, there is an increase in the neutron population, denoted supercritical, while when less than one, $k<1$, there is a decrease in the neutron population, denoted subcritical. [9] To control the neutron balance, the *main recirculation pumps* and the *control rods* are used. The control rods are shaped as crosses and can be inserted between the fuel assemblies. They are made of stainless steel and boron carbide, where the steel serves as a cladding and protection for the good neutron-absorber boron carbide. The fuel assemblies together with the control rods are often mentioned as the *reactor core*. [12]

The *main recirculation pumps* both cools the reactor core by circulating water over the fuel assemblies and controls the thermal reactor power. When increasing the flow rate of the recirculated water, the temperature of the water becomes lower, which increases the density so that neutrons from the fission process passing through the water slows down and the reactivity increases; thus, the thermal power increases. If there is an increase of the water temperature, the thermal power will automatically decrease. In “Oskarshamn 3”, there are eight main recirculation pumps. [12]

The steam generated in the reactor needs to dry before it enters the turbine island. The reasons for this are the requirements to increase the efficiency, minimize erosion and decrease the amount of corrosive radioactive products in the downstream equipment. For this purpose, *steam separators* and *steam dryers* are used. The steam leaving the steam separators generally contains between 0-10 wt-% water and enters the steam dryer where the water content is decreased to less than 0.1 wt-%. [12]

2.3 Turbine island

As explained earlier, the *turbine island* is the part of the process where electricity is generated. This is performed by letting hot and pressurised steam expand over the *high-pressure turbine* and the *low-pressure turbines*, which will rotate the shaft connected to the *synchronous generator* that produces electricity. The expanded steam is then condensed in the *condenser*, using seawater as coolant. The condensed water is then pressurised with the *condensation pumps* and is pre-heated before it enters the *feedwater vessel*. The feedwater vessel serves both as a storage vessel and a heater, using drainage from the *re-heaters* and *pre-heaters* for additional heating. The water is then pressurised with the *feedwater pumps* and additionally pre-heated before it enters the reactor vessel. A simplified process flowsheet diagram is presented in *figure 5*.

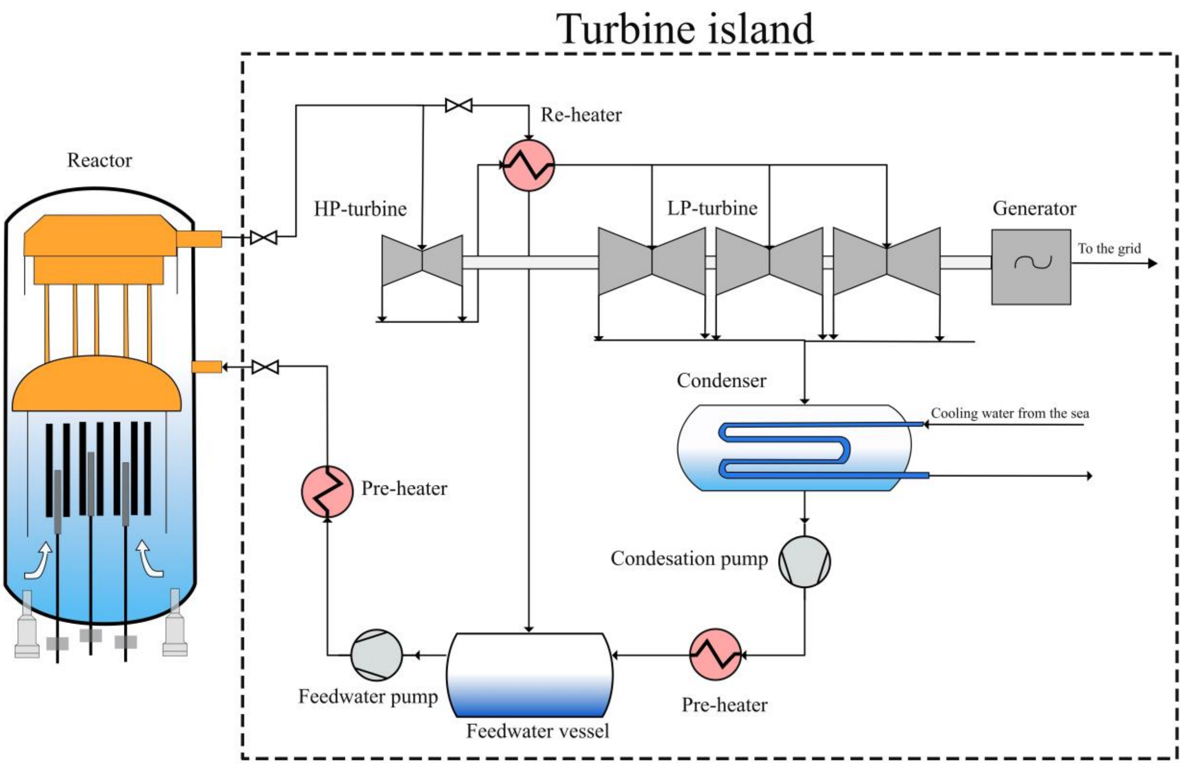


Figure 5: *Process flowsheet diagram for the turbine island* ***[10]***

2.3.1 Rankine cycle

To determine the maximal theoretical energy that can ideally be achieved in a steam-generating power plant, the ideal thermodynamic cycle called the *Rankine cycle* is commonly used. In *figure 6*, the Rankine steam-cycle for a nuclear power plant equipped with a BWR and re-heating is shown in a Temperature-Entropy diagram.

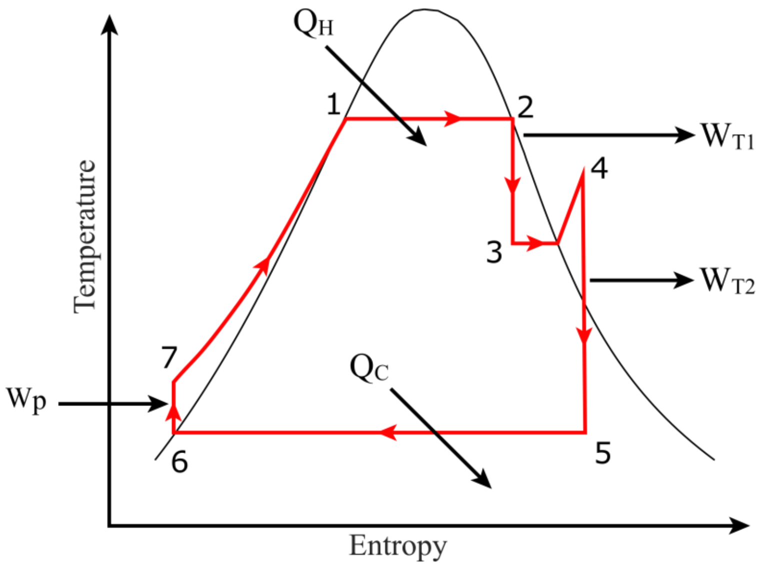


Figure 6: *The red line is the idealised thermodynamic Rankine cycle for the nuclear process. The black curve is the saturation line for water-steam.* Q_H *is the heat supplied to the system,* Q_C *is the heat removed from system by cooling,* W_{T1} *and* W_{T2} *are the work obtained from the system and* W_P *is the work needed for the pumping.*

The red lines represent the water-steam cycle and the black curve represents the saturation line for water-steam. From **1** to **2**, the water in the reactor vessel evaporates isobarically to saturated steam at an over pressure of 6.9 MPa, where Q_H is the energy supplied from the nuclear fission reactions. The steam then expands isentropically in the high-pressure turbine to produce shaft work (W_{T1}) in **2** to **3**. In order to increase the efficiency in the plant, the steam is re-heated in **3** to **4**, before it expands isentropically over the low pressure turbines in **4** to **5**, where more shaft work is produced (W_{T2}). In **5** to **6**, the steam isobarically condenses to water, where Q_C is the energy transferred to the cooling water. The water is then pressurised in **6** to **7** and pumped to a higher pressure where W_P is the work consumed by the pumps. Lastly the water is pre-heated to its saturation temperature in **7** to **1**. [11]

2.3.2 Turbines

As already mentioned, the steam first passes through the high-pressure turbine before it enters the low-pressure turbines. In the high-pressure turbine, ideally around 40 % of the total work is obtained, and then the steam is re-heated to reduce its wet content. Then the steam hits the three low-pressure turbines for additional expansion and more thermal energy converts to mechanical energy, where each low pressure turbine gives 20 % of the total work. All turbines are using double flow, meaning the steam enters in the middle of the turbines and expands on both sides. In "Oskarshamn 3", there are one high-pressure turbine and three low pressure turbines. [12]

2.3.3 Synchronous generators

In nuclear power plants, synchronous generators are used for the conversion of the mechanical energy to electrical energy, where the electrical energy comes in the form of an *alternating current, AC*. An alternating current have a periodic change in its instantaneous voltage, compared with its counterpart *direct current*, *DC*, that have constant voltage. The instantaneous voltage, *v*, for AC can be described with the formula below, *equation 1*,

$$\nu = V_{max} \cdot sin(\omega \cdot t) \quad (1)$$

where V_{max} is the maximum voltage, *t* is the time and *ω* is the angular velocity given by,

$$\omega = 2 \cdot \pi \cdot f \quad (2)$$

where *f* is the frequency. For a synchronous generator, the mechanical energy provided by the turbines rotates a shaft, which makes a rotor surrounded by a stator rotate. The rotor consists of a magnet, either permanent or electrically magnetised, with a minus pole and a plus pole. The stator contains coils that together with the rotor create an electric field. From the coils, electrons are transferred to the transmission line, which gives an electrical current. In power plants, three-phase generators are used, meaning that there are three individual coils, each of them producing an AC-current. The rotation speed of the shaft gives the frequency for the current and the correlation between them is given by the equation below,

$$n = \frac{f}{p} \cdot 120 \quad (3)$$

where *n* is the rotation speed per minute, *f* is the frequency and *p* is the number of poles. In *figure 7* the rotor and the stator are shown. [13]

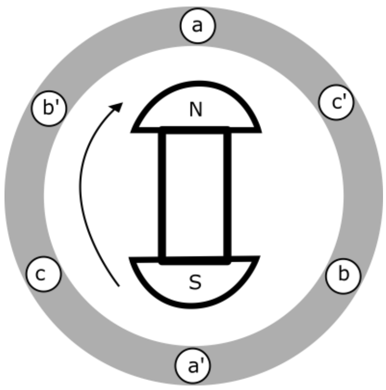


Figure 7: *A simplified drawing of a generator with the rotor in the middle and the coils surrounding, for the three-phase system.*

3 Methods

The methods for evaluating the possibility of load following in "Oskarshamn 3" consist of different steps where each individual step will give important information to the next one. First, there will be an analysis for which scenarios load following can be applicable. Secondly, there will be an analysis of different limitations in the existing plant and components that may get affected when applying load following. Thirdly, simulations are performed for the analysed scenarios to find out how the components of the plant will be affected. Lastly, a discussion with evaluations and recommendations is presented of how well load following works for the nuclear power plant in respect to the simulations. In *figure 8*, the procedure for the methods is given.

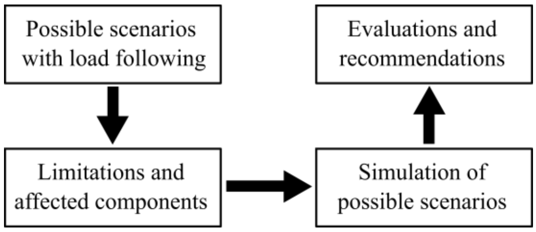


Figure 8: *Methods for evaluating the possibility of load following in "Oskarshamn 3"*

Possible scenarios with load following

The possibilities of load following are plenty and differs between different power grid system. First, an overview of what the current Swedish grid system looks like and how it is operated is given. Subsequently, a discussion of the energy production, its demand and its variations during days, weeks and seasons. Furthermore, there will be an analysis about the future energy production and supply, where intermittent energy sources will have a great impact. It will also be investigated how the nuclear power plants affect the current grid. From this information, suggestions to possible scenarios for load following will be given.

Limitations and affected components

From previous experiences in other nuclear power plants and from literature, the limitations of load following for BWRs will be given. Also, on-site experiences with "Oskarshamn 3" will give additional information that will be needed for this. The analysis of potential affected components will be given from both literature and previous experiences together with on-site knowledge.

Simulation of possible scenarios

The simulations for load following in the nuclear reactor Oskarshamn 3 will be carried out with the simulation software APROS 6.07. APROS 6 is used in nuclear and combustion industries where it can be applied for assuring projects to reach the maximum safety and operational performance. It will in this thesis be used for investigating the possible impact on the process for different scenarios with load following. As for every simulation software, it is important to understand the mathematics and models that are being used to know its limitations. Detailed explanations about the mathematics behind APROS 6 can be found in "The constitutive equations of the Apros six-equation model" (Hänninen, M; Ylijoki, J & Kurki, J). [14]

Evaluations and recommendations

From the simulated results, there will be an evaluation and discussion of impacts on the nuclear process.

4 Possible scenarios for load following

For operation in load following, good understanding of the current energy market and production in Sweden is needed to know when load-following should be applied.

4.1 Swedish power grid system

The Swedish power system is based on the energy producers, the energy consumers and the power grid. The governmental company responsible for maintaining a stable grid is *Svenska Kraftnät (SvK)*. They must to by law maintain the balance between the production and consumption of electricity in Sweden. To manage bottle necks that may occur in the power grid system, the country is divided into four different electricity regions, which can be seen in *figure 9*.

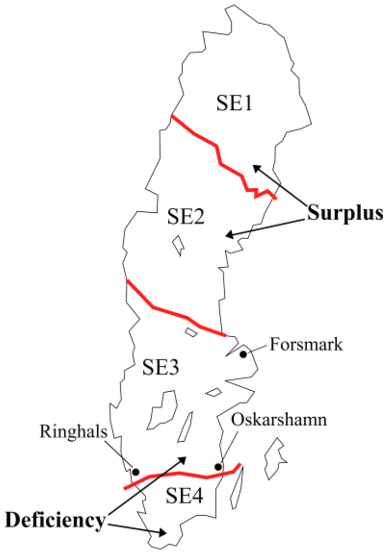


Figure 9: *The four electricity regions in Sweden, SE1, SE2, SE3 and SE4, and the locations of the currently operating nuclear power plants* ***[15]***

In the regions SE1 and SE2, there is a surplus of electricity and most of the hydropower is produced here. In SE3 and SE4, there is a deficiency of electricity where most of the power is consumed. All nuclear reactors that are currently operating in Sweden can be found in the region SE3 and their locations have been chosen in order to give good stability and electricity transfer from the regions with surplus of electricity to regions with electricity deficiency. [16]

4.1.1 Production and consumption

For the year of 2018, nuclear power had a total share of 41 % of the total electricity production in Sweden and hydropower had a total share of around 39 %, as may be seen in *figure 10*.

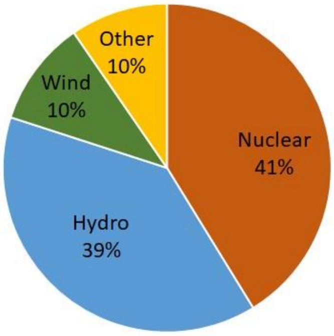


Figure 10: *The share of electricity production in Sweden 2018 for different energy sources* ***[1]***

Wind power had a total share of around 10 % and other energy sources like thermal energy had a total share of around 10 %. From this information, it can be noted that as yet the nuclear power is still one of the main energy sources of electricity production in Sweden.

The electricity production and consumption are constantly fluctuating every hour, day and week and will therefore give obstacles for the grid planning. In *figure 11*, the electricity production and consumption during one weekday day in February can be seen.

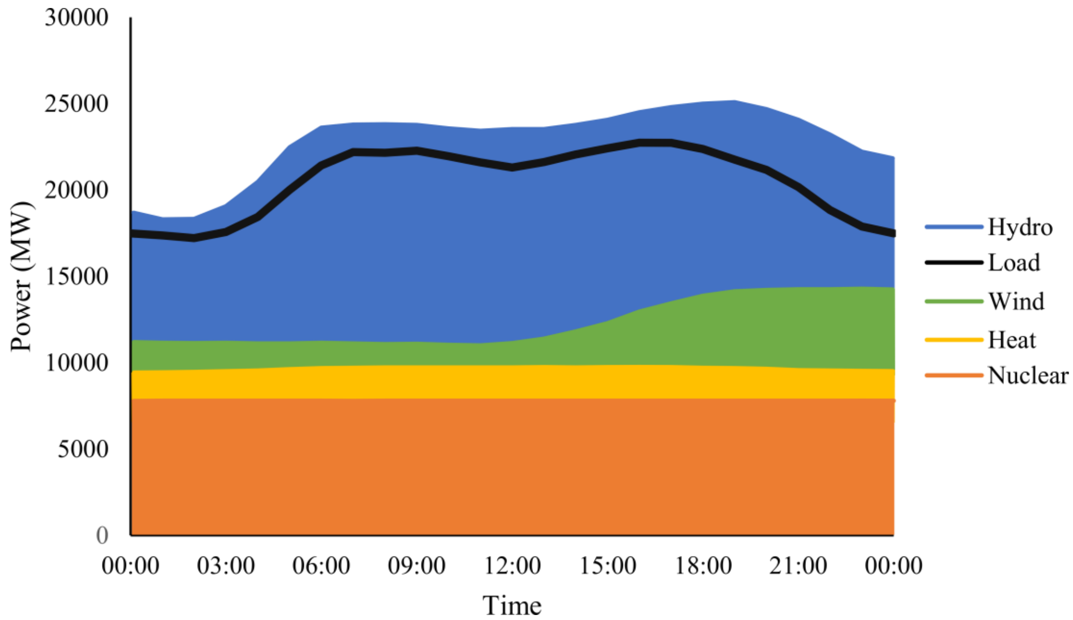


Figure 11: *The electricity production and consumption in Sweden for 4th of February 2020. The load is the consumption of electricity and hydro, wind heat and nuclear are the energy sources for the production of electricity.* ***[17]***

From *figure 11*, it can be concluded that the demand of power peaks at two times, one around 6:00 AM in the morning and one around 16:00 PM in the afternoon. The consumption is also higher during the day and drops during the night. The total electricity production follows the shape of the load, though with a surplus of energy. *In figure 12*, the production and consumption for each hour during a week in February can be seen.

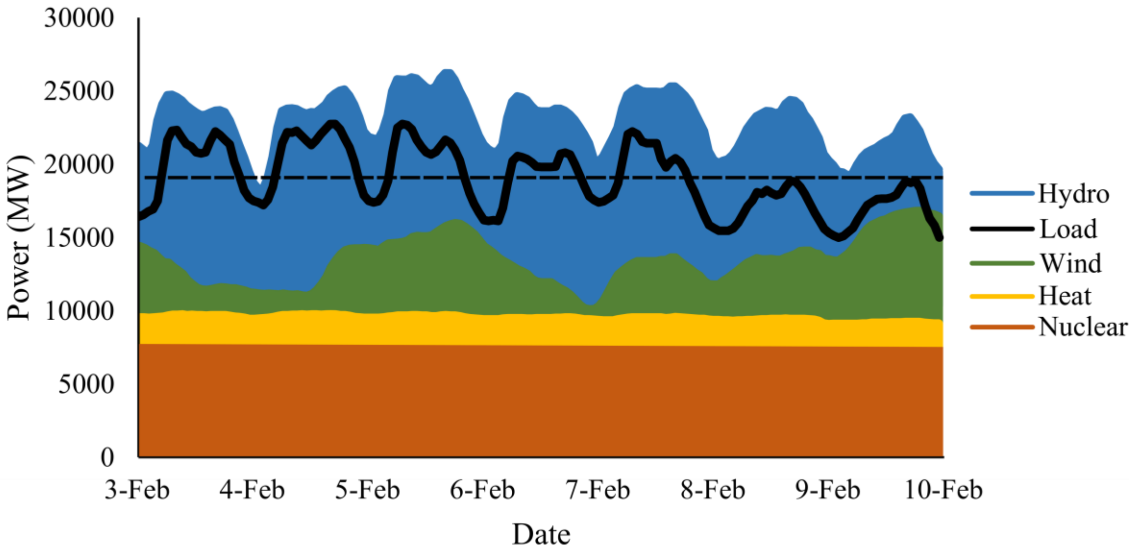


Figure 12: *The electricity production and consumption in Sweden for one week in February 2020, where the load is the consumption of energy in Sweden and hydro, wind, heat and nuclear are the energy sources for the production. The dashed line indicates the peak of consumption during a weekend.* ***[17]***

As can be seen in *figure 12*, the total electricity consumption is constantly shifting during a normal week. The energy consumption is significantly lower during the weekends compared to the consumption during a normal weekday. The figure also displays the amount of power each energy source produces during a week. Nuclear power contributes with the same amount of power during the whole week, regardless of the time of the day; thus, it operates as baseload. However, the intermittent wind power fluctuates constantly in power production and do not follow the variations of the load. Lastly, the hydropower can be seen operating flexible; thus, it follows the load during the whole week.

Both the production and the consumption of electricity differs each month of the year. It is decreasing during the summer and increasing during the winter. The monthly production and consumption for a year in Sweden can be seen in *figure 13*.

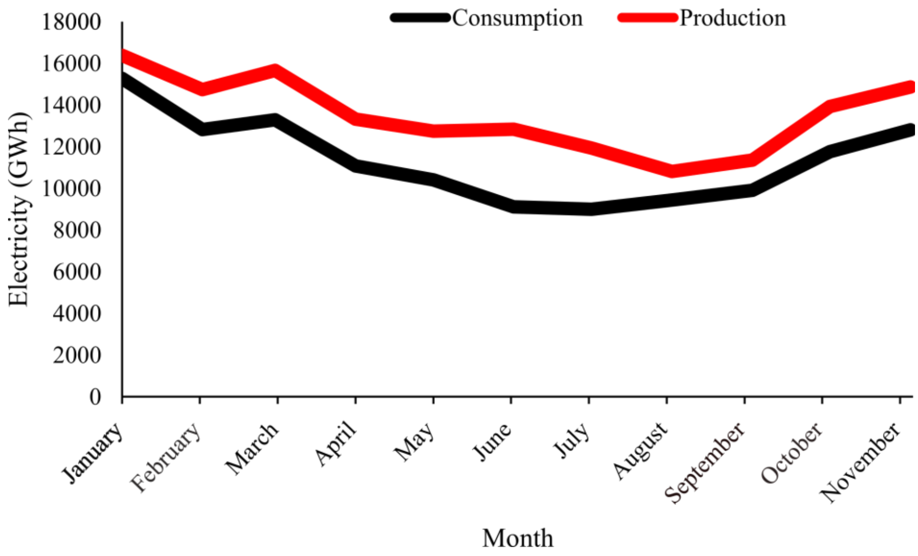


Figure 13: *The energy production/consumption monthly for the year of 2019* ***[18]***

4.1.2 Mechanical inertia in the grid

When there is fluctuation in the balance between consumption and production in the grid, the power generating units need to be regulate to compensate this. Due to a time delay between the fluctuation and the action of compensation, the frequency in the grid may fluctuate. Today, these fluctuations can be minimized with the help of rotating parts in turbines and synchronous generators that are continuously rotating. The rotational parts serve as a short-term buffer due to stored rotational energy. The speed of rotation is connected to the grid frequency. When there is a shortage in energy production, the grid frequency will decrease as well as the rotational speed. When the frequency increases, the rotational speed will also increase. These phenomena, which is called *mechanical inertia*, will slow down the rate of frequency change and therefore minimize frequency deviations. The more rotational units connected to the grid, the more inertia, which makes the grid more stable to rapid power changes. In *figure 14*, it can be seen how the turbine and the synchronous generator serve as a buffer between the energy production and consumption. [19]

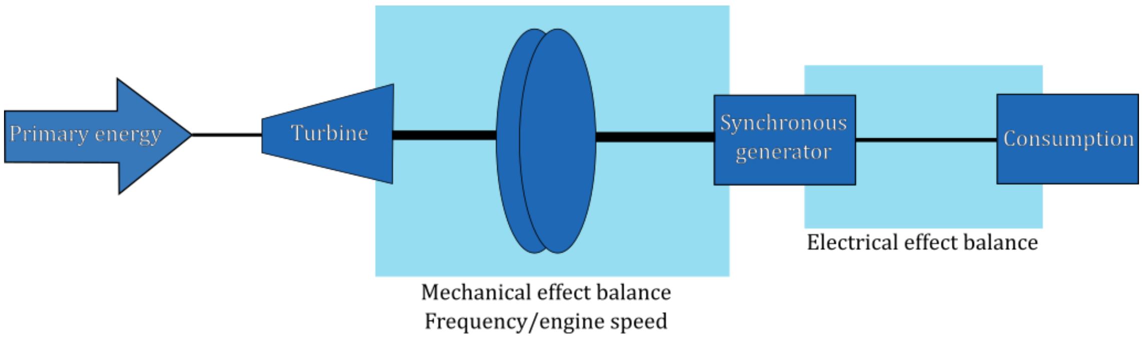


Figure 14: *The balance between production and consumption of power for rotational units* ***[19]***

With an increasing share of renewable energy sources like wind and solar power, the total inertia will decrease since these energy sources work in a different way. Even though wind turbines may have a rotational turbine, most of them are using AC-converters to generate power to the grid and therefore the rotational speed is not directly connected to the frequency of the grid. Solar cells are constructed without any rotating parts; thus, they will not contribute to the inertia. [19]

It is not only power generating units that contributes to the inertia, but also consuming units such as electrical motors that are directly connected to the grid will give some inertia. When there is a production shortage and the frequency decreases, the motors will rotate slower and as a result use less energy, which then will decrease the energy consumption. Currently, there is a trend where these directly connected motors are changed to more energy-efficient motors with frequency converters that are not dependent on the frequency of the grid, causing a decrease in inertia. [19]

The quantitative constant for the inertia is denoted as H [s]. This constant describes how many seconds of stored energy there are in synchronous rotational parts. For a nuclear power plant, this constant is around 7 seconds and for hydropower around 2 seconds. For the Swedish grid today, this constant is averaged to about 4 seconds, but is assumed to decrease due to the shutdown of nuclear reactors. In future scenarios, the inertia is expected to drop and thus possibly in worst case give a system with an inertia constant of around 1 second. [19]

4.1.3 Frequency regulation

The frequency on the Swedish (and Nordic) power grid is intended under normal operating conditions to be 50 Hz. For the regulation of the frequency, there are two different methods to be used. The first one is the "Frequency Containment Reserve - Normal" (FCR-N), which primarily regulates small deviations in the interval of 49.9 to 50.1 Hz with a total allocated power of ±600MW for the Nordic grid. The second one is the "Frequency Containment Reserve - Disturbance" (FCR-D), which is used when there is a larger deviation in the frequency, such as loss of a production unit. This regulatory unit can be used when the frequency is between 49.5 and 49.9 Hz. The first method to control the frequency is used often, while the second is used relatively often; however, they are not likely to affect the grid system and its users. [19]

When the frequency drops below 49.5 Hz, stand-by units such as gas turbines are put in operation and heavily energy consuming units get disconnected automatically. If the frequency continues to drop below 49.0 Hz, parts of the grid will be disconnected automatically and if it drops below 47.5 Hz, large heat generating power blocks are disconnected due to large reductions in flow rates for synchronous pumps that will drastically change the process parameters too much for stable operation. If the frequency continues to drop, parts of the power grid system will most likely collapse. [19]

When a large production unit disconnects from the grid, the frequency drops significantly. An example of this happened 4th of November 2011, when “Oskarshamn 3” suddenly disconnected while operating at full power. The frequency dropped to 49.36 Hz before returning to a higher frequency. In *figure 15*, the change of frequency can be seen. [19]

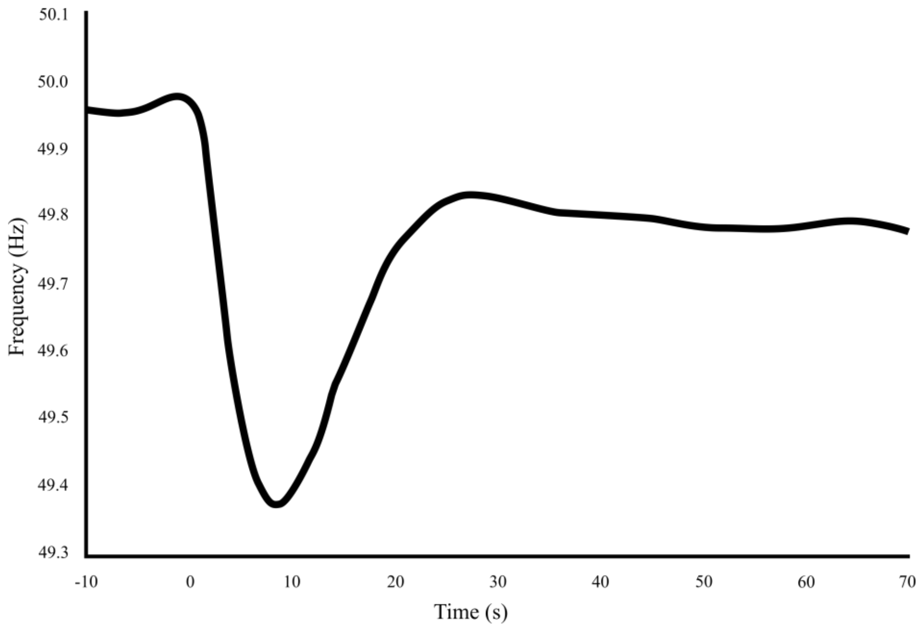


Figure 15: *Oskarshamn 3 suddenly disconnected during full load operation 4th of November 2011* ***[19]***

The definition of *frequency control* is to change the electrical power output to control the frequency in the grid. For a nuclear power plant, there are different ways of frequency control that can be performed and they will briefly be discussed here. One way to control the frequency is continuously, where the reactor power output is controlled automatically and can be able to respond the frequency change within a few seconds. Units operating like this contributes to the Frequency Containment Reserve. Another way is to control the frequency outside specified frequency ranges. With this technique, the electrical power output will be changed if the frequency hits the minimum or maximum allowed frequency deviations. The response should be within a few seconds and may serve as a supplement or instead of continuous frequency control. Lastly, the frequency can also be controlled within a predefined power range. This action is performed automatically and may be used to reduce or increase the power output from a signal from the grid operators or plant generation planners. The response time to change the power should be within a few minutes. [4]

4.1.4 Voltage stability

In an electrical power system, there are three different kinds of power, *the apparent power*, *the active power* and *the reactive power*. The apparent power is the total power generated from the generator and can be divided in active power and reactive power. The active power (sometimes called the real power) is the power that leaves for the grid, while the reactive power is the power required for components that makes up the power grid. In *figure 16*, the correlation between these is given. [13]

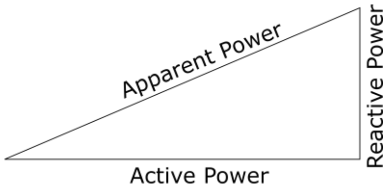


Figure 16: *The reactive, active and apparent power, where the apparent power is the hypotenuse of reactive and active power*

Occasionally the power grid is exposed to disturbances that may affect the voltage. The ability for the grid to handle these voltage disturbances and return to a new equilibrium in voltage is defined as *voltage stability*. To maintain good voltage stability, each individual part of the grid needs to have sufficient reactive power delivered; thus, if there is a deficiency of reactive power, parts of the grid may collapse. Reactive power is difficult to transfer long distances and therefore needs to be produced at crucial places in the grid. [16]

4.1.5 Rotor angle stability

To describe how well the rotor angels of different synchronous generators relate to each other in the power system, the concept of *rotor angle stability* is commonly used. Normally it is used as a damping to compensate for the differences in rotor angle between different synchronous generators; however, when the angle is too large, generators will be disconnected due to the loss of synchronisation. When disturbances occur, the rotor angles will change and this may lead to oscillations in power between the generators. Generally, the system can handle small disturbances by damping the effect; thus, if the disturbances are larger than the system is designed to handle, it may collapse. The ability of how well the system can handle a disturbance is the inertia and the damping effect from the rotors. [16]

4.2 Nuclear power in Sweden

In Sweden, the nuclear power companies together with governmental companies and authorities are in charge of the nuclear energy production. The companies responsible for the production of nuclear energy in Sweden are *OKG AB*, *Forsmark kraftgrupp AB* and *Ringhals AB*. As mentioned earlier, *Svenska kraftnät (SvK)* is the company responsible of the grid. The authority responsible to secure that the nuclear power plants are operating safe and without significant environmental contamination is *Strålsäkerhetsmyndigheten* (SSM). SSM is in charge by law to control that the nuclear power plants follow the regulations which mostly concern areas like stable operation, robust construction, safety systems, emergency preparedness and much more. The cooperation between the nuclear power companies and SvK mostly concern the power production, inertia, disturbance stability and the voltage control. Between SSM and SvK there are no direct cooperation; however, they need to have a good understanding of each other’s decisions. [16]

4.2.1 Contributing factors for a stable grid

The nuclear power plants in Sweden have a significant impact to the stability of the grid, where some contributing factors are of extra importance. These contributing factors are mainly *frequency stability*, *voltage stability* and *rotor angle stability*. The nuclear power plants contribute today with a lot of mechanical inertia and active effect to the grid system and thereby supports the frequency stability of the grid. As mentioned earlier, if reactors are shut down, the mechanical inertia will decrease, which will give a negative impact on the frequency stability. This will in the long-term perspective lead to higher demands for the reactors that are still in operation to be more flexible to provide better frequency stability. [16]

The nuclear power plants contribute a lot to voltage stability in the grid system due to their large synchronous generators that are connected to the grid. These generators have been designed to give a reactive power in normal operation which is 1/3 of the active power. The generator in a nuclear power plant has an automatic voltage control that supports the voltage to the grid by changing the reactive power during operation. When nuclear reactors are closing, there will be a higher demand for the remaining reactors to contribute to the voltage stability. [16]

Also, the rotor angle stability is improved by the nuclear power plants. The large generators in the Nordic power system are equipped with damping functions like the PSS (Power System Stabilisers) to respond to rapid power oscillations; therefore, giving the ability for more uniform power flows which will give better margins for the rotor angle stability. Also, the strategic locations of the power plants will contribute to cope with issues in the grid and help with a stable transfer of power from the electricity regions in the north to the electricity regions in the south. [16]

4.2.2 Control modes for Oskarshamn 3 (O3)

Oskarshamn 3 can be controlled in several ways to obtain the desired net power. For controlling the power without changing the control rod pattern, where only changing the pump flow rate from the recirculation pumps, the process operators have three different control modes to choose between and they are listed in *table 1*.

Table 1: *The control modes available for the process operators* ***[12]***

Control mode	**Explanation**
Flow control of recirculation pumps	The operator gives a setpoint for the flow rate
Power control	Operator gives a fixed setpoint for the chosen power output
Frequency control	The frequency of the grid determines the power output

Usually, *power control* is the control mode which is used most often. It can be used for both baseload operation as well as load following. The *frequency control* that is used to compensate the grid frequency is using the *pressure controller* in the reactor and the *power controller*. The pressure in the reactor vessel is allowed to oscillate between a few bar in this mode. In *figure 17*, a simplified control scheme for a BWR from ASEA-ATOM is shown. [12]

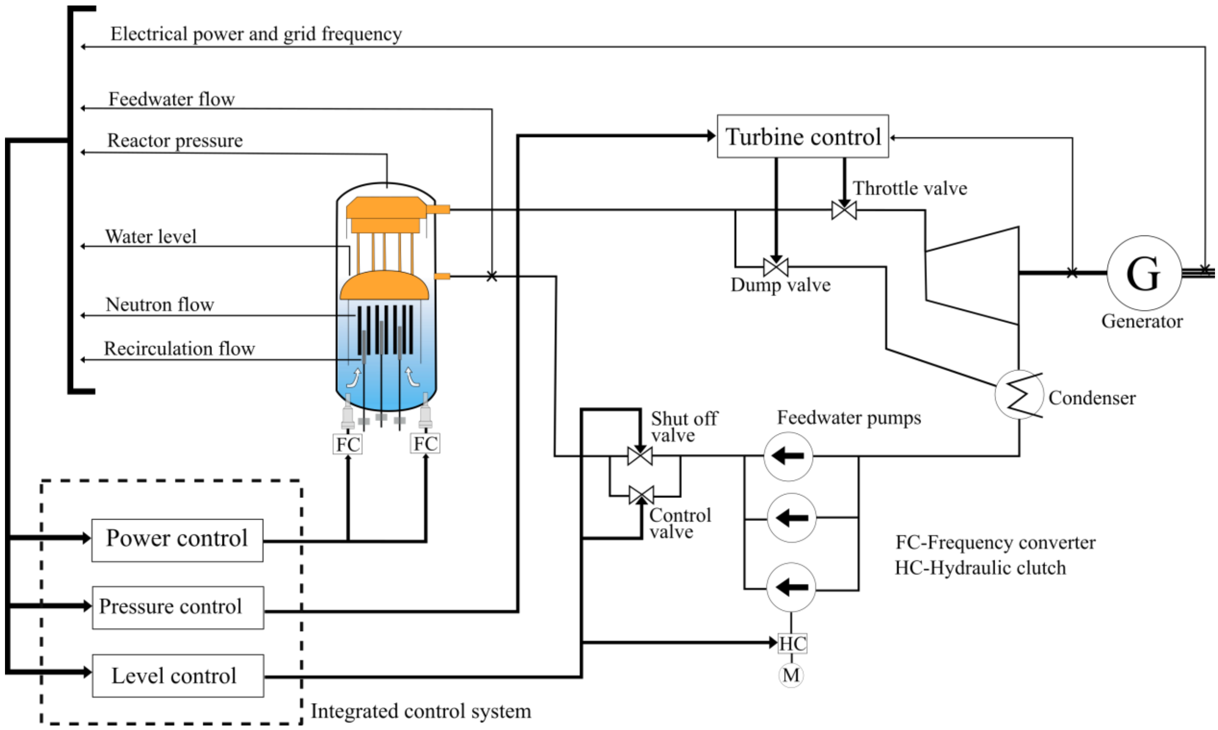


Figure 17: *The control system for a BWR from ASEA-ATOM. There are three major control blocks for the control of different parameters in the reactor; which are power control, pressure control and level control* ***[12]***

4.3 PSPA - Pressure Set Point Assessment

There is a unit built-in in some BWRs control systems, e.g. "Oskarshamn 3", which is called *Pressure Set Point Assessment, PSPA*. The idea behind this unit is to momentary increase the power output through a rapid decrease in the reactor pressure; thus, the steam flow to the turbine quickly increases for a few seconds. For a shorter time period, the flow of steam leaving the reactor vessel will be higher than the produced steam in the reactor vessel. The unit has never been used commercially since the frequency in the grid mostly is adjusted with hydropower; thus, there is no need for additional frequency compensation. However, it has been proposed that the function could be applicable in future scenarios. As an example for a suggestion when to use the PSPA-unit, the frequency drops below 49.85 Hz with a derivative of -0.04 Hz/s in order to rapidly contribute with additional the power to the grid. [16]

The control mode that should be activated for the use of the PSPA-unit is *frequency control*. When there is a significant disturbance of the grid frequency, the power control block, see *figure 17*, will change the speed of the recirculation pumps. Meanwhile, the pressure control block will increase the valve position for the throttle valve connected to the turbines. The pressure will decrease with a maximum of a few bars. [20]

Today, Swedish power plants do not have the requirement to be able to operate with frequency control; though, they need to be able to operate with power control. These requirements can be read about in SvKFS 2005:2. The ability for frequency control have as yet never been used in commercial nuclear power plants in Sweden. [16]

The PSPA-unit could potentially have the ability to cope with voltage disturbances when there is a significant voltage drop in the grid. A short drop in voltage would temporarily decrease the pump flow rate for the recirculation pumps, which would decrease the thermal power in the reactor and thus a lower output in electrical power. To compensate the reduction in electrical power, the pressure can momentarily be decreased in the reactor; thus, there will be an increase of steam hitting the turbines. This action will support the grid while the recirculation pumps are ramping up in pump speed.

4.4 Possible simulation scenarios

There are numerous scenarios where load following can be applied for Oskarshamn 3, thus, it exists three main factors for determining suitable scenarios. The first one is to do load following on a daily basis. As could be seen in *figure 11*, the demand was higher during the day and lower during the night. A suggestion could therefore be to start reducing the thermal power in the reactor after the second peak at around 6 PM and then increase it before the consumption hits its first peak in the morning at around 6 AM.

The second important factor is to apply load following on a weekly basis. In this way, the power could be reduced during some days before it returns to baseload. As already seen in *figure 12*, the demand of power is generally higher during normal weekdays and less during the weekend. Therefore, a possible scenario could be to reduce the power when the weekend starts and return to normal before the weekend hits its end.

Thirdly, a possible scenario could be to operate load following on a monthly basis, meaning there will be a reduction of power for a couple of weeks in a row. As seen in *figure 13*, the power demand is less during the summer and greater during the winter. Therefore, a suggestion is to apply load following during the summer months with the lowest power demand.

Apart from reducing the power to a constant setpoint, it should also be investigated if the reactor can operate flexible with the power frequency control activated. This will be a way to apply load following in a much narrower time frame where the power demand and production are unpredictable. The PSPA-unit could also be interesting to simulate in order to see how it copes with the frequency control system.

Lastly, it could be of high interest to see how the PSPA-unit works when there are certain voltage disturbances. The possible simulation scenarios are listed in *table 2*.

Table 2: *The possible scenarios for load following that can be simulated*

Scenario	Strategy
Daily	Reduction of power during the night and back to normal over the day
Weekly	Reduction of power during the weekend and back to normal during the weekday
Monthly	Reduction of power during the summer months when the demand of electricity is low
Frequency control	Letting the grid frequency determine the net power
Voltage disturbance	See how the reactor copes with voltage disturbances

5 Analysis of limitations and affected components

Operation of load following in nuclear power plants may affect several components, both in the nuclear reactor and the turbine island, as well as the operational parameters in a different way compared with baseload operation. Therefore, different problems and obstacles will be discussed together with proposals for the simulations that will be performed in APROS 6.

5.1 Varying the thermal power

As already described in the earlier sections, the main recirculation pumps together with the control rods can be used to control the thermal power in the reactor. For the ability of variation in power, there are four commonly used parameters for describing this; *rate*, *depth*, *duration* and *frequency*. The *rate* gives the speed at which one can go from one power level to another. The *depth* gives how much reduction in power that is possible without losing the capability to easily go back to the initial power level. The *duration* gives the time the reactor stays on one power level and the *frequency* gives the significance of how often the changes in power levels are. It is important to be aware of these parameters when planning load following as they differ for each nuclear power plant and they will set limitations to scenarios with load following. [21]

For load following between 60-100 % of maximum thermal power, usually only manoeuvring the flow rate of the main recirculation pumps is needed, where an increased speed leads to more effective cooling of the core and higher reactivity, which leads to an increase in the effect. Changing the mass flow rate of the pumps is used for fast control of the reactor. The other way to control the effect is by manoeuvring the control rods which can decrease the power in the interval between 20-100 %. Control rods are used for slow control of the reactor effect. From previous experiences, it is recommended to avoid changing the control rod pattern due to risks of increased stresses in the fuel rods since the relative power distribution will be uneven, causing an increase in temperature changes that adds to the stress. When changing the pump flow rate, parameters like pressure and temperature remain constant in the reactor vessel. [22] [23]

5.2 Reported effects of load following

There have been several reported effects from load following and it is important to be aware of these effects and the damage they may cause. Some of these effects will increase the wear and tear and ageing of components, like *fatigue, vibrations, erosion corrosion* and *chemical impurities*. Other will affect the manoeuvrability of the reactor core, like *xenon poisoning* and *pellet cladding interaction*.

5.2.1 Effects on lifetime of components

Fatigue

Fatigue is the phenomena when components from metallic materials are losing their mechanical strength due to load cycling. The structural changes of the material are permanent and increases under conditions with fluctuating stresses. Cracks and fractures are the outcome from the fatigue mechanism. In nuclear power plants, failures of components can usually be located back to the fatigue mechanism; thus, this usually limits the lifetime of the components. The components are thus designed to manage numerous oscillations and changes in process conditions during their operational lifetime. When operating more flexible with load following, there will be an increase of load cycles and temperature transients that will affect the margins for fatigue. Also, the impact of fatigue is increased when there are a lot of small cyclic stresses compared with only a few large stresses. [4] [24]

Vibrations

For process plants in general, vibrations are a great issue which will affect different components during the operation. They are caused by different excitation mechanisms, like electrical, mechanical or fluid flow excitation sources and the response gets influenced by the dynamic behaviours. The dynamic behaviour of a component together with the excitation sources may make vibrations to occur. The components are normally designed and optimised to give as little vibrations as possible during baseload operation; though, when process parameters change due to load following, the risk of getting significant vibrations at some parts of the plant may increase. One of the reasons why vibrations should be reduced or avoided in a nuclear power plant is that it can cause fatigue failures, which may give a shorter lifetime of the components. The reduced lifetime of the components can increase the need of maintenance, both in time and material. For load following operation, the vibration levels for individual components and different power levels should be analysed to avoid damage. [25]

Erosion corrosion

Erosion corrosion occurs at the surface of a metal, for example in a pipe, when the water flow reaches turbulent conditions. The mechanism is that the naturally occurring film with corrosive products, which is quite intact under laminar conditions, is disrupted and the corrosive products move from the surface, which will increase the corrosion rate. The damage from erosion corrosion is usually that metal tubes becomes thinner, which in the long run can lead to pipe failures. This phenomenon happens in all components and pipes in a nuclear power plant made of carbon steel. The mechanism of erosion corrosion can be seen in *figure 18*. [24]

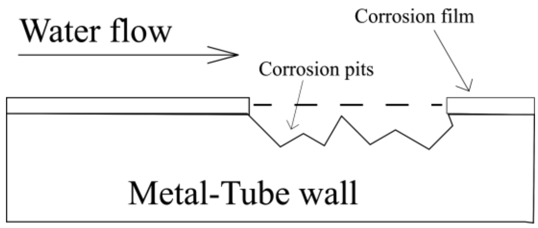


Figure 18: *The erosion-corrosion mechanism* ***[26]***

When operating flexible, the local flow rates in the process may be changed compared to baseload operation. If the flow rates increase, there will be a risk of increased erosion corrosion; thus at other parts of the plant, the flow rates could instead decrease, which will give less impact from erosion corrosion. [4]

Chemical impurities

The chemical impurities may arise from corrosion due to fluctuations in parameters like temperature, pressure and flow rate. When operating flexible, the corrosion might increase, which gives more corrosion products that will be transported around in the plant. The corrosion products could possibly lead to an increase of radioactive materials that may give an increase to the personal dose rate. However, from experience, flexible operation have shown no to small changes in corrosion products. Although, if there is an increase of chemical impurities, specific components of the process may get damaged. [4]

5.2.2 Effects on the manoeuvrability of the reactor

Pellet cladding interaction - PCI

In the fuel rods, there is a difference in the thermal coefficient between the uranium oxide and the cladding. The cladding consists of zircaloy and have a lower thermal coefficient than uranium oxide. When the temperature of the fuel increases, it will expand quicker than the cladding which will give a deformation of the fuel pellets which will increase the friction of the cladding. Later on, the cladding will deform as well due to the expansion. This expansion will give a stress to the fuel rods that may give a crack. [27] In load following, it is therefore important to have control over the power ramping, so that cracks will not appear due to this difference in thermal coefficients. The fuel rods may have been designed with larger gaps between the fuel pellets and the cladding, thus, the stress will be smaller. Also, the design of the fuel pellets have been optimized for higher tolerance to PCI. For the operation of nuclear reactors, there are thresholds for PCI; thus, below these power-level ramps, PCI would not be expected. In *figure 19*, a simplified sketch of the phenomenon can be seen. [4] [22]

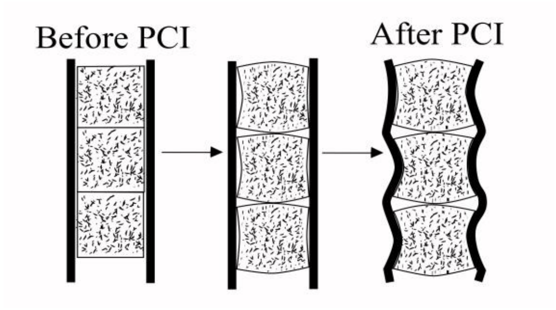


Figure 19: *The fuel and the cladding expand differently due to the differences in the thermal coefficients* ***[27]***

Xenon poisoning

In all nuclear reactors, a problem with radioactive fission products that affects the reactivity of the reactor occurs. One of the most problematic fission products is the isotope xenon-135. In normal operation, around 3.5 % of all the uranium-235 forms the fission product tellurium-135, which rapidly decays to iodine-135. Iodine-135 then decays into xenon-135 with a half-life of 6.61 hours. Xenon-135 has a very large cross-section; thus, it will absorb neutrons to form the stable isotope xenon-136. The rest of the xenon-135 which do not absorb neutrons decays to cesium-135 with a half-life time of 9.10 hours. The cesium-135 then has a half-life time of around 2 million years before it decays into the stable isotope barium-135. Around 2.5 % and 0.6 %, respectively, of the uranium-235 turns directly to the fission products iodine-135 and xenon-135. The decay series for xenon-135 from uranium-235 is shown in *figure 20*. [28]

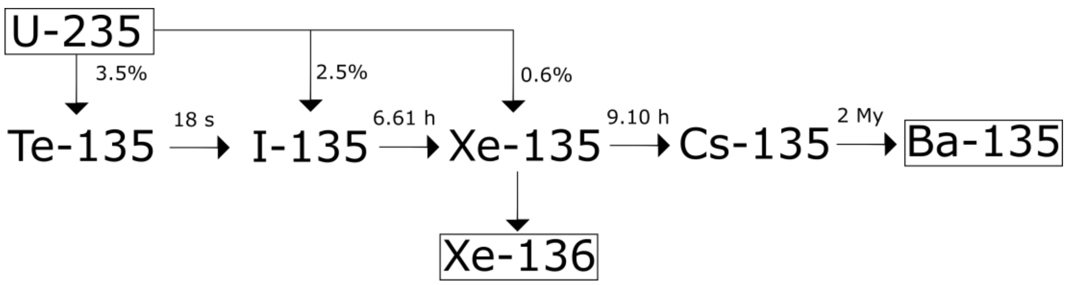


Figure 20: *The decay series for xenon-135*

In continuous operation of the nuclear reactor, this phenomenon is well-known and the control of the reactor is manoeuvred in such a way that the concentration of the neutron-absorber xenon-135 is maintained constant, thus an equilibrium is achieved. However, when going from baseload to flexible operation, the xenon concentration will no longer be in equilibrium and hence the reactivity of the reactor will change. When decreasing the power of the reactor, the neutron flux also decreases. This will decrease the absorption of neutrons for xenon-135 to xenon 136; though, there will still be formations of xenon-135 due to the decay from iodine-135. As a result, there will be a peak of xenon-135 after the power reduction. The xenon-135 will however drop after a certain time due to the decay to cesium-135.

If the reactor power increases only after a short period at a lower power level, there will still be a lot of xenon-135 that absorbs neutrons; hence, an increase in reactivity needs to be performed aided by the main recirculation pumps and control rods. When the concentration of xenon-135 drops due to both absorption and decay, the reactivity rapidly increases, which may lead to that the reactor reaches a supercritical state, $k > 1$. The phenomenon for when xenon-135 affects the reactivity of the reactor is called *xenon poisoning*. For load following, xenon poisoning will have great impacts for the controllability of the reactor and will set limitations for the operation of the reactor. [28] [29]

Load cycle which should be avoided

Refuelling of fuel in the nuclear reactor is periodically performed for each fuel cycle. After each refuelling, the nuclear fuel needs to be conditioned. The conditioning of nuclear fuel limits the periods when load following is suitable. Therefore, the first period after a refuelling, only baseload operation should be performed. In addition, calibration of equipment is done during the conditioning. The conditioning typically takes around 7-14 days. Also, close to the end of the fuel cycle, flexible operation should be avoided due to a reduction in reactivity margins in the core and the conditioning of the existing fuel. This period can be up to a month or even longer. [4] It is also important to avoid load following when a fuel failure have been detected. This is due to previous experiences where even small temperature changes may lead to secondary damages of the fuel rods. [30]

5.3 Component analysis in nuclear reactor

Several components in the nuclear power plant may or will get affected by load following. Therefore, crucial key components in the nuclear process have been analysed which may need further evaluation for the impact from load following. In *table 3*, analysed components in the nuclear reactor are presented.

Table 3: *Analysed components in the nuclear reactor* ***[21]***

Component	Potential impact
Control rods	Increased usage of control rods for reactivity change
Fuel rods	Increased temperature changes
Reactor core	Increased reactivity changes
Instrumentation	Measurements at different power levels
Steam dryer	Changes in power levels
Recirculation pumps	Mass flow changes

Control rods

Usually it is recommended to only change the power in the reactor with the recirculation pumps when operating in load following. However, if one wants to reduce the power below the limit which only the recirculation pumps can handle, the control rods are used. As mentioned earlier, the recirculation pumps can normally alone reduce the power from 100 % to 60 %. The increased usage of control rods will most likely increase the wear and tear of them, which may decrease their lifetime. Also, the neutron absorbing material will burn up more quickly and it will be more unevenly distributed in the core. Furthermore, the increased time for the control rods inserted in the reactor will increase the chemical corrosion. Also, the control rod drive mechanism, which serves as the motor for the movement of the rods, will most likely also exhibit increased wear. [4] [21]

Fuel rods

When applying load following, the fuel rods may get impacts from several factors. Most importantly, the potential impact from pellet cladding interaction, PCI, will give the greatest damage on the fuel rods; thus, it is important to choose a rate of power change that will be within margins to avoid this. Also, there will be changes in the local power density where the temperatures could deviate at different locations of the fuel rods. Apart from PCI, most of the issues that may occur with fuel rods are increased thermal and mechanical cycling that may lead to more failures with defective fuel elements. [4] [21]

Reactor core

In the reactor core, the thermal and neutronic behaviour will change when performing load following. With extensive reductions in power levels, there may be an excess of unburned fuel. To cope with this, one could either reschedule the fuel outtake until more fuel have been burnt or take out the unburned fuel and deal with the huge economical loss due to unused fuel. A third way to deal with the problem is to during the last period of the fuel cycle, only operate at baseload to burn the excess fuel. In the reactor core, xenon poisoning will limit the speed of ramping between different power levels, thus, the manoeuvrability of the reactor will decrease. [21]

Recirculation pumps

As earlier mentioned, the recirculation pumps are used for power control and will therefore exhibit increased variations of loads, which may lead to problems with wear and tear and fatigue. [4] Also, operation at specific loads may give an increase of vibrations or resonance frequency. The recirculation pumps are designed and optimised for baseload operation at full power and a reduction in power will lead to operating conditions below the optimal operating point for the pumps. [21]

Instrumentation
When on a frequent basis changing the power levels, the history of the local neutron flux and power history will change. This may have an impact on the accuracy in the instrumentation of the reactor. Therefore, one should consider to increase the calibration of the instruments. Especially the Local Power Range Monitor, LPRM, and the Average Power Range Monitoring, APRM. [21]

Steam dryer
For steam dryers, there may be an increase of higher load cycling due to load following, which may increase thermal fatigue cracking. Also, the increase of high cycle fatigue should be considered due to the increasing fluctuating thermal loads. [4] Another problem that may arise in the steam dryers are acoustic resonances at the branch connections to the main steam piping. This can cause fluctuations of pressure loads and cracking of the steam dryer. This phenomenon can occur both when increasing and decreasing the power level. [21]

5.4 Component analysis in turbine island

Components that may be affected in the turbine island are listed in *table 4* below.

Table 4: *Analysed components in the nuclear reactor* ***[21]***

Component	**Potential impact**
Turbine	Changes in steam flow
Condensate pumps	Changes in mass flow
Feedwater pumps	Changes in mass flow
Feedwater heaters	Changes in feedwater flow and steam conditions
Condenser	Changes in steam flow
Steam pipes	Changes in mass flow
Generator	Changes in power

Turbine
Several parts of the turbine will be affected due to load following. When reducing the reactor power, the moisture content in the steam will potentially increase in the last stages of the low-pressure turbines. This will increase both the wear and the seal clearances. Also, the control valves used for turbine control will most likely get an increased wear due to greater usage of them. [4] The turbine rotor will also be affected due to the variable loading in the turbine, which may give torsional

vibration. Apart from that, the variable steam pressure, temperature and condenser back pressure will affect the thermal and mechanical fatigue. [21]

Condensate and feedwater Pumps

In the turbine island, there are several condensate and feedwater pumps that are working in parallel. The condensate pumps increase the pressure for the condensate from the condenser and the feedwater pumps pump the water from the feedwater vessel to the reactor vessel. For load following, the feed flows will change; thus, this will impact the pumps. The operating point will move further away from the optimal point at the pump head curve where the highest efficiency is obtained. The risk of increased vibrations in the pumps will be greater as the operating point changes. There can also be increased stresses due to internal recirculation that will reduce the lifetime of the pump and fluctuations in flow rate may occur as the downstream pressures may change. [21]

Feedwater heaters

For the feedwater heaters, the main issue is the decrease of water flow that may give changes in the water levels in the heaters and the heater drain system capacity. This puts higher demand on the level control system to be able to maintain the level even when the flows are decreased. Also, the pressure difference for successive stages of heaters will be impacted. [21]

Condenser

The condenser will be subject to changes in mass flow due to load following. This will, however, not make any increased impact from normal operation. In some power plants, turbine bypass can be used for operation in load following, meaning some of the steam is dumped directly to the condenser without hitting the turbines. Normally, the condenser is designed for some extent of turbine bypass; though, if it occurs in an extended time, problems like increased fatigue may occur. [21]

Steam pipes

When operating flexible, there will be a risk with an increase of load cycling. This may give high cycle fatigue since vibrations may occur due to operation away from the optimal operating range. Also, an increase of thermal loads will affect the high cycle fatigue in flexible operation, where especially the weld joints will get affected. [4]

Valves

Similar to steam pipes, the valve may also get affected with high cycle fatigue due to vibrations in the valves at different operating ranges. Thermal loads will also give an increase of high cycle fatigue. There will also be an increased potential that valves will be put in throttling positions, which may increase the need of rebuilding the valves. The wear and tear due to more active valves will also increase. [4]

Generator

Several parts of the generator can potentially get affected by load following, such as the rotor, the stator and the windings. Most of the problems that may occur can be derived from temperature fluctuations that may give thermal transients and cycling. In the rotor, increased mechanical stress and fatigue loading together with thermal transient vibrations may be increased. For the stator, there may be an increased wear due to thermal fatigue loading. Also, the windings will get affected due to temperature fluctuations, where increased fatigue loadings may be a potential issue. [21]

5.5 APROS simulations

From the determined possible scenarios in section 4 and with the knowledge of plant limitations given in this chapter, the scenarios that will be simulated in APROS 6.07 will be given in this section. The rate of reduction and increase in power levels will be limiting factors as well as the duration of the reduced power.

5.5.1 Power control

First, simulations with only power control activated will be performed. The rate of power reduction will be the same for all simulations; though, the rate of ramping in power back to full power will be different for each simulation. The reason to have different rates of ramping is to be sure to have enough margins to prevent any failure that could occur in the reactor core, like xenon poisoning and PCI. The duration for operation at reduced power level will be assumed to be at the frequency of daily basis; thus, for more extended duration at reduced power, the rate of ramping back to full power will be much slower.

To perform one simulation scenario, several days are needed for the computation in APROS. Therefore, the simulated duration at the reduced power level will be much less than it potentially could be for saving computation time. It is however important to aim for the simulation to reach steady state at the reduced power level before ramping the power back to full. The APROS-model used for the simulations is *O3_PULS_607_M167*.

The lowest scenario which will be simulated is at 95 % thermal power, where 129.1 % is the maximum. Simulating lower scenarios may require significant longer ramping times. The power level at 100 % will be an interesting power level, since this is the power level for which "Oskarshamn 3" initially was built for. Moreover, at 109 % is an interesting power level since this is the power level that "Oskarshamn 3" first got upgraded to. Lastly, it will be interesting to see how the reactor copes with a small reduction in power, like 120 %. The simulations that will be performed with power control are listed in *table 5*.

Table 5: *The scenarios that will be simulated with the given reduction in power level from full rated thermal power 129.1 %. Also, the rate down and the rate up in power is given together with the allowed duration at the reduced power level.*

Number	1	2	3	4
Reduced power level	95 %	100 %	109 %	120 %

5.5.2 Frequency control with PSPA-unit

The second part of the simulations is to simulate how the plant copes with frequency control and the PSPA-unit activated, where the APROS-model *O3_PULS_607_M168* is used with additional changes in the control structure for the PSPA-unit. In the model, the frequency is constant at 50 Hz. For simulating disturbances, a frequency disturbance will be applied to the frequency signal in APROS. In *figure 21*, the logic behind the frequency disturbance that was applied in APROS is shown.

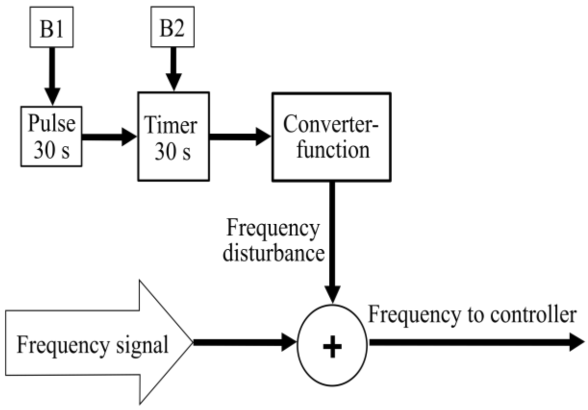


Figure 21: *Control structure for frequency disturbance in the APROS-model. For activation of the disturbance, the binary signal B1 is activated and B2 deactivated. The pulse block gives a binary signal to the timer for 30 seconds. The timer converts the binary signal to an analogous signal that counts to 30 seconds. The converter function converts the time to its corresponding frequency drop given by the user.*

By using similar design of the control as in one of the reactors owned by *Forsmarks Kraftgrupp AB,* the control structure for the frequency control will only be active when the frequency drops below 49.6 Hz or above the 50.2 Hz; thus, the simulations will only be performed with frequency drops below 49.6 Hz. [20] The scenarios that will be simulated are listed in *table 6*.

Table 6: *The initial power level during frequency control and the maximum drop in frequency*

Number	5	6	7
Power level	109 %	109 %	109 %
Frequency (Hz)	0.5	0.71	1

The profiles for the frequency drops are inspired by real measured values of frequency drops that have historically occurred when large production units have been disconnected, as already shown in *figure*

15. The total time for the disturbances will be 30 seconds in total, with the lowest frequency obtained after 10 seconds from when the disturbance is applied. The profiles for the frequency after the disturbances are applied are shown in *figure 22*.

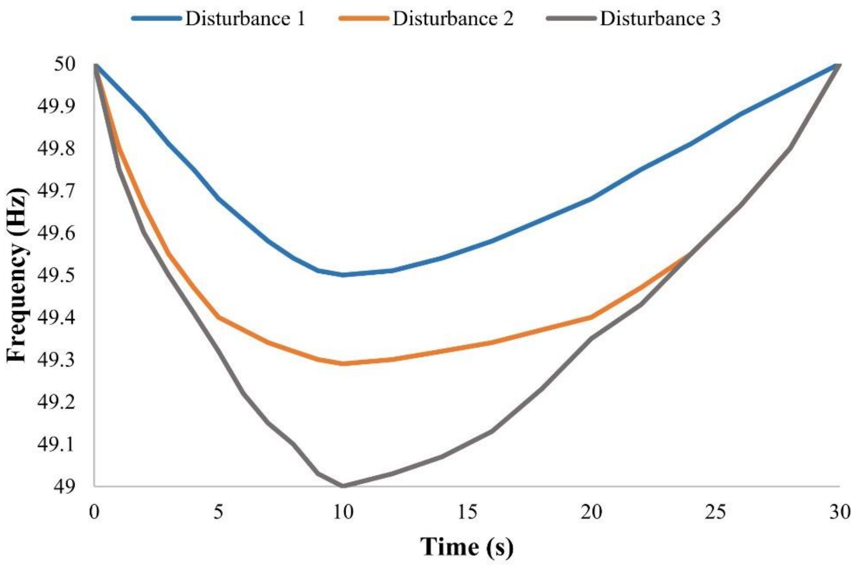


Figure 22: *The frequency profiles after the frequency disturbance have been applied*

Other scenarios that are interesting to simulate is how a change in the control structure for the frequency controller will give results that can improve the PSPA-unit. As mentioned above, the frequency controller starts to work after the frequency drops below 49.6 Hz; though, with modification in one of the control blocks, the controller can be set work in the interval between 49.85 Hz to 50.15 Hz, with only minor changes in the reactor pressure. [20] With the new modification, the output signal will be a maximum of 4 % of the original value when it reaches its maximum. The difference between the original value and the modification can be seen in *figure 23*.

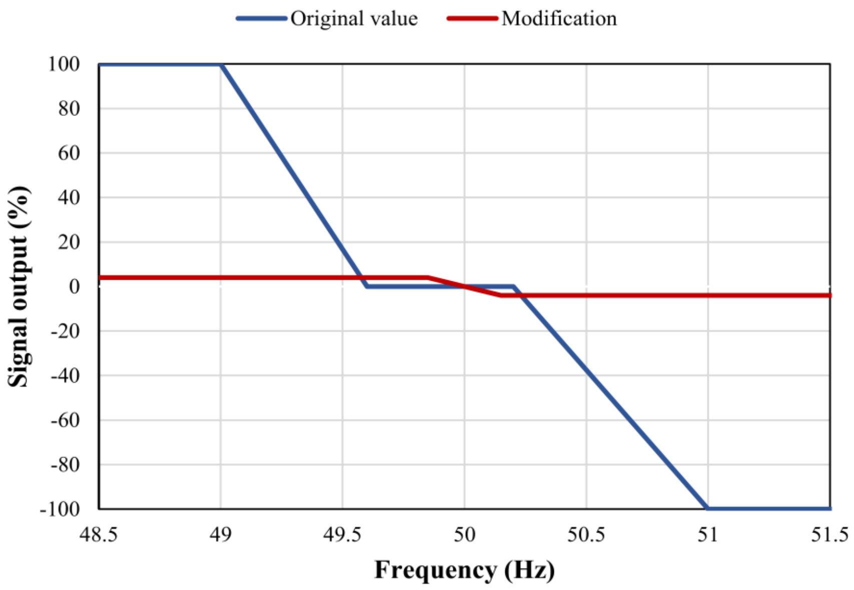


Figure 23: *The modification of the frequency controller, where the frequency corresponds to a signal output from the controller. The output signal is given in %, where 100 % corresponds to the original value at maximum signal. As seen in the figure, the new modification will give a signal with much lower magnitude. The modification is inspired by reference* ***[20]***

There will be one simulation for the modification with the frequency controller at the power level 109 %, where the frequency drops with 0.5 Hz. The simulations are listed in *table 7*.

Table 7: *The simulation that will be performed with the modified frequency controller*

Number	8
Power level	109 %

Apart from the contribution with frequency stabilization, the PSPA-unit can also be activated when there is a large voltage drop in the grid. Therefore, this feature will be simulated to understand how the control system copes with this. Four scenarios with voltage drops below 26 % will be simulated, two at the power level 109 % and two at 129.1 %, with frequency control activated respectively deactivated. The PSPA-unit will give the same pressure decrease regardless of the magnitude of the voltage drops as long as it is within predefined limits. The simulations with voltage drop are given in *table 8.*

Table 8: *The APRM with or without frequency control activated for simulations with voltage drops*

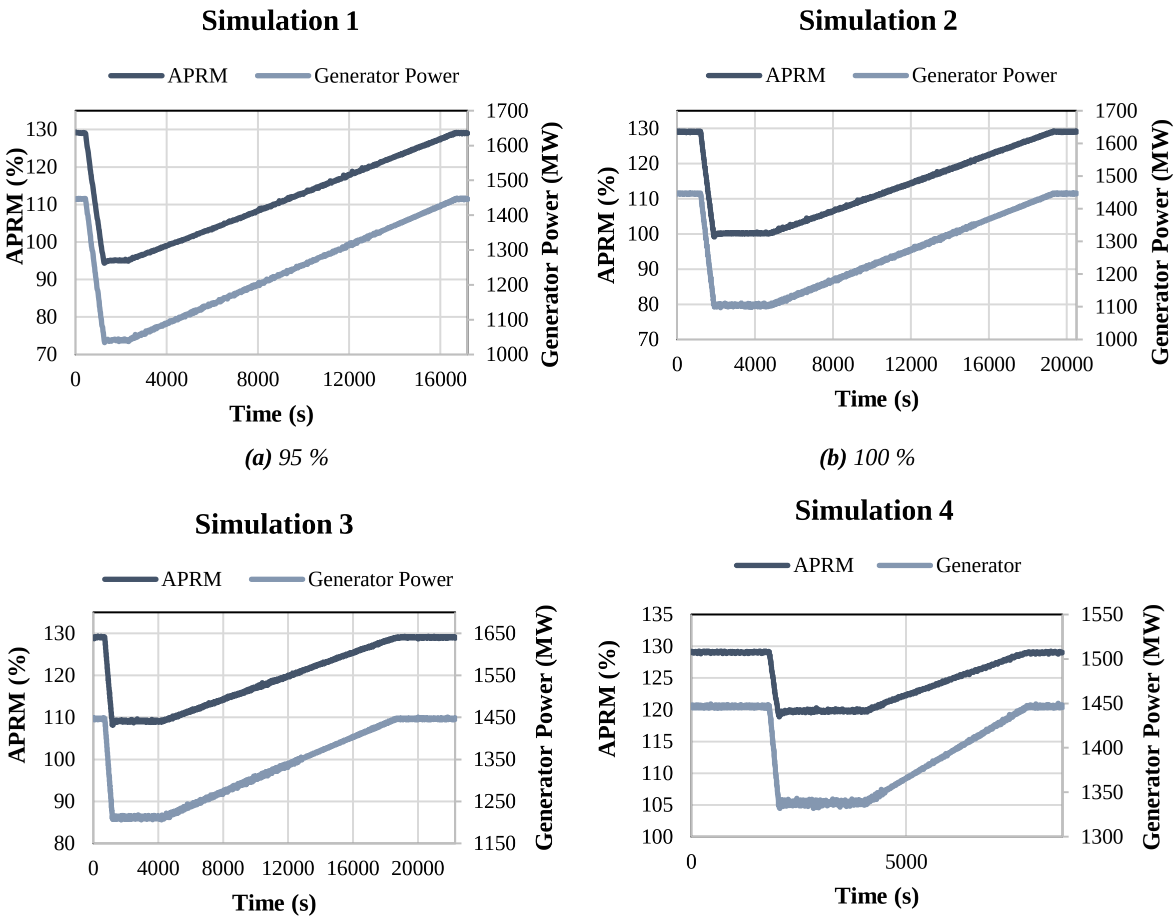
Number	9	10	11	12
Power level	109 %	109 %	129.1 %	129.1 %
Frequency control	Yes	No	Yes	No

6 Simulation results

A total of 12 simulations were performed, where simulations 1-4 simulated load following with power control, simulations 5–8 the tests of the frequency controller and 9-12 the tests with voltage disturbances where the PSPA-unit is active.

6.1 Power control

For power control, four scenarios were simulated with different reductions in power levels at 95 %, 100 %, 109 % and 120 %. First, the thermal power together with the generator power is simulated towards the time, as can be seen in *figure 24*. For simulation 4, there has been a correction with the results, where the data from the initial simulation at 3000 seconds to 58 000 seconds have been removed due to long simulation time at the reduced level. The correction gives better presentation in the graph.



(a) *95 %* ***(b)*** *100 %*

(c) *109 %* ***(d)*** *120 %*

Figure 24: *The thermal power, measured as % APRM, and generator power for 95%, 100%, 109% and 120 %.*

As seen from *figure 24*, the generator power changes accordingly to how the thermal power is changing. The durations for the simulation times are different, where the reduction and ramping at power level

120 % using significantly lesser time compared with the other three simulations that reduces to lower power levels.

The mass steam flow rates to the steam turbines decreased accordingly to the power changes in the reactor which gave the decrease of the generator power; although the pressure in the reactor vessel remained constant during all simulations.

The simulations showed that the water level in the condenser will change due to the power reduction; thus, in scenario 1 & 2, the water level returns to its initial value when the thermal power returned to 129.1 %. For simulations 3 & 4, the condenser level did not return to its initial value; thus, the valve positions for the control valves downstream the condenser was not correctly operated for these simulations. The decreases of the water level also affected the pressure in the condenser.

It was observed that there was an impact on the water level in the feedwater vessel. For simulations 1 & 2, the water level remained constant during the whole simulation; thus, a smaller transient was obtained in the ramping due to a significant change of the position of a control valve. For simulation 3 & 4, the level in the feedwater vessel also remained constant during almost the whole simulation. In the end of the simulation, the water level changed from being at a constant level, due to control valves upstream that are not correctly operating, which are the same valves as for the condenser.

The mass flows for the condensate pumps decreased due to the changes in power levels. Similarly, other pumps like the feedwater and recirculation pumps also got a reduced mass flow rate during the reduction in power. It was observed that one of the pumps upstream the feedwater vessel (though not included in the PFS, *Figure 5*) got an increased mass flow rate when the power was reduced in simulations 1 & 2; thus, in simulations 3 & 4, the mass flow rate decreased for this pump. Also, the greater the changes in power levels are, the more significant changes in process parameters like mass flow rate in pumps are observed.

During all simulations, it has been seen that some control valves have been actively changing their valve positions when there have been changes in the power levels. Below in *Table 8*, some of the affected components are listed.

Table 8: Some of the components affected by load following and the changes in their main process parameters

Component	Parameter changes
Recirculation pumps	Mass flow changes
Pumps in turbine island	Mass flow changes
Generator	Changes in power loads
Valves	More actively operating
Feedwater vessel	Changes in water level
Condenser	Changes in water level and pressure

6.2 Frequency control

The results from the simulations with frequency control will be given here, where both the original design and the modified design can be found.

6.2.1 Original design

The generator power increased when there was a reduction in frequency. In *figure 25* below, the drop in frequency and the profile for the increase in generator power is shown. The simulations are performed at a thermal power level of 109 %.

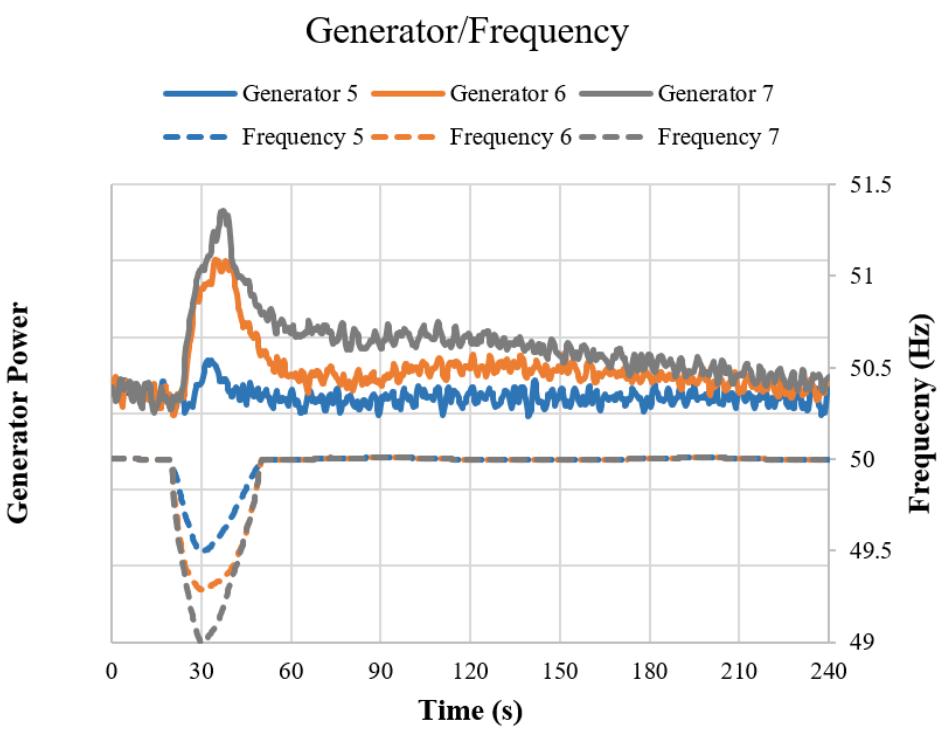


Figure 25: *The profile for the generator power and the change in frequency for a thermal power of 109%*

The frequency drop to 49 Hz gave the highest peak in generator power, while the frequency drop to 49.5 Hz gave the lowest peak in generator power. As already mentioned, the PSPA-unit manipulated the pressure controller, which gave a rapid reduction in reactor pressure. The pressure decrease momentarily increased the flow rate of steam to the turbines. After the frequency disturbance peaked, the pressure slowly returned to its normal set-point. The flow rate of the main recirculation pumps increased during the disturbance, giving an increase in thermal power as a result. In *figure 31*, the profile for the increase in thermal power and the pressure decrease are shown for the initial thermal power level at 109 %.

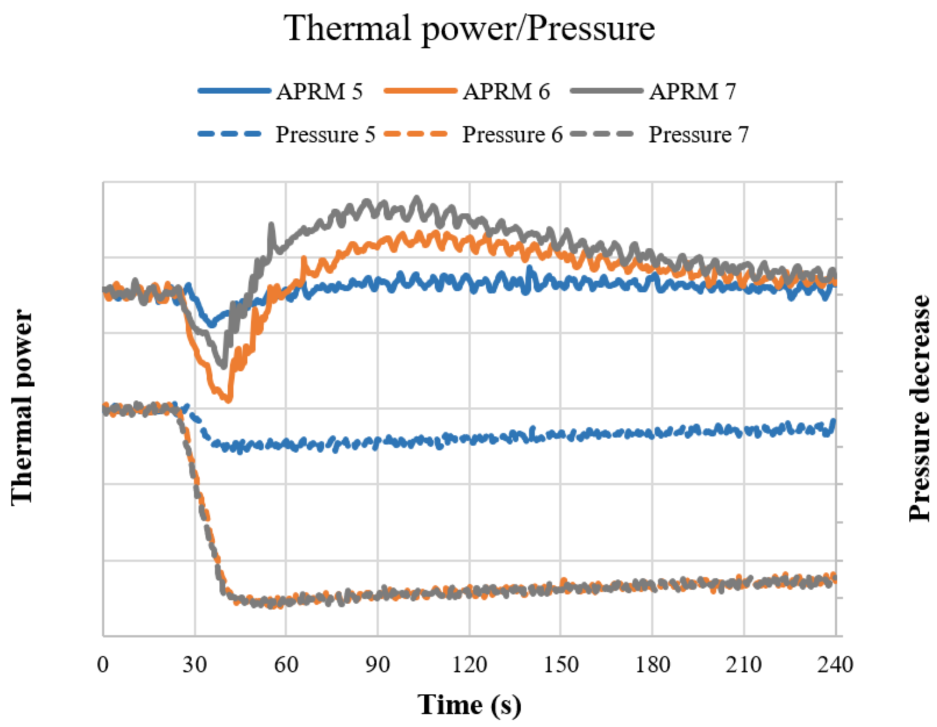


Figure 26: *Profile for the increase in thermal power, measured as APRM, and profile for pressure decrease at 109 %*

The larger frequency drops gave more significant increase in thermal power and a greater pressure drop compared with the lower frequency drop.

The usage of the PSPA-unit affected several parts of equipment of the process. There were small changes of the water level in the feedwater vessel, the steam flow to the turbines got slightly higher and the pumps in the turbine island got a slightly change for the mass flow rate. Moreover, some control valves were seen to work more actively during the frequency drop. The higher drops in frequency gave more significant effects on the equipment compared with the lower frequency drops; though, for the thermal power level of 109 %, the changes can be considered relatively small.

6.2.2 Modified controller

The modification with the controller was simulated at a thermal power level of 109 % for simulation 8. The frequency dropped with a maximum of 0.5 Hz, and thus, the results will be compared with the simulations without the modifications in the controller. In the figure below, the profile for the change in generator power is shown together with the frequency change.

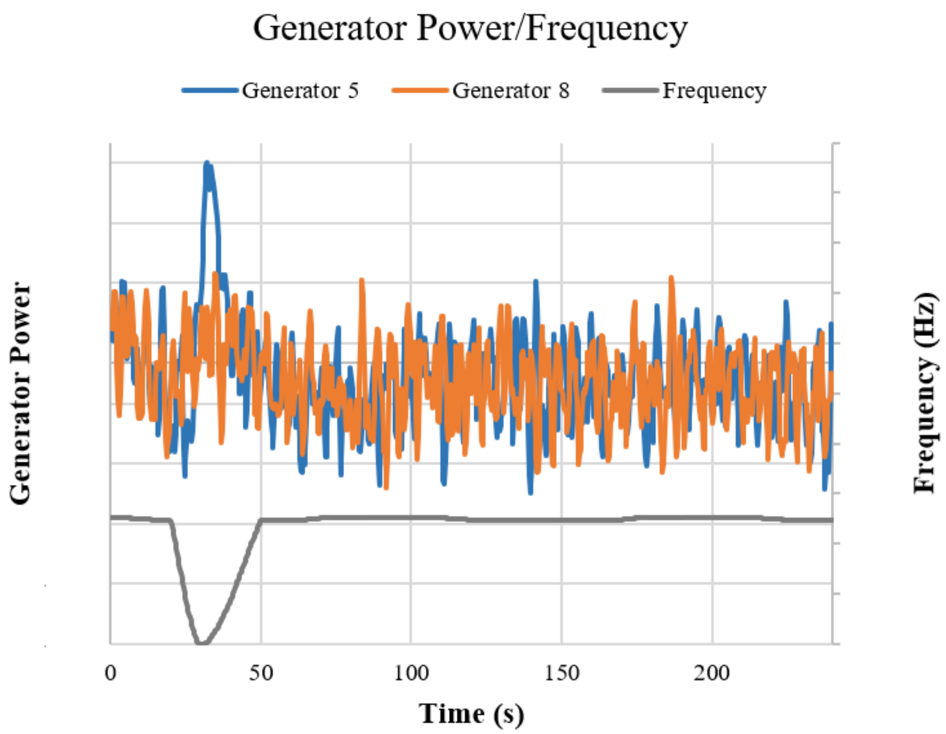


Figure 27: The profile for the generator power increase and the frequency change with the modified controller and the original controller at 109%

The simulation with the modified controller, simulation 8, gave no significant peak in generator power compared with the simulation with the original controller, simulation 5. In *figure 28*, the profile for the increase in thermal power and the profile for the pressure decrease are shown.

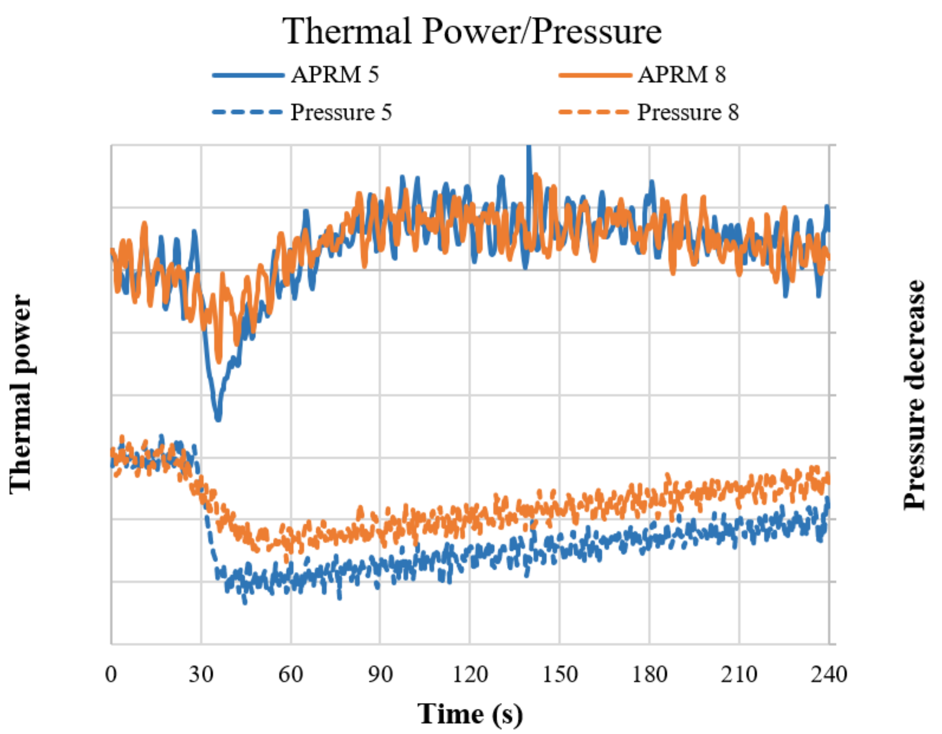


Figure 28: The generator power and the frequency for 109%

The decreases in thermal power and pressure are initiated earlier with the modified controller, simulation 8, compared with the original controller, simulation 5; though, the decreases are less significant with the modification.

6.3 Voltage disturbance

The simulations with the voltage disturbances were performed at 109% respectively at 129.1 % thermal power. Comparison between having power control active or frequency control active have been simulated. Simulations 9 and 11 are with frequency control activated and simulations 10 and 12 are with power control activated.

From the results, it was seen that the generator power increased for all simulations when there was a voltage drop, where the frequency control gave more significant results in the increase of generator power compared with power control for all simulations. The pressure in the reactor vessel also showed a significant difference regarding whether frequency control or power control was activated, where the frequency control gave more significant results here too. There was no indication for any drop in the mass flow rate for the recirculation pumps. The equipment got affected in a similar way as with the frequency disturbance in subchapter 6.2.1. The feedwater vessel got smaller changes in the water level, steam flow to the turbines got slightly higher and the pumps in the turbine island got a slight change of mass flow rate. Also, certain control valves was seen working more actively with their valve openings when the voltage disturbance was applied.

7 Discussion

The results from the simulations can be used for an evaluation of how Oskarshamn 3 can be used for flexible operation.

7.1 Power control

From the simulation with power control, it was seen that depending on the reduction in power, the operating parameters changed differently. As was mentioned in the results, a more significant decrease in power will most likely give more significant changes in certain process parameters, like steam flow to the turbines, mass flow rate in pipes, more actively changes of the positions of certain valves and changes in mass flows for several pumps in the process.

From the simulation results, it can be concluded that further analysis need to be performed for how each individual pump in the plant gets affected by the reduction in mass flow rates, since the operating point will move away from the optimal operating point at the pump curve, where too far away on the pump curve will increase the risks of improved damaging mechanisms and the pump will work less effectively.

The profile for the generator power followed the shape of the thermal power, which indicates that no unexpected surprises with the generator power will occur.

Due to the changes in condenser levels that was shown, there should be analysis how well the condenser can handle the improved load cycling. Also, the pressure changes will affect the process, where a lower pressure in the condenser will improve the total efficiency of the plant, while a higher will decrease the efficiency of the plant.

For the feedwater vessel, there should be analysis how a smaller change in the water level will affect it. The transients that occurred should also be considered when evaluating the impact on the feedwater vessel.

Due to more active valves, there should be an analysis on how well the current valves can handle more frequent changes in the valve positions. Certain valves may need to be re-built to handle this potential increase of usage.

The simulations showed different results in the condenser level, feedwater vessel level and certain valve positions for simulations 1 & 2 compared with simulations 3 & 4. This is most likely due to mistakes in the simulations for 3 & 4, where certain adjustments in process are needed to be performed when ramping in power.

The scenarios from 95% to maximum 120% should all be possible in regards of the simulation results. No safety system was activated and the changes in power could be performed on a daily basis. However, there have been no simulations of how the plant handles a longer reduction in power, like during a weekend. This could potentially be simulated for future work.

Yet, only certain parameters were simulated. Before making any decisions, further simulation should be performed with more parameters, like pressure and temperature for specific components. Also new core calculations should be performed before a potential applying of load following, for knowing which the maximum ramping rate allowed and when only baseload operation is suitable.

If it will be economically feasible to perform load following, a recommendation should be to first try the thermal power of 120% since this will give the smallest changes in core conditions and process parameters and also quicker response in ramping.

7.2 Frequency control

For the frequency control and the usage of the PSPA-unit, it was shown that the generator power peaked during a frequency disturbance. As was seen in the results, the larger frequency drops gave a larger increase in generator power.

It should also be noted that the simulations with the PSPA-unit are assumed to be close to how it should work practically. The control structure in APROS got a modification compared with the original control structure made by the manufacture, which was needed to get the PSPA-unit to properly work. This modification however needs to be verified with how the PSPA-unit are built in the plant to do simulations that will work more properly. The verification can only be done when the reactor is closed for maintenance, which was supposed to take place after this thesis was expected to be finished. Therefore, for this case it is only an assumption that the current design of the PSPA-unit works properly.

Apart from the smaller modification in the control structure, it was also simulated how a change in the frequency controller could improve how the plant copes with smaller frequency deviations. As already given, the drop of 0.5 Hz was tested with and without modification, where the modification only compensated the frequency in the range of 49.85 Hz to 50.15 Hz. With this modification, the pressure decrease will be smaller compared with the original one and the pressure decrease will be activated much earlier. The increase of generator power and thermal power was very small compared with the original value, meaning that the controller need further improvement. The controller should be tested with larger frequency drops and should give larger impacts to the recirculation pumps and the PSPA-unit than what was simulated here.

7.3 Voltage disturbances

With the activation of voltage disturbances, it could be seen that the generator power increased while the voltage dropped. There were different results depending on whether power control or frequency control was activated. The reason why the generator power increased much more for frequency control compared with power control is that in the frequency control mode, the thermal power is allowed to deviate, which makes the recirculation pumps increase their pump speed. This increases the thermal power, which will give a higher output in generator power. For power control, the reactor aims to hold the same thermal power in the reactor at all times; hence, with the voltage drop, the power control will still aim to hold the power constant at its given setpoint. The results from the voltage drop needs further validation due to that a voltage drop should ramp down the recirculation pumps, which the simulations in APROS did not consider. Therefore, investigations about how the pumps cope with voltage drops will be needed before enabling proper results. As mentioned in previous subchapters, there should be an analysis of how specific equipment will be affected.

8 Conclusions

From this thesis work it can be concluded that load following could be applicable for Oskarshamn 3. Potential scenarios are during night, weekends and the summer months. When the fuel is in its beginning, respectively the end of the fuel cycle, load following should not be applied. Some equipment like pumps and valves should be extensively monitored and evaluated to see how they will get affected by load following.

The PSPA-unit gave results showing an increase in generator power and drops in pressure after a disturbance in the grid frequency occurred. Equipment in the process may get affected due to the changes in the process conditions; thus, these need to be evaluated. The PSPA-unit have been tested with modifications in the control structure which could be further improved.

The PSPA-unit gave good response for voltage drops, both in power control mode and in frequency control mode. The generator power increased as a compensation for the voltage drop. The APROS-model should be improved, due to the lack of reduction in mass flow rate for the recirculation pumps that most likely will occur.

References

[1] Energimyndigheten, January 2020. [Online]. Available: www.energimyndigheten.se/statistik/den-officiella-statistiken.

[2] C. Bruynooghe, A. Eriksson och G. Fulli, ”Load-following Operating mode at Nuclear Power Plants (NPPs) and incidence on Operation and Maintenance (O&M) costs - Compatibility with wind power variability,” JRC - European Commission, 2010.

[3] ”Technical and Economic Aspects of Load Following with Nuclear Power Plants,” NUCLEAR ENERGY AGENCY, 2011.

[4] ”Non-baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation,” INTERNATIONAL ATOMIC ENERGY AGENCY, Austria, 2018.

[5] G. Choppin, J.-O. Liljenzin, J. Rydberg och C. Ekberg, ”Chapter 3 - Nuclei, Isotopes and Isotope Separation,” i *Radiochemistry and Nuclear Chemistry (Fourth Edition)*, Fourth Edition red., G. Choppin, J. Liljenzin, J. Rydberg och C. Ekberg, Red., Oxford, Academic Press, 2013, pp. 31-64.

[6] G. Choppin, J.-O. Liljenzin, J. Rydberg och C. Ekberg, ”Chapter 5 - Unstable Nuclei and Radioactive Decay,” i *Radiochemistry and Nuclear Chemistry (Fourth Edition)*, Fourth Edition red., G. Choppin, J. Liljenzin, J. Rydberg och C. Ekberg, Red., Oxford, Academic Press, 2013, pp. 85-123.

[7] B. Viswanathan, ”Chapter 5 - Nuclear Fission,” i *Energy Sources*, B. Viswanathan, Red., Amsterdam, Elsevier, 2017, pp. 113-126.

[8] M. F. L'Annunziata, ”Chapter 10 - Neutron Radiation,” i *Radioactivity (Second Edition)*, Second Edition red., M. F. L'Annunziata, Red., Boston, Elsevier, 2016, pp. 361-389.

[9] K. E. Holbert, ”Nuclear Reactors,” i *Kirk-Othmer Encyclopedia of Chemical Technology*, American Cancer Society, 2017, pp. 1-45.

[10] OKG AB, May 2020. [Online]. Available: okg.se.

[11] K. D. Kok, Nuclear Engineering Handbook, CRC Press, 2009.

[12] B. Pershagen, Lättvattenreaktorers säkerhet, Stockholm: Energiforskningsnämnden (Efn), 1986.

[13] M. A. El-Sharkawi, Electrical Energy - An introduction, 3 red., CRC-Press, 2013.

[14] M. Hänninen, J. Ylijoki och J. Kurki, ”THE CONSTITUTIVE EQUATIONS OF THE APROS SIX-EQUATION MODEL,” 2012.

[15] ”Nord Pool,” May 2020. [Online]. Available: www.nordpoolgroup.com.

[16] M. Lundbäck, ”Kärnkraftens roll i kraftsystemet,” Svenska Kraftnät, 2019.

[17] H. Klomp, ”Elstatistik,” February 2020. [Online]. Available: https://elstatistik.se/.

[18] Statistikmyndigheten SCB, January 2020. [Online]. Available: www.scb.se.

[19] D. Karlsson och A. Nordling, ”Svängmassa i elsystemet - En underlagsstudie,” Kungl. Ingenjörsvetenskapsakademien (IVA), 2016.

[20] T. Smed, ”Delivering flexible power and ancillary services with nuclear power [PowerPoint],” April 2019. [Online]. Available: https://energiforsk.se/media/26159/nuclear_forsmark_smed.pdf.

[21] ”Program on Technology Innovation: Approach to Transition Nuclear Power Plants to Flexible Operations,” EPRI, Palo, CA, 2014.

[22] L. Holger, T. Salnikova, A. Stockman och U. Wass, ”Load cycling capabilities of German Nuclera Power Plants (NPP),” *International Journal for Nuclear Power,* vol. 55, 8 2010.

[23] B. Gjorgiev och M. Cepin, ”Nuclear Power Plant Load Following: Problem Definition and Application,” i *Nuclear Energy For New Europe 2011,* Bovec, 2011.

[24] M. Bakirov, ”7 - Impact of operational loads and creep, fatigue and corrosion interactions on nuclear power plant systems, structures and components (SSC),” i *Understanding and Mitigating Ageing in Nuclear Power Plants*, P. G. Tipping, Red., Woodhead Publishing, 2010, pp. 146-188.

[25] R. Nordmann och C. Ranisch, ”Vibrations caused by load-following in NPPs,” Energiforsk AB, 2018.

[26] W. C. Lyons, G. J. Plisga och M. D. Lorenz, Red., ”Chapter 4 - Drilling and Well Completions,” i *Standard Handbook of Petroleum and Natural Gas Engineering (Third Edition)*, Third Edition red., Boston, Gulf Professional Publishing, 2016, pp. 4-1 - 4-584.

[27] S. Aas, ”The effects of load-following operation on fuel rods,” *Nuclear Engineering and Design,* vol. 33, pp. 261-268, 1975.

[28] G. Choppin, J.-O. Liljenzin, J. Rydberg och C. Ekberg, ”Chapter 19 - Principles of Nuclear Power,” i *Radiochemistry and Nuclear Chemistry (Fourth Edition),* Fourth Edition red., G. Choppin, J. Liljenzin, J. Rydberg och C. Ekberg, Red., Oxford, Academic Press, 2013, pp. 595-653.

[29] A. A. Rashdan och D. Roberson, ”A Frequency Domain Control Perspective on Xenon Resistance for Load Following of Thermal Nuclear Reactors,” *IEEE Transactions on Nuclear Science,* vol. 66, pp. 2034-2041, 9 2019.

[30] J. Persson, K. Andgren, M. Engström, A. Holm, L. T. Pettersson, K. Ringdahl och J. Sandström, ”Lastföljning i kärnkraftverk,” ELFORSK AB, 2011.