Improved control strategies for primary frequency control in Swedish combined heat and power plants

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Abstract

A model of the Swedish power plant Mälardalen Energi, developed by Solvina AB was simulated in Dymola with different types of control strategies in order to evaluate if they could improve the operational flexibility of the plant and, thus, its ability to deliver frequency control to the Swedish power grid. Several different control strategies and process modifications were tested and compared to previous simulations done by Solvina. Overall, the results show that improvements could be done to the systems deviation in steam net pressure and district heating temperature by implementing a slightly more complex control structure or by modifying the system slightly. The simulations showed that implementing a feed forward on the already existing control structure would improve the deviations of the outlet temperature of the district heating network. Furthermore, implementing a split range control structure that first throttled the steam exhaust drains and then opened the turbine inlet valve, decreased the steam net pressure drop when increasing the production demand. Lastly, modifying the turbine with inlets at different pressures and letting a split-range controller manipulate the flows between them gave the overall best performance. Finally, several factors such as economy, performance, difficulty to implement and potential confusion for the operators need to be considered in order to determine which of the control structures that are the best.

Acknowledgements

This project was done for the department of automatic control in cooperation with the company Solvina AB as a master thesis for the master’s program in chemical engineering at Lund University. The scope of the project was to evaluate different control strategies and process modifications in order to investigate the possibilities for Swedish combined heat and power plants to deliver frequency control to the power grid. This was a continuation of previous work done at the company. Special thanks and gratitude to the staff at Solvina AB for all the help and a special credit to my mentors Tore Hägglund and Henrik Granberg for assisting in the project.

Contents

1. Introduction

In the power grid the produced and consumed electricity always has to be the same. If more or less power is produced than what is needed the frequency of the generators in the grid will deviate from their nominal value of 50 Hz. If that occurs for long periods of time it can lead to equipment damage or failure. In Sweden, hydro power plants are designed to handle this issue via frequency control, meaning that when too much or too little electricity is produced and the frequency of the grid changes, they can quickly alter their production accordingly. Swedish combined heat and power plants, however, are today not designed to be able to deliver frequency control to the grid. In the future it is predicted that the hydro power plants alone will not be sufficient in delivering this service, due to the rise in intermittent renewable energy sources such as wind and solar, the removal of nuclear power plants and future dryer climate from global warming. Hence, it is of great interest to research the potential possibilities for the combined heat and power plants. According to Svenska Kraftnät, to be allowed to deliver frequency control one must be able to alter their production and deliver 63% of their frequency control in in less than 60 seconds and 100% of the power in 3 minutes (Svenska kraftnät, 2018). In this master thesis a model of a typical Swedish power plant has been built in the simulation software Dymola. Different scenarios and control structures for the boiler, turbines and district heating system have been simulated to investigate how well the system would be able to respond to changes in electricity production. Additionally, the dynamic response of the steam net pressure and district heating temperature were studied and used to evaluate the system. This master thesis was done in cooperation with Solvina AB and it was a continuation of previous and ongoing projects that the company has done in this subject of implementation of frequency control in power plants.

1.1 Outline of thesis

The following chapters of the thesis describe the background of the project, the methods and findings. Chapter 2 describes the model that was used in the project and how combined heat and power plants work. Chapter 3 describes the methods and control strategies that were tested and chapter 4 displays the results and findings.

2. Background

The following sections describes a general combined heat and power plant, the process model that was used in Dymola to model the system and some of the control structures used in the project.

2.1 Combined heat and power plant

The process studied in this project is a swedish combined heat and power plant. Typically, combined heat and power plants produce energy and district heating by burning fuel which produces steam. The steam is then fed through turbines where electricity is generated. The steam at the outlet of the turbine is then condensed, which generates heat for the district heating. Lastly, the condensed steam is pumped back to the boiler and the cycle is completed. Overall, the process consists of the following 4 main unit-operations.

- Boiler
- Turbine
- District Heating Network
- Feed Water and condensing Tank

A general schematic of the process is displayed in figure 2.1. In the boiler of the power plant, water is evaporated through combustion of a fuel source. The fuel is often some type of carbon compound mixture like trash, wood chips or natural gas etc. Consequently, the heat released during the combustion is transferred to the incoming water which causes it to evaporate. In order to improve the efficiency of the process, the boiler often has additional parts such as an economizer for preheating the feed water or an additional heater to produce superheated steam to generate more electricity in the turbines. Depending on the type of fuel and the demand of heat and electricity the boiler is often ran at different loads. If for instance the fuel is some type of trash, some of the plant’s revenue will come from the combustion. Hence, those type of power plants are often operated at the highest possible base load. If the fuel, on the other hand, is costly the plant will generally be operated such that the most amount of electricity is produced per kg of fuel. This in turn impacts things such as the potential to use direct condensation valves to control quick changes in pressure or how the drains from turbine are used in cooperation with the district heating. Lastly, to avoid equipment damage it is paramount to keep the pressure in the steam net of the boiler and turbine below a critical value. For the plant used in this study its 58 bar.

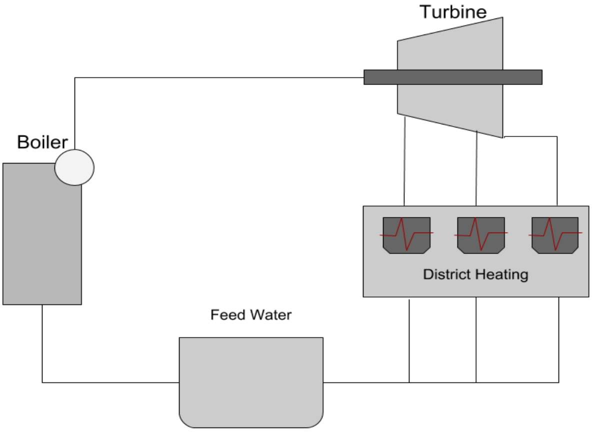

Figure 2.1 Combined heat and power plant

After the water has been evaporated it is fed through the turbines where all the electricity is generated. The turbine produces electricity from the mechanical rotation of the blades which is caused by the incoming steam flow. The incoming steam has a higher pressure than the steam in the outlet of the turbine. The difference in pressure causes the steam to expand which in turn is what creates the rotation of the blades that generates the electrical work. To improve the overall performance of the process via preheating and to generate heat for the district heating network some steam is drained at different pressures throughout the turbine. Figure 2.2 shows a conceptual design of how it can look like.

In the district heating network, the outlet steam from the turbine is condensed, which releases heat. This heat is then transported to the incoming district heating water via a heat exchanger. The warm water can then be sold and used by municipals. Thus, by generating both heat and electricity the overall profitability of the plant is increased.

Lastly, the condensed steam from the preheating and district heating drains is mixed in a feed water tank. The liquid is then pumped back to the boiler and the cycle is completed.

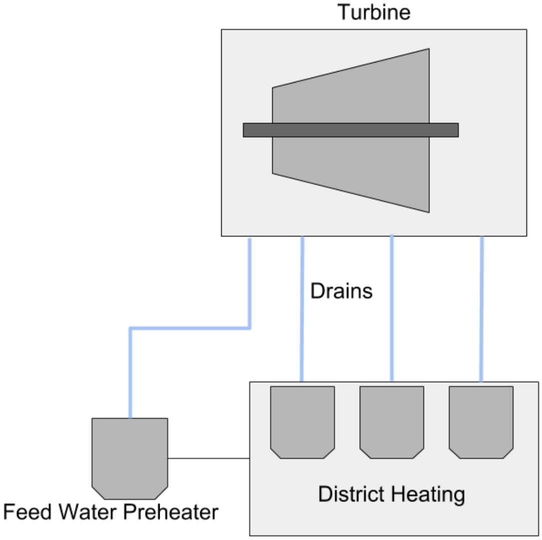

Figure 2.2 Turbine with drains

2.2 Dymola and process model

Dymola is a simulation software that is used throughout this project. It uses the modelica coding language and consists of an interface where different blocks are dragged and dropped from a library in order to model a system. Each block has its own characteristics and mathematical correlations. By using multiple blocks and connecting them a system, for instance a turbine, motor, pump, heat exchanger etc. can be modeled. The software can then simulate the created system for a set amount of time and the results can be exported. Generally, Dymola simulates the system by solving the mass, energy and momentum balances as well as some additional empirical correlations for things such as pressure drops, power generation etc. for the blocks. By doing that the behavior of the system can be predicted and one can investigate how it will respond to different changes. Furthermore, different controllers and control structures can easily be implemented in the model in order for Dymola to see how a system will respond to different control structures. This feature is used extensively in this project (Modelon Dymola Introduction course 2017). The model used in this project is developed by Solvina AB and is based on the power plant Mälardalen Energi, with some slight modifications to make it more representable of a general Swedish plant. The plant has a maximum capacity of 41 MW of electricity production and the model has a hierarchical structure consisting of the following main units which are described in more detail below. In addition, the model has been used in an ongoing project in the same topic. The interface of the Dymola model is displayed in figure 2.3.

- Boiler
    - Combustion chamber
    - Steam Dome
    - Superheater with temperature control
    - Economizer

- Turbine with drains

- Condenser for preheating of feed water

- Feed water tank

- District heating system

The goal of the boiler model is to, based on the characteristics of the feed water, compute the correct amount of steam with the right properties such as pressure, temperature etc. Consequently, it should have the correct dynamic response to changes in load, feed water temperature, air flow etc.

To capture this behavior, the model contains mathematical equations for combustion dynamics and heat transfer, as well as sub models such as superheaters; economizer; steam dome; internal control system etc. The structure of the boiler model and its interface in Dymola can be seen in figure 2.4.

The various blocks in figure 2.4 represent the different parts of the boiler, such as combustion chamber, economizer, superheater, steam dome, flue gas preheater etc. Additionally, the blue lines represent how the water flows in the boiler, the green lines show the flow of air and fuel, and the red lines represent the generated heat flows. The yellow dashed lines are control signals to regulate the level of the steam dome, the correct air to fuel ratio, steam outlet temperature, feed water pressure etc.

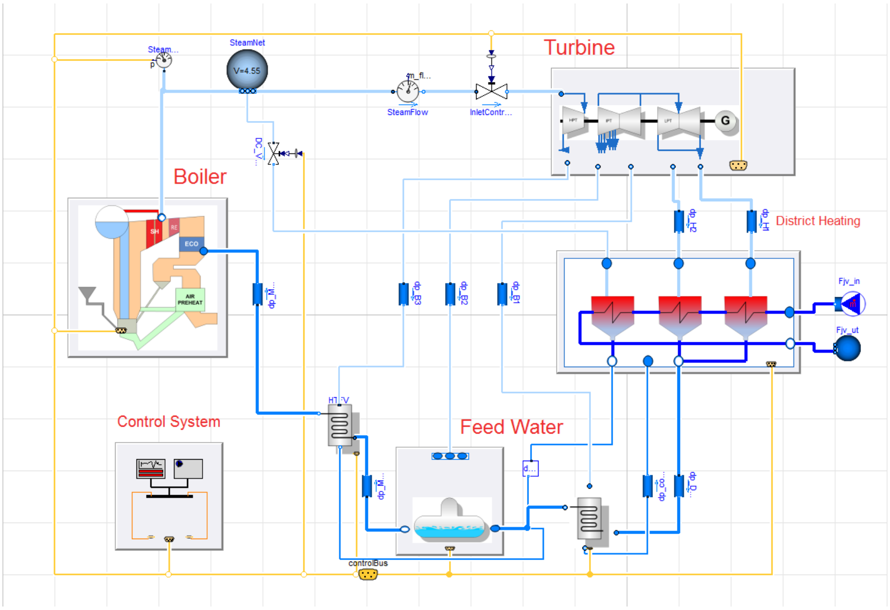

Figure 2.3 Interface of Dymola process model

The turbine is based on models with single turbine steps which utilize enthalpy differences in the inlet and outlet steam to compute the generated power. Additionally, there are connecting drains after each of the single turbine steps. Using this correlation the model is able to compute the electricity production, steam flow and pressure drops. The interface of the turbine model is displayed in figure 2.5.

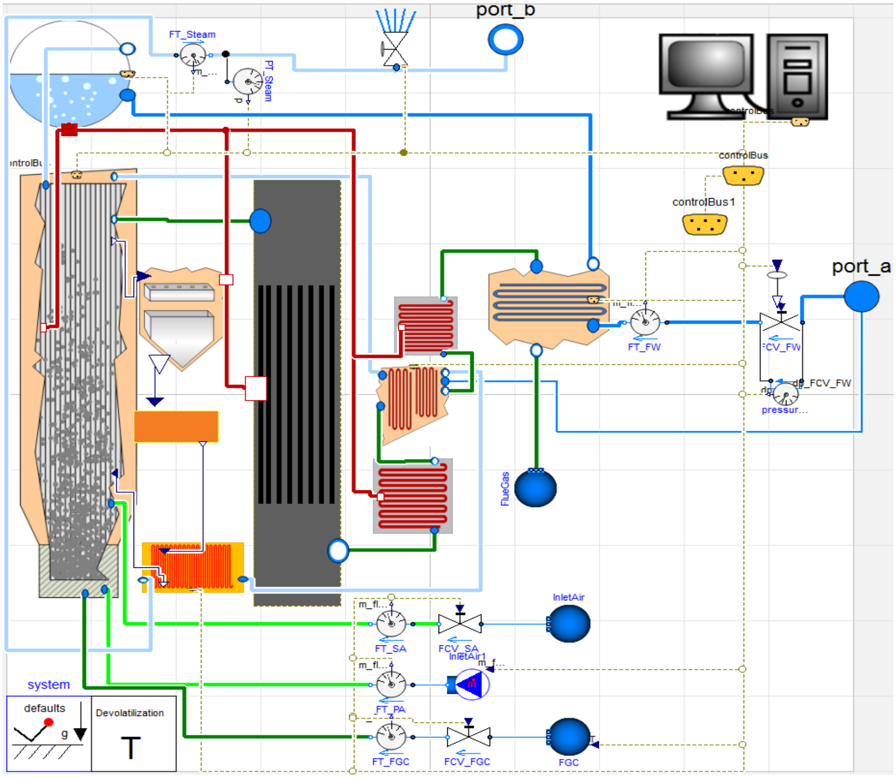

Figure 2.4 Boiler model interface

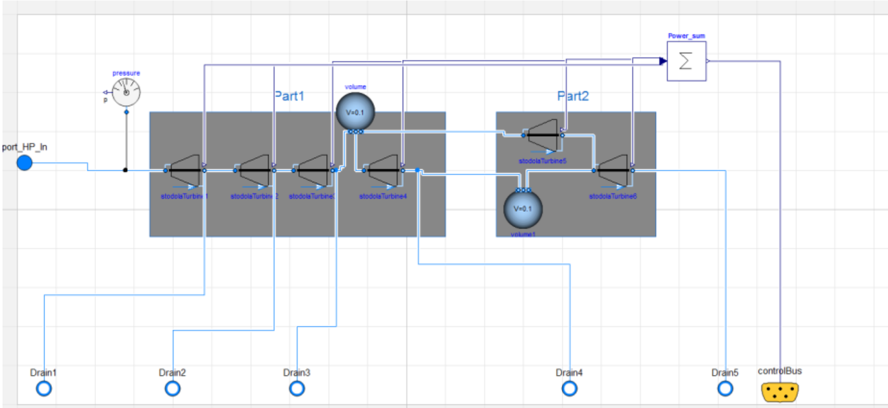

Figure 2.5 Turbine model interface

The preheaters and condensers are modelled as shell and tube heat exchangers in order to compute the heat transfer between the steam and the feed water. The transferred energy is computed using common heat exchanger energy correlations with heat transfer coefficients and logarithmic mean temperature difference.

The district heating system is modeled similarly to the preheaters and condensers. The target of the model is to capture the effects on the outlet temperature, depending on the different control strategies used. This can then be used as one possible evaluation criteria for the control system. The sub model of the district heating network is presented in figure 2.6.

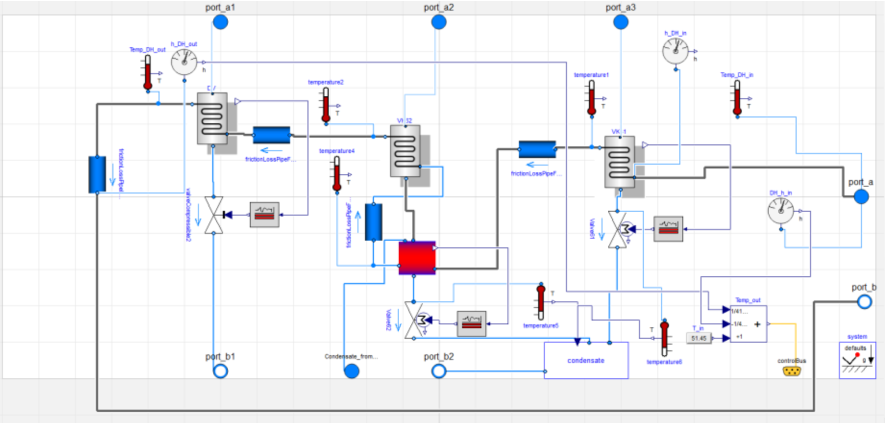

Figure 2.6 District heating model interface

The dark thick line shows how the how the water flows through the system. The grey and black boxes are the condensers where the heat transfer from the drained steam and the district heating water occur. Lastly, the blue boxes represent the pipes and the consequent pressure drops that transpire.

2.3 Control structures

Feed forward

Feed forward is a control strategy that is used in a lot of applications and can often improve the performance of a system. It consist of measuring a disturbance and converting that to a signal that is added to the controller. If this is done correctly, the system is able to counteract disturbances quicker by not having to “wait” for the disturbance to propagate in the process. An example for this is for instance temperature control of a heat exchanger. By measuring both the incoming and outgoing temperature and forwarding that information to the temperature controller, the process becomes better at handling fluctuations. Generally, for simplicity, feed forward is implemented by measuring the deviation of the disturbance and then multiplying that by a factor K_f. That signal is then added to the controller to partially compensate for it. Figure 2.7 shows a block diagram of a general feed forward control structure (Forsman 2005; Hägglund 2008).

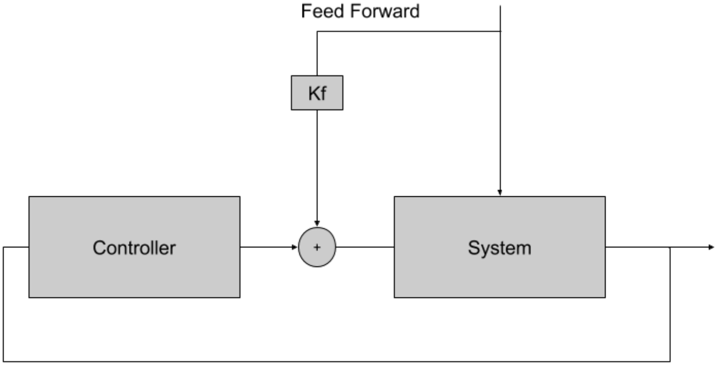

Figure 2.7 Feed forward block diagram

Mid-Ranging

Mid-ranging is a control strategy that is used when you have one measurement signal and two control signals to regulate a process variable. A typical example can be if you have two valves that are used to control the flow through a pipe. To make the two valves cooperate, a mid-ranging structure can be used. Mid-ranging works by letting one of the controllers control the process variable, whilst the other is in charge of controlling the output signal of the other controller. This means that the input signal to the other controller is the output signal of the first. Going back to the example with two valves and one pipe, one valve is used to control the flow of the pipe and the other is used to make sure that the other valve operates at 50% of its opening. For this to work well, the valve controlling the flow should be quick and able to handle small changes, whilst, the other should be slow, robust and able to cope with larger changes in flow rate. A block diagram of a mid-ranging strategy can be seen in figure 2.8 below (Forsman 2005; Hägglund 2008).

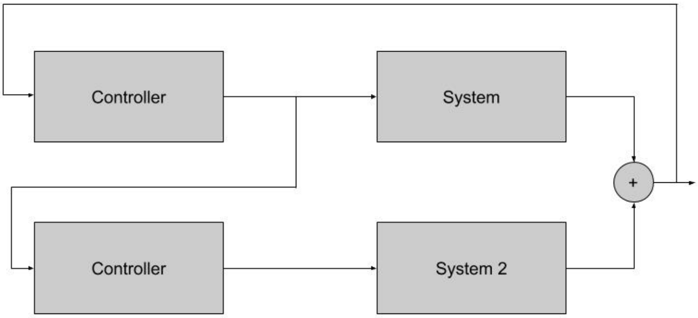

Figure 2.8 Mid-ranging block diagram

Split-Range

Split-range is a control structure that is used when you have one controller and multiple output control signals. It is used when you have units that should take turn in controlling the process variable, depending on the output signal of the controller. For instance, you may have one tank with two outlets and depending on the conditions of the process and the output of the controller you might want to use them individually or simultaneously. This is possible with a split-range control structure. It works by splitting the control signal into different segments depending on the output of the controller. Figure 2.9 below shows a split range controller that controls the flow through a turbine. Firstly, two smaller valves open to control the flow and, lastly, a larger one if more is required (Forsman 2005; Hägglund 2008).

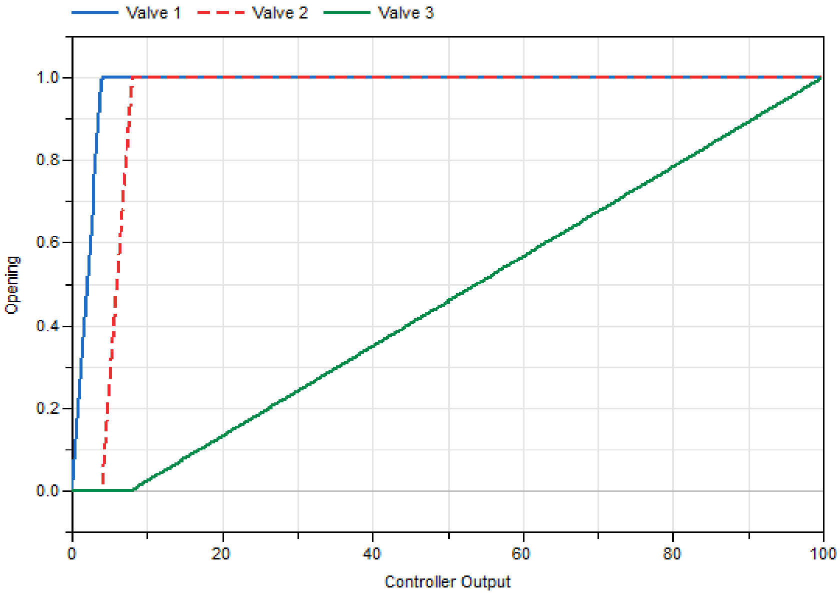

Figure 2.9 Split range controller

2.4 Previous work

This topic has been researched previously by Solvina where they investigated whether or not it could be technically and economically possible for Swedish combined heat and power plant to be able to deliver frequency control. The conclusions there where that if the boiler and turbines were fast enough and able to operate at different loads, it should be technically feasible. However no detailed model was simulated so the dynamics of a plant were unknown (Eng et al 2014). Moreover, Solvina is currently doing a project for Energiforsk, where they have been investigating the implementation of primary frequency control in Swedish combined heat and power plants by using the Dymola model described above. This project is about to be finished and some of the results from it is what this master thesis will build upon and be compared to.

In Denmark, combined heat and power plants are already used to deliver frequency control. This is done by running the plant at part load and using a direct condensing valve to regulate quick changes in the pressures in the steam net (Hasselbalch et al 2011).

Furthermore, research in this topic or similar has been done in other countries as well. Zhao et al, investigated the operational flexibility of a coal-fired power plant by regulating the extraction steam from the high-pressure preheaters and by varying the flow in the feedwater bypass. They found that quick changes in electricity production around 10 s could be done by throttling the valves from the extraction steam outlets. Another method to quickly change the production of power plants that has been investigated is by letting the plant run with a slightly throttled turbine inlet valve (around 30-50%). By then slightly opening or closing the valve, quick changes in electricity generation can then be made. This works due to the built-up steam in the pipes between the boiler and turbine. Doing this will momentarily cause the pressure in the steam net to drop, however if it does not drop below a critical value, the process is not damaged (Alobaid et al 2016; Esmaeili et al 2017; Hübel et al 2014; Stevanovic et al 2018; Zhao et al 2018).

Overall, from previous studies, the two general methods to quickly enough alter the electricity production for a power plant seems to be by either changing the extraction steam for the preheaters or by changing the opening of the turbine inlet valve.

3. Method

The model based on Mälardalen Energi (previously described in section 2.2) was used in all the simulations. A base case for electricity production for the system was set up at part load. Consequently, a set point step change in electricity production was introduced to the model. The base load and set point changes was determined based on previous simulations done by Solvina in order to compare the performance. The dynamics of the system was then simulated in Dymola to investigate how it would respond to quickly changing production demand. Consequently, results were saved and used to evaluate the process.

Different control strategies and modifications were made to the process model in Dymola, and the results of steam net pressure, generated electricity and district heating temperature were exported and compared to previous simulations done by the company, referred to as “standard case” in sections below. The different strategies and modifications that were made, as well as the different scenarios, are explained in more detail below. Lastly, not all possible combinatorial combinations of the control strategies were tested to limit the amount of work in the project.

3.1 Boiler Feed Forward

The setpoint of electricity production for the plant was set at a partial load at 27 and 30 MW. Consequently, a step change of size 7.3 MW was introduced and kept for 1 hour. This corresponds to the maximum potential delivered frequency control for the plant. Figure 3.1 shows the change in the setpoint for produced electricity for the 27 MW case.

The electricity production of the plant was regulated by manipulating the opening of the turbine inlet valve. The load of the boiler was manipulated based on the delivered temperature of the district heating network and the direct condensation valve was set to control quick changes in the steam net pressure. Furthermore, the steam flow into the turbine was measured and the deviation from its nominal value was added to the boiler via a feedforward factor. This was done to hopefully speed up the boiler and reduce the pressure loss in the steam net and deviation of the temperature in the district heating network. Figure 3.2 displays conceptually how the scenario was set up. Lastly, all process variables in this and consequent strategies were controlled using PI-controllers.

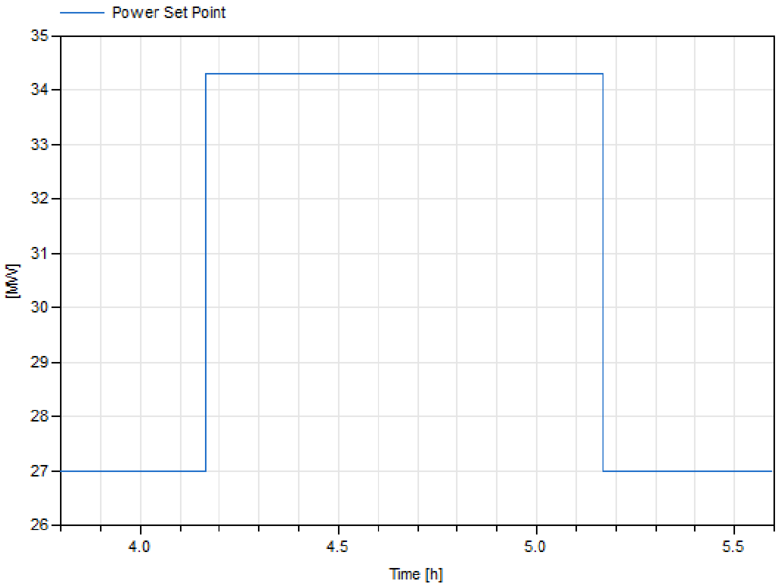

Figure 3.1 Electricity production set point change

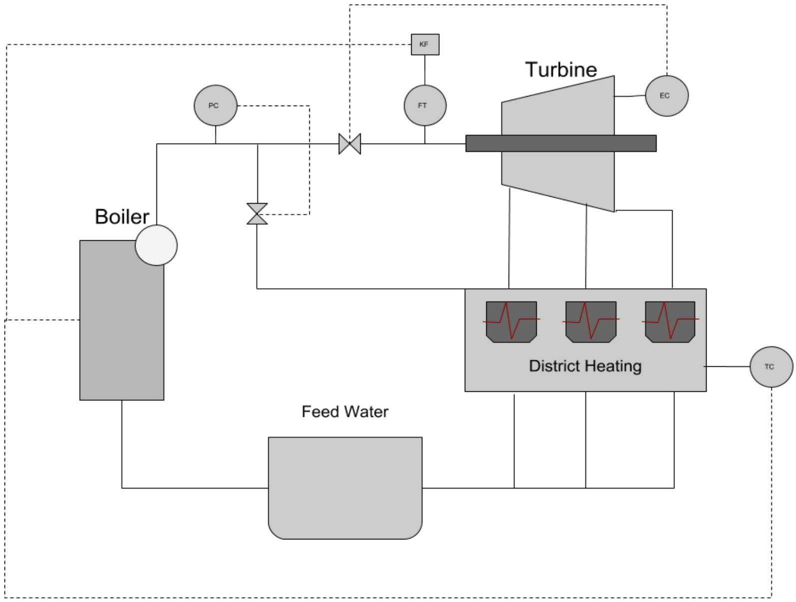

Figure 3.2 Feed forward control strategy

3.2 Primary Air Overshoot

The second scenario was set up similarly to the first one. Setpoint of electricity production was set to 30 MW and the step change was sized at 7.3 MW. The Production of electricity was controlled using the turbine inlet valve and the load of the boiler was changed based on the outlet temperature of the district heating water. Furthermore, the direct condensation valve controlled quick changes in steam net pressure and the steam flow into the turbine was measured in order to use it as a feed forward to the boiler. Lastly, an overshoot to the primary air was introduced if the pressure in the steam net were to fall from 74 to below 73 bar. If that happened the setpoint of primary air would get an additional factor which would ramp down when the steam net pressure would become larger than 73 bar again. Figure 3.3 shows how the overshoot of primary air was introduced.

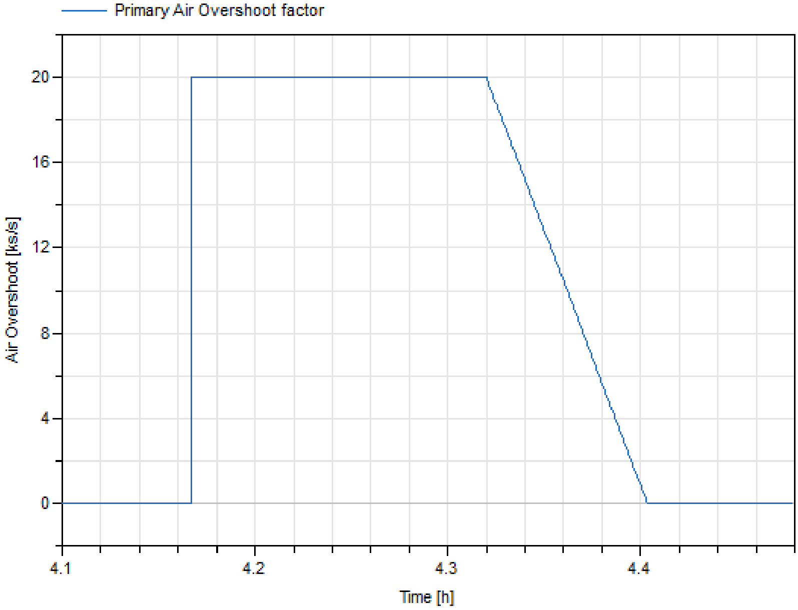

Figure 3.3 Primary air overshoot

The goal of this scenario was to investigate whether additional air could be used to temporarily speed up the production of steam from the boiler and, thereby, increase the steam net pressure quicker. Generally, the air dynamics in the boiler are quick, which is why this could potentially improve the performance of the plant. The decision of using primary air instead of secondary was based on experience from the company.

3.3 Steam extraction from Turbine via split range control

A step change in the electricity production set point was introduced from 27 to 34.3 MW. This and all consequent strategies were tested at that base load to be able to compare them to previous work done at Solvina AB. Quick changes in steam net pressure was controlled using the direct condensation valve. Furthermore, the load of the boiler was altered using two controllers. One controller utilized the outlet temperature of the district heating water and the other utilized the pressure in the steam net. The control signal that was used was chosen with a maximum value filter. Lastly, the electricity generation was controlled using the inlet valve of the turbine and its first two drains. Using a split-range controller, the system would first throttle the turbine drains for small changes in load and if that was not sufficient it would open the inlet valve of the turbine more. Since the inlet valve of the turbine does not have to change its opening as much as in the previous strategies, the pressure of the steam net would hopefully not drop as much, which would then improve the performance of the system. Lastly, if the load of the boiler were to be controlled using only the outlet temperature of the district heating, it would not work when the production is increased. When the setpoint of electricity production is increased the turbine drains will be throttled which causes more steam to be condensed in the district heating network. This makes the temperature too high which in turn signals the boiler controller to lower the load. This is the opposite of what the boiler should do in this case. When the production demand is increased the boiler-load must increase otherwise not enough steam is produced to maintain the pressure of the steam net. Hence, the introduction of the maximum value filter. Figure 3.4 illustrates how the overall control structure was done.

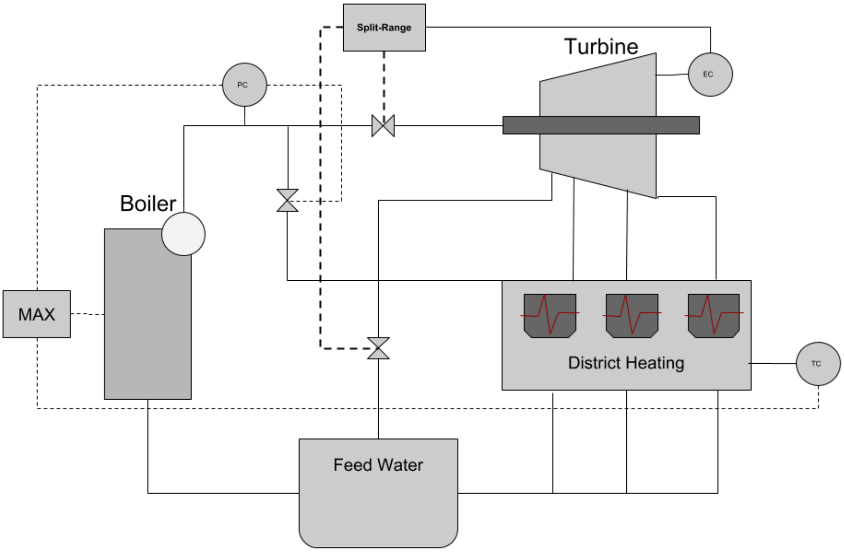

Figure 3.4 Split-range control strategy

3.4 Mid-range control of direct condensation valve via boiler with changing valve setpoint

Similar to the previous strategies a step change in production was done from 27 to 34.3 MW. Electricity production was controlled using the turbine inlet valve and the steam net pressure was controlled using the direct condensation valve. This time however the boiler was controlled depending on the position of the direct condensation valve via a mid-ranging strategy. When the pressure in the steam net drops the direct-condensation valve closes to counteract this, which in turn signals the boiler to increase the load. To be able to simultaneously control the outlet temperature of the district heating network, the setpoint of the direct condensation valve was changed depending on the flow rate from the turbine drains to the district heating. This means that when the production is increased, the system should be able to somewhat counteract the increased flow to the district heating via the drains by decreasing the position of the direct condensation valve and in turn keep the outlet temperature constant. Figure 3.5 displays conceptually how this was done in Dymola.

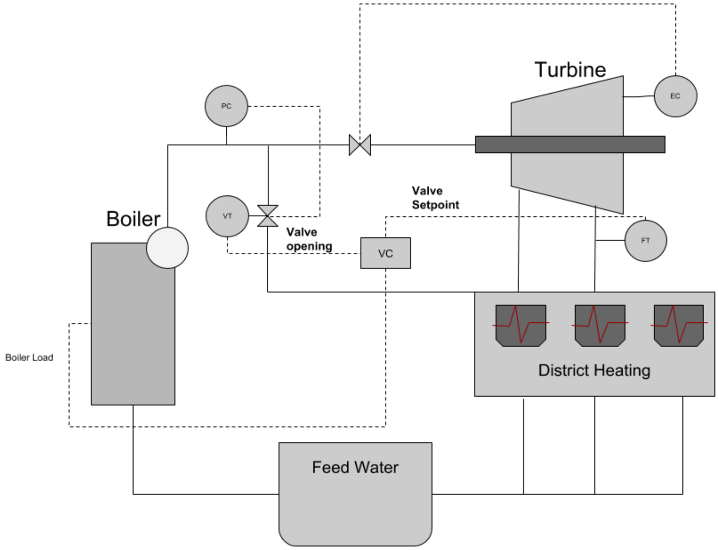

Figure 3.5 Mid-ranging control strategy

3.5 Combined split-range steam extraction and mid-range direct condensation valve control

One of the later scenarios that was investigated was a combination of the split-range and the mid-range strategy. Meaning that the electricity production was controlled by the inlet valve to the turbine and by throttling two of the preheating drains. Furthermore, the boiler load was controlled depending on the position of the direct condensation valve and the set point for the valve was determined depending of the flow rate from the turbine to the district heating network. This design should hopefully be able to have a lower pressure drop in the steam net and still small deviations in the temperature in the district heating network, whilst, still being able to quickly alter its electricity production. Figure 3.6 illustrates how this was implemented in Dymola.

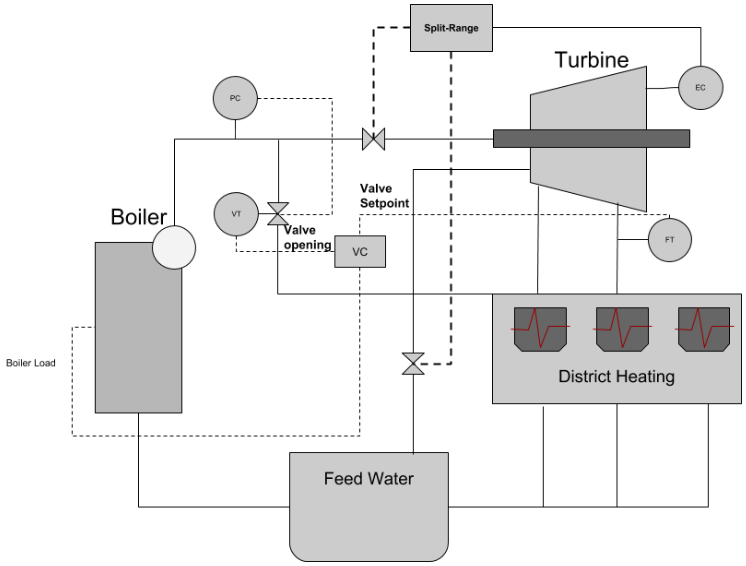

Figure 3.6 Combined split and mid-range strategy

3.6 Turbine flow distribution with feed forward and mid ranging

The second last strategy that was tested also involved some slight modifications to the process. The turbine was modified to have two inlets, one at the start and one after the first turbine stage. Using a reduction valve some of the flow from the inlet was bypassed and inserted after the first stage at a lower pressure. Doing this less steam flows through the entire turbine and, thus, the efficiency of the turbine is slightly decreased. The operational flexibility, however, is in this case greatly improved since the opening of the reduction valve can be adjusted to quickly change the electricity production without affecting the steam net pressure. A split range controller was introduced to control the electricity production. The controller would first throttle the reduction bypass valve and then open the inlet valve. Doing this the inlet valve would not have to be opened as much as in the standard case, hence, the steam net pressure drop would be improved. Consequently, to reduce the deviation of the district heating outlet temperature, this was tested with two of the different strategies from above. Firstly, the turbine flow distribution was tested with the feed forward strategy and after it was combined with the mid ranging strategy described earlier. Figure 3.7 and 3.8 show conceptually the two combinations that were tested and how they were implemented.

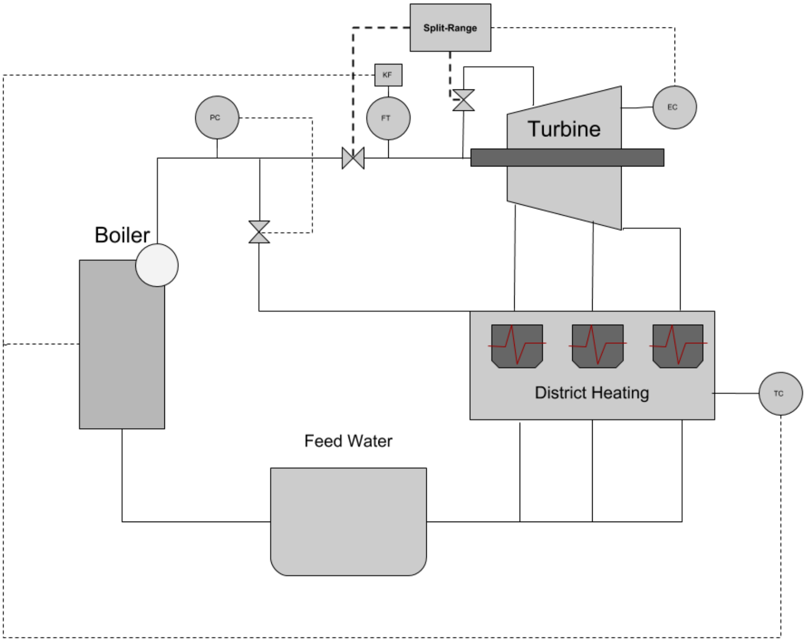

Figure 3.7 Flow distribution and feed forward combination

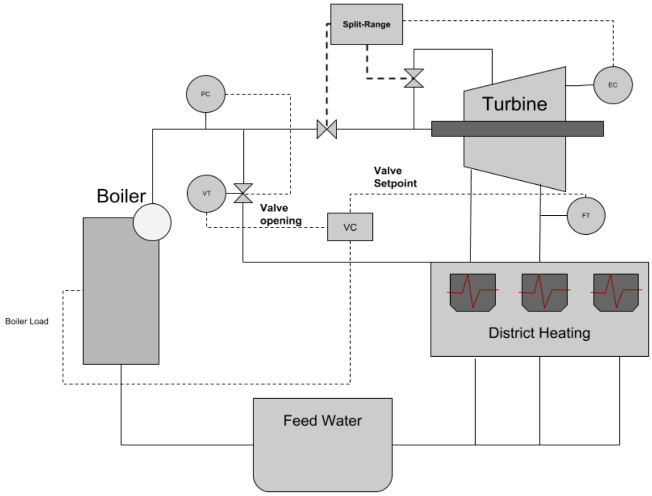

Figure 3.8 Flow distribution and mid-ranging combination

3.7 Combined turbine flow distribution steam extraction and mid-range direct condensation valve control

The final control strategy that was simulated was a combination of many of the previous ones. It utilized a split range control that would, firstly, throttle the turbine flow distribution reduction valve, secondly, the turbine drains and, lastly, open the inlet valve. Additionally, fast changes in steam net pressures were controlled using the direct condensation valve. Finally, the mid-ranging control strategy, described above, was used to control the outlet temperature of the district heating network. Since this strategy used both the reduction valve and turbine drains before opening the inlet valve the steam net pressure drop would hopefully be almost eliminated. This combined with the dynamic set point of the direct condensation valve should also reduce the deviation of the district heating temperature. Figure 3.9 shows how everything was set up.

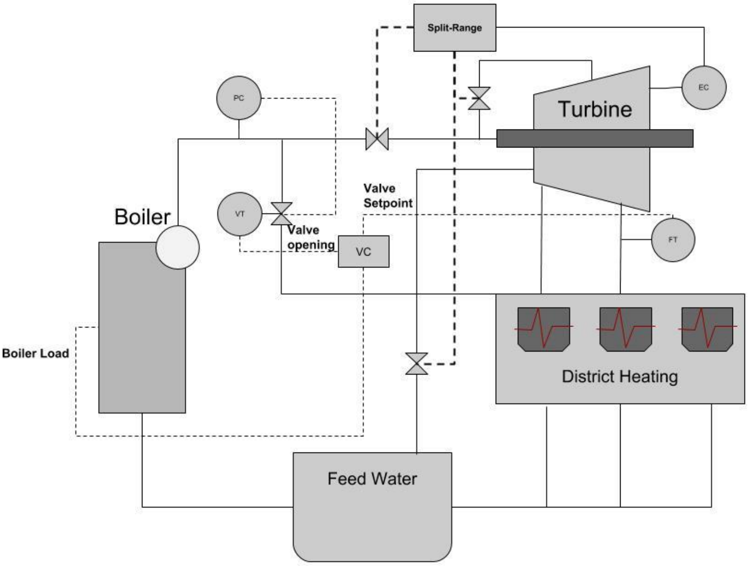

Figure 3.9 Combined flow distribution turbine drain and mid-ranging control strategy

4. Results and Discussion

4.1 Feed Forward

The outcome of the simulations can be seen in figures 4.1-4.6. The figures show the response of the electricity production, pressure in the steam net and district heating temperature after a step change in the production set point. The figures display the dynamics for a case with and without the feed forward to the boiler and for the two different base loads.

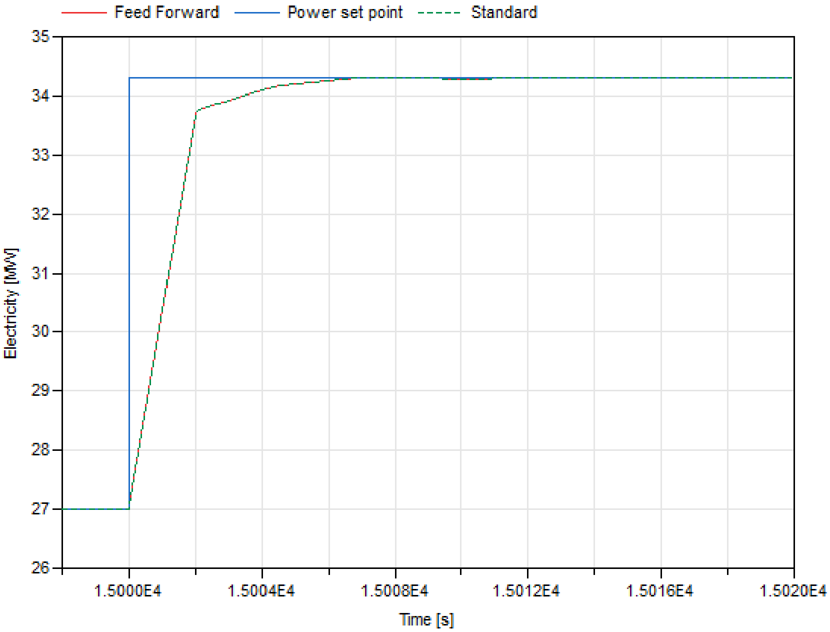

Figure 4.1 Electricity production 27 MW base load

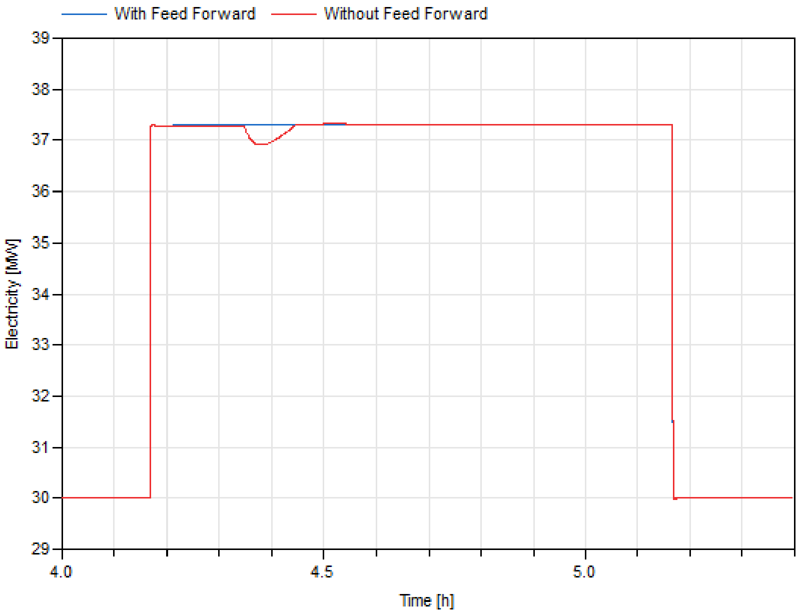

Figure 4.2 Electricity production 30 MW base load

Figure 4.1 shows that the system is able to quickly deliver a higher amount of electricity. The response time is around 12 seconds to reach 100 % of the delivered frequency control, which is much less than the demand from Svenska kraftnät. At a base load of 30MW, however, the regular system is not able to deliver the set amount of electricity throughout the entire 1 h step change. This is due to the boiler not being quick enough to increase its steam production to compensate for the extra flow of steam into the turbine. This can be seen further in the figure 4.3 displaying the steam net pressure. In all the cases where the system manages to produce sufficient steam the time to increase the generated electricity is almost instant. It takes only a few seconds. This is expected since valves generally have fast dynamics and the controllers are trimmed to respond rapidly. Furthermore, there is no difference in electricity production with and without feedforward for the 27 MW case. This is also expected since the dynamics of the valve should not be affected by the boiler load. What should be impacted, however, is the pressure in the steam net. Lastly, since delivered frequency control is much quicker than the demand from Svenska kraftnät, it could be argued that the electricity controllers should be trimmed more defensively. This might also reduce the drastic drop in the steam net pressure, reducing strain on equipment etc.

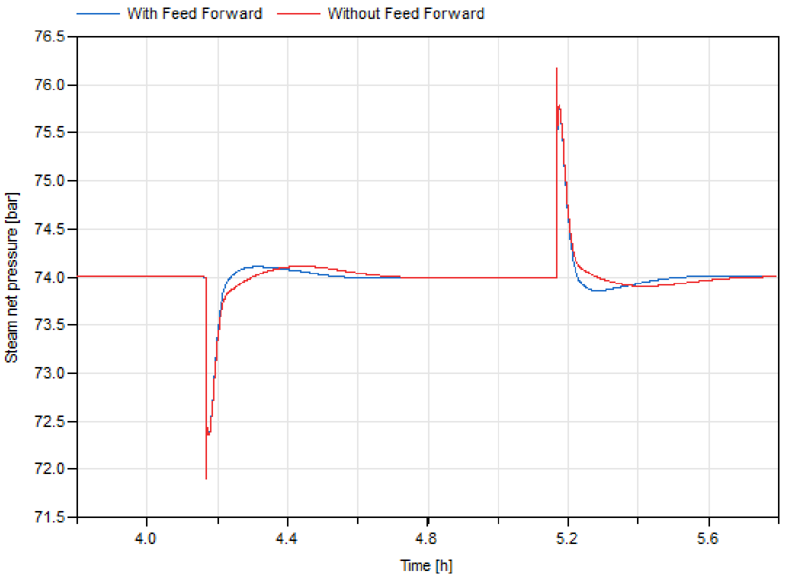

Figure 4.3 Steam net pressure 27 MW base load

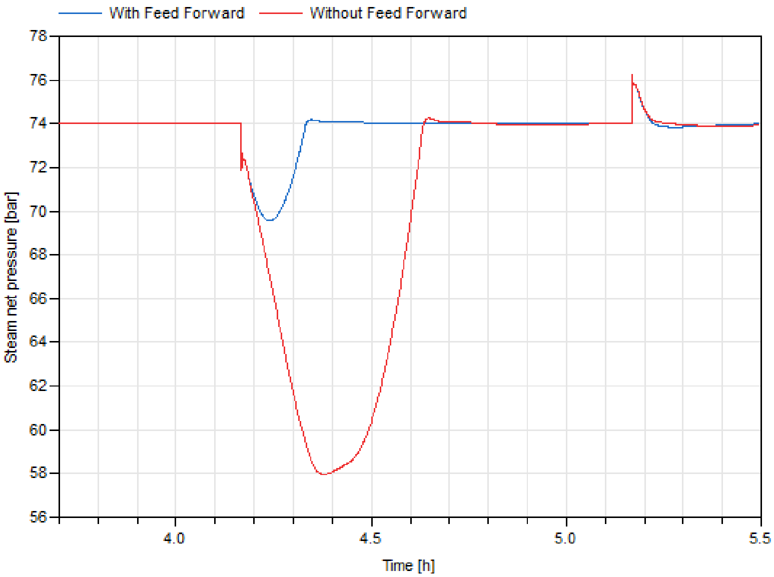

Figure 4.4 Steam net pressure 30 MW base load

Figures 4.3 and 4.4 shows the response of the pressure in the steam net after the 7.3 MW step change, for a base load of 27 and 30 MW. The figures show that for a base load of 27 MW there is little difference with and without feed forward in the pressure response. This is because of the quick changes in the opening of the direct condensation valve. In the 30 MW base load case, however, the pressure drops drastically without feed forward, which explains why that system is not able to deliver electricity throughout the 1-hour step change. With feed forward the boiler seems to be able to cope with the increased production demand and, thus the steam net pressure does not drop nearly as much. This is expected since the feed forward should speed up the response of the boiler. Overall, implementing a feed forward greatly improves the system pressure response at the higher base load and does not affect it at the lower base loads. Lastly, by enabling the process to run at a higher base load and simultaneously delivering its maximum allowed frequency control can lead to increased yearly profits since more electricity can be sold to customers. Whether this is the most economic base load to run the plant at will not be discussed any further in this report since it is outside the scope of this project.

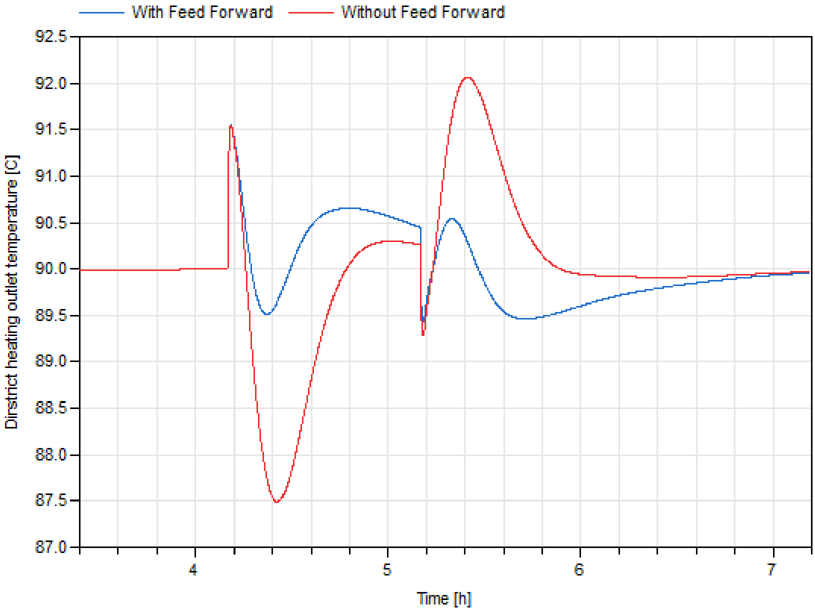

Figure 4.5 District heating temperature 27 MW base load

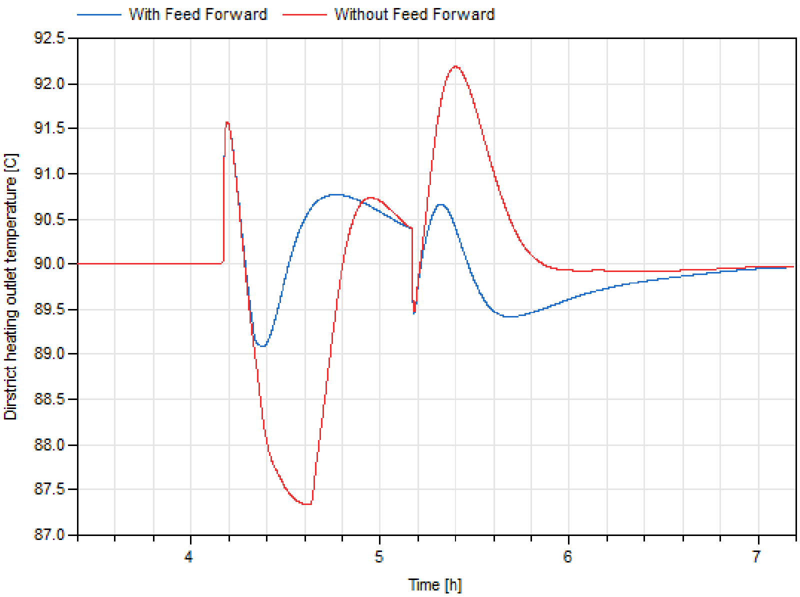

Figure 4.6 District heating temperature 30 MW base load

Figures 4.5-4.6 displays the effect on the district heating temperature after the step change. Overall, implementing a feed forward makes the temperature deviate less from its reference value at 90 ºC and, thereby, improves, the performance of the system. This is true for both cases. The temperature response of the process looks rather peculiar and can be explained followingly: Firstly, after the production set point is increased the inlet valve opens more which causes more steam to flow through the turbine and, thus, more steam condenses and heats up the incoming water. This creates the initial peak in the outlet temperature seen in the figures 4.5 and 4.6. Consequently, after a short period of time the pressure in the steam net drops which causes the direct condensation valve to close, which in turn means that less total steam condenses and heats up the water. This is what causes the consequent drop in the outlet temperature. Lastly, when the temperature drops, the boiler responds, produces more steam and, hence, the temperature goes back towards its reference value. Implementing a feed forward speeds up the response of the boiler, which causes the outlet temperature to deviate less than without. The reversed reasoning can be made to explain the temperature response when the electricity setpoint goes back to the base load. Nonetheless, implementing a feed forward seems to improve the performance of the system and should be considered when designing a combined heat and power plant.

4.2 Primary Air Overshoot

The outcome of the simulation for the primary air overshoot strategy can be seen in figures 4.7-4.9. The figures show the response for the electricity production, steam net pressure and district heating outlet temperature. Results from only using feed forward is also included in the figures to compare the effect of increasing the air flow to the boiler. Overall, introducing a primary air overshoot, seems to have only smaller impacts on the system dynamics.

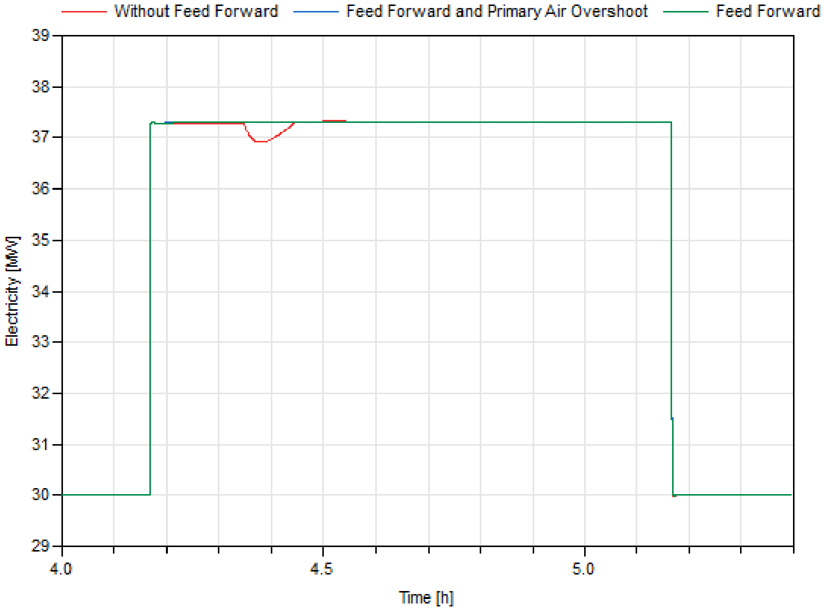

Figure 4.7 Electricity production 30 MW base load with primary air overshoot

Figure 4.7 shows that this design is also able to deliver an increased electricity production in very short time. Increasing the primary air has close to no impact on how fast the system responds. This is expected since the turbine inlet controls the amount of generated electricity.

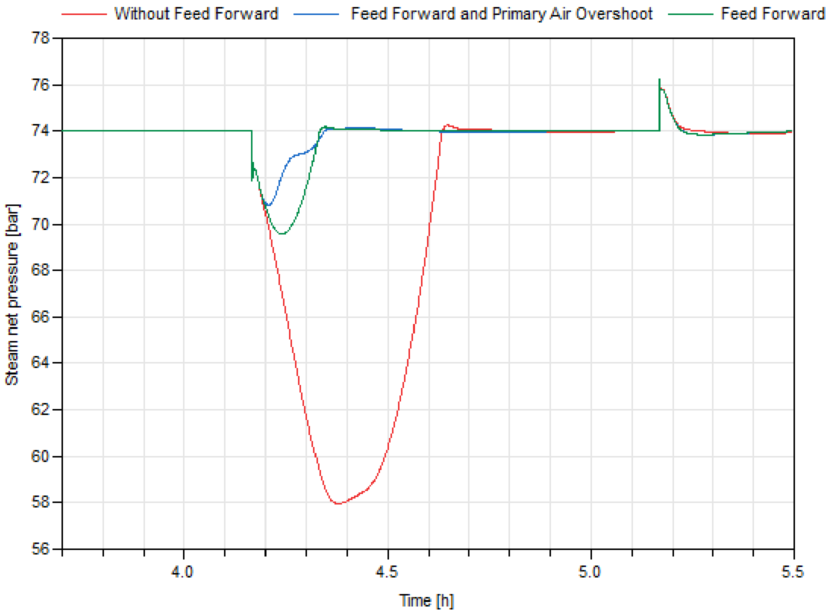

Figure 4.8 Steam net pressure 30 MW base load with primary air overshoot

Contrary to the electricity production, momentarily increasing the flow of primary air seems to have an impact on the steam net pressure, which can be seen in figure 4.8. It does not drop as much as with only a feed forward and it recovers back to 74 bar quicker. The stale section of the pressure-increase when it reaches over 73 bar can be explained by the ramping down of the overshoot factor. Lastly, introducing a primary air overshoot only seems to have a minor effect on the district heating outlet temperature when increasing the production demand. This can be seen in figure 4.9.

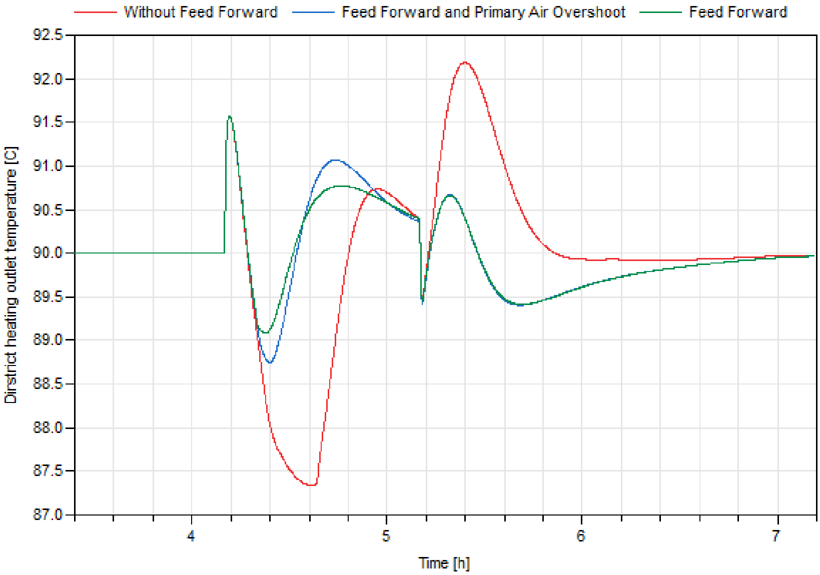

Figure 4.9 District heating outlet temperature 30 MW base load with primary air overshoot

4.3 Steam extraction from Turbine via split range control

The outcome of the simulation can be seen in figures 4.10-4.12. Results from electricity production, steam net pressure and district heating temperature have been exported and compared to the base case scenario.

Firstly, like the results above, the responses for electricity production are generally the same compared to the standard case. The split-range system is able to respond in around 12 seconds whilst, the other reaches the set point in around 8 seconds. This indicates that the split range control structure works and that the dynamics of firstly throttling the drains and then opening the inlet valve is not significantly slower than only using the turbine inlet valve to control electricity production. Additionally, both are much faster than the 3-minute demand from Svenska kraftnät.

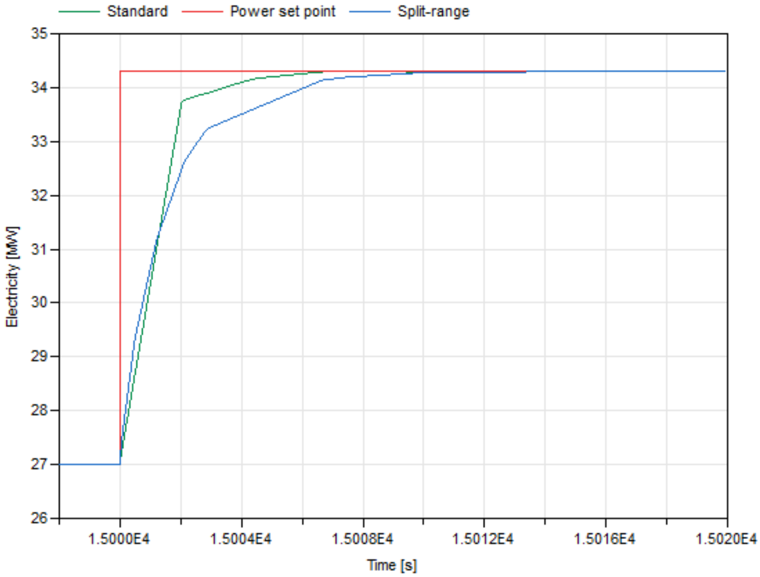

Figure 4.10 Electricity production split-range control strategy

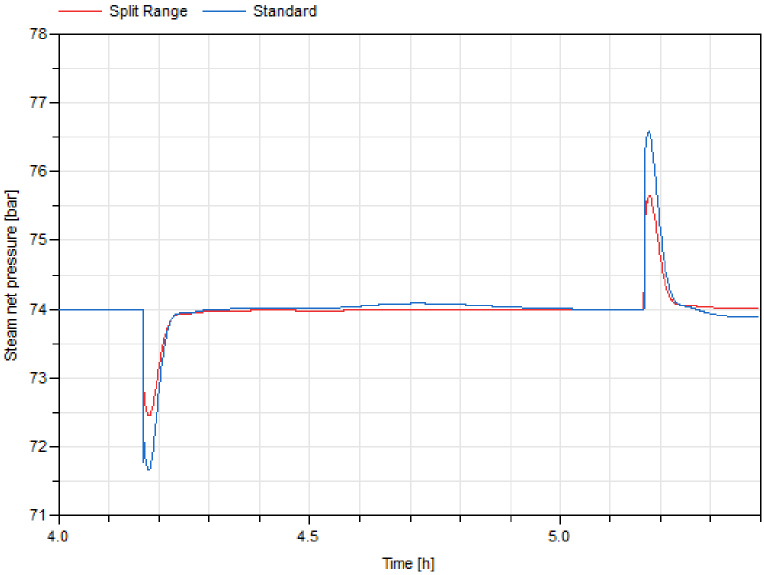

Figure 4.11 Steam net pressure split-range control strategy

Secondly, figure 4.11 shows that the steam net pressure has a smaller drop when using this control strategy compared to the standard one. This is expected since the turbine inlet valve does not have to be open as much because of the throttling of the drains. Nonetheless, using this split range control structure decreases the fluctuations in steam net pressure and, thus, improves the performance of the process.

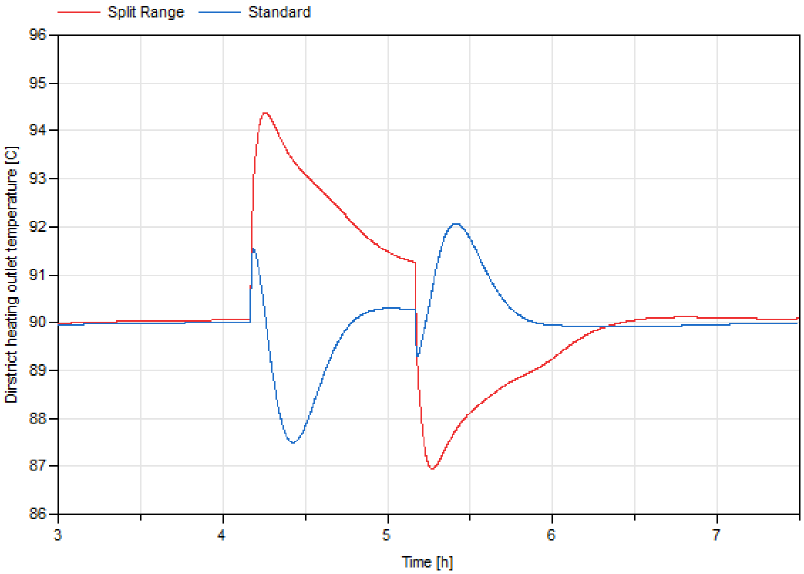

Figure 4.12 District heating temperature split-range control strategy

Lastly, the response of the district heating outlet temperature, differs greatly compared to the standard control strategy. This can be seen in figure 4.12. The response can be explained by the increased steam flow due to the throttling of the first two drains. When they are closed more steam flows to the end of the turbine and then condensates and transfers heat to the district heating water. This combined with a higher total amount of steam flowing through the turbine, since the inlet valve is also opened more, is what causes the temperature to rise. Additionally, what causes the drop in temperature when the electricity demand is decreased is the reopening of the drain valves and the closing of the turbine inlet valve. Nevertheless, whether this strategy is better or worse than the standard one to control the district heating temperature is hard to tell. Comparing the area under the two curves might give a fair comparison.

4.4 Mid-range control of direct condensation valve via boiler with dynamic valve setpoint

The outcome of the simulation can be seen in figures 4.13-4.15. Electricity production, steam net pressure and district heating outlet temperature have been compared to the standard strategy. Similar to the feed forward strategies, the difference in electricity production and steam net pressure performance seem to be unchanged compared to the standard case. This is due to the initial dynamics of the turbine inlet valve and direct condensation valve being the same. The Mid-range control strategy does, however, have a slight overshoot compared to the standard case, implying that the regulators are trimmed more aggressively.

Looking at the district heating outlet temperature, however, figure 4.15 shows that the mid-ranging control strategy has an increase in performance. The outlet temperature deviates less from its nominal value.

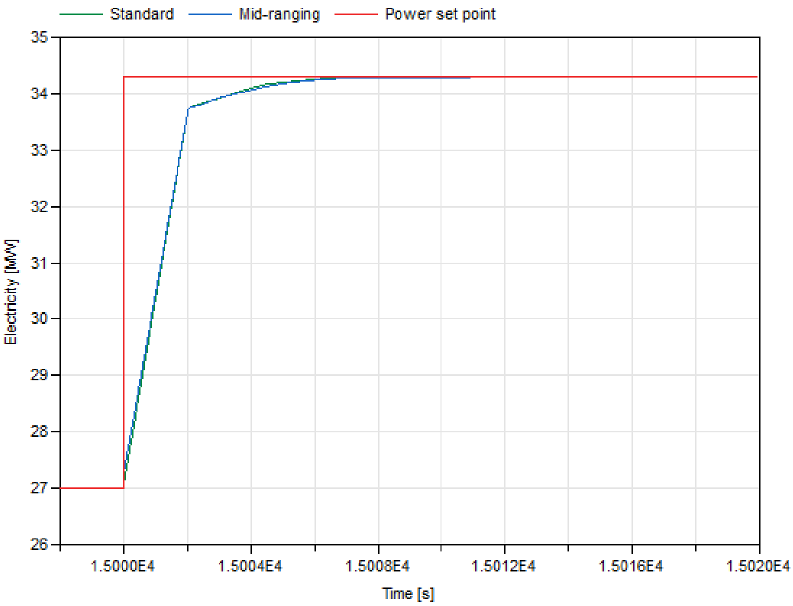

Figure 4.13 Electricity production mid-range control strategy

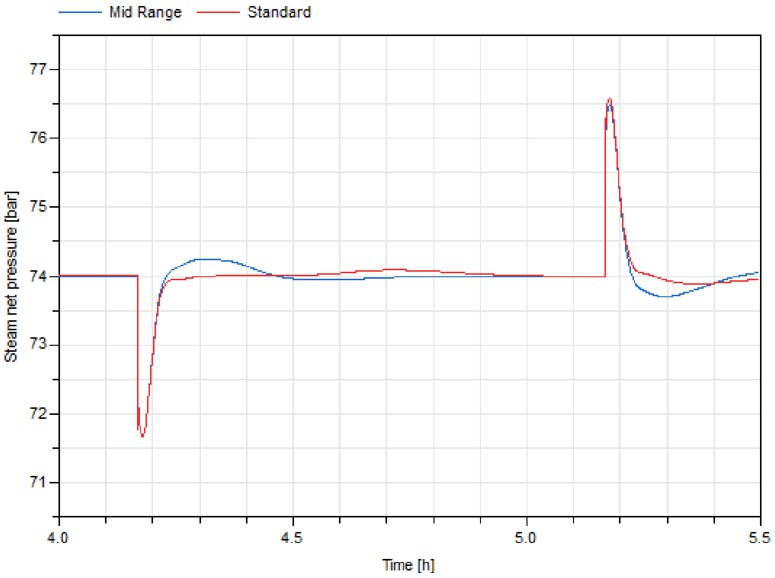

Figure 4.14 Steam net pressure mid-range control strategy

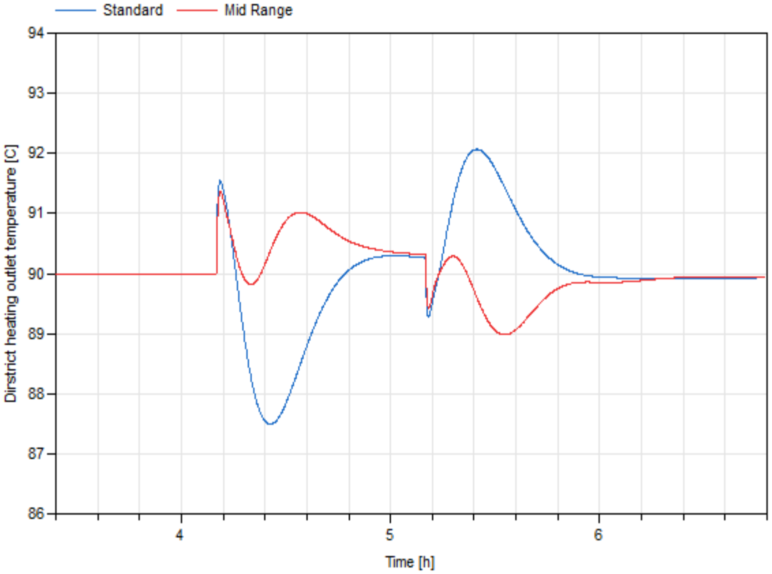

Figure 4.15 District heating temperature mid-ranging control strategy

4.5 Combined split range steam extraction and mid-range direct condensation valve control

The outcome of the combined control strategy can be seen below in figures 4.16-4.18. Similar to the other strategies, the difference in electricity production between this and the others are very small, which is seen in figure 4.16. Both manage to deliver the increased electricity before 3 minutes.

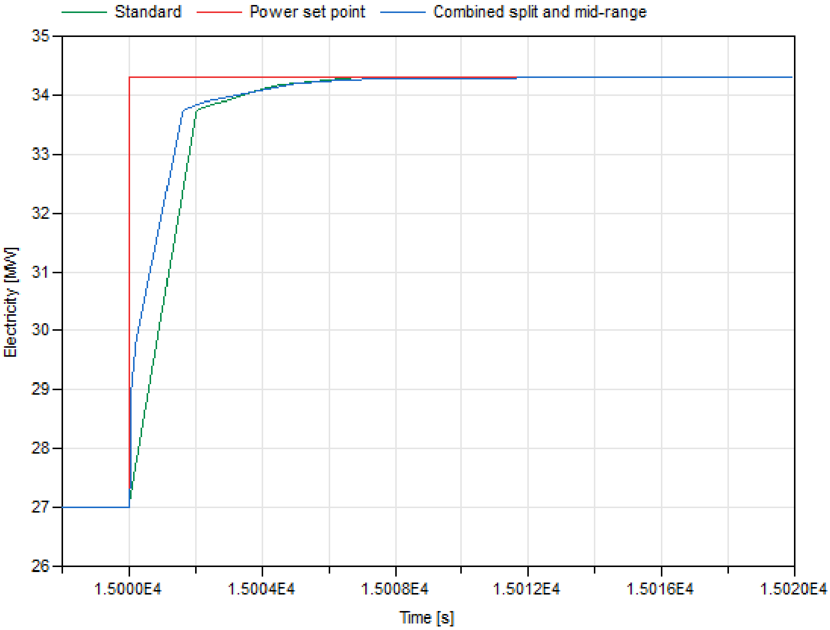

Figure 4.16 Electricity production combined split and mid-range control strategy

This control strategy, however, manages to improve the systems performance in terms of steam net pressure. As can be seen in figure 4.17 the pressure does not drop as much as with the standard control strategy when the electricity set point is increased. This is expected since two of the drains are throttled and, thus, the inlet valve does not have to open as much to deliver the required electricity. This is the same result as with the split range structure alone.

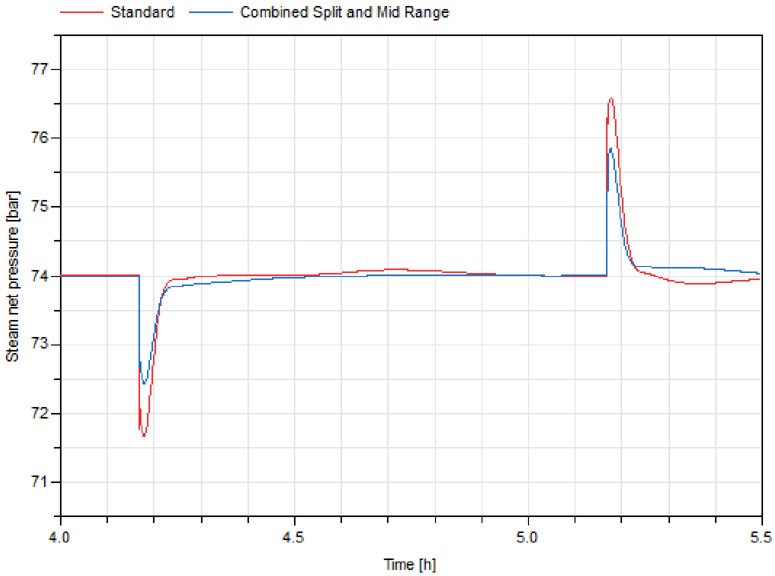

Figure 4.17 Steam net pressure combined split and mid-ranging control strategy

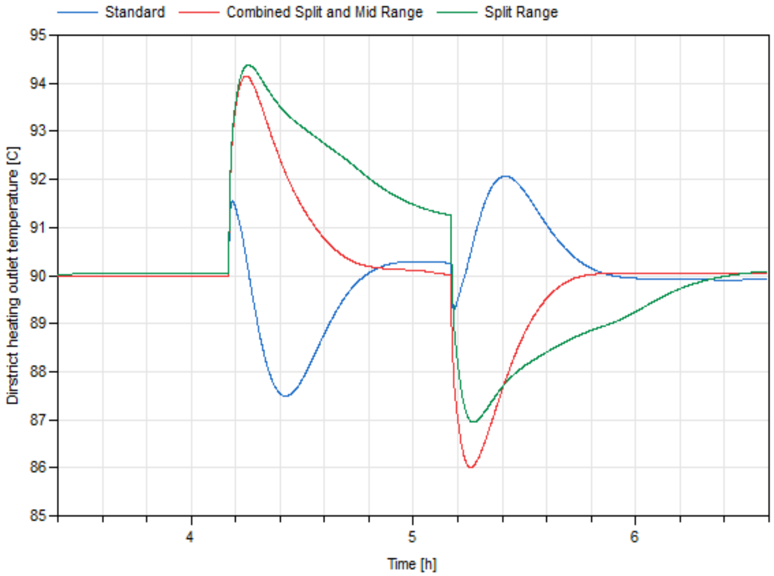

Figure 4.18 District heating temperature combined split and mid-ranging control strategy

This strategy also has the same response to the district heating water outlet temperature as the previous one. The same explanation as with the split-range control strategy, described in section 3.4 above, can be used to rationalize the response of the process. With this control strategy, however, the outlet temperature recovers to 90 °C quicker than by using only the split range control. This shows that combining the two mid-range and split range strategies does improve the performance of the system compared to only using split range. The time to recover to 90 °C is as quick as with the standard strategy.

4.6 Turbine flow distribution with feed forward and mid ranging

The outcome of the simulation can be seen in figures 4.19-4.21. The figures display the system response for electricity production, steam net pressure and district heating temperature. Both the response from the feed forward combination and the mid ranging are displayed together with the standard control strategy. Overall, the flow distribution controller seems to work and is able to improve the performance of the system.

Figure 4.19 shows that the turbine is able to increase its electricity production almost as fast as with the standard strategy despite the process modifications. Furthermore, the system is able to increase the electricity production in around 12 seconds, which is way quicker than the 3-minute requirement.

Figure 4.20 shows the dynamic response of the steam net pressure from the simulation. As expected, the modification to the turbine does increase the operational flexibility of the system and, thereby, the pressure drop is not as large. The pressure drop for this design is less than 1 bar which is a significant improvement. Furthermore, there is little difference for the feed forward and mid-ranging strategies, which is reasonable since the quick changes in steam net pressure is handled by the direct condensation valve. Its quick dynamics should not be different for those two scenarios.

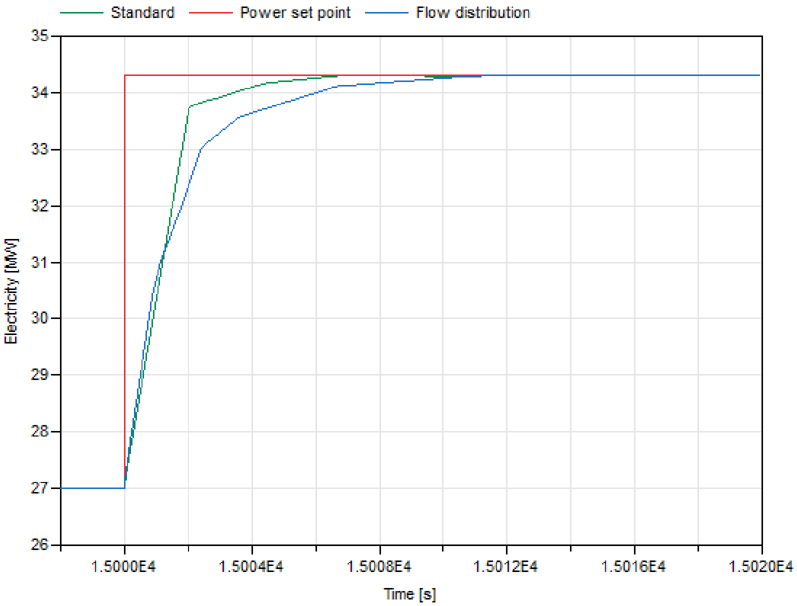

Figure 4.19 Electricity production flow distribution control strategy

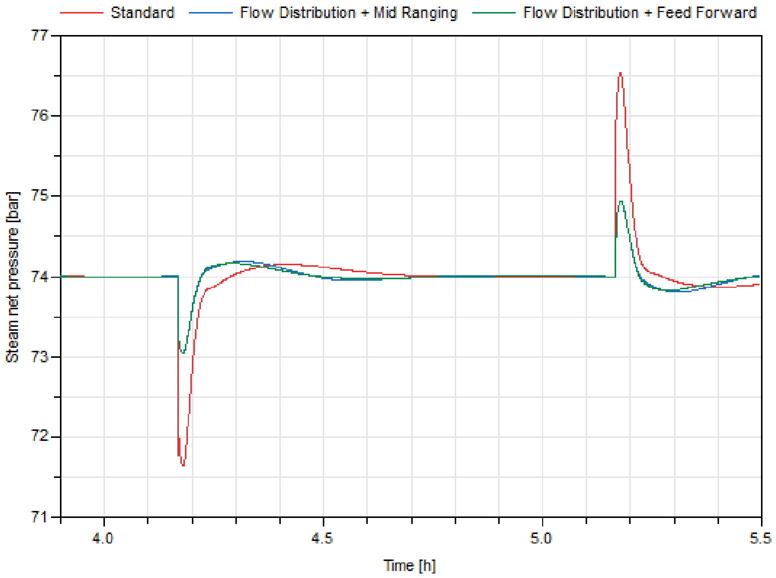

Figure 4.20 Steam net pressure flow distribution control strategy

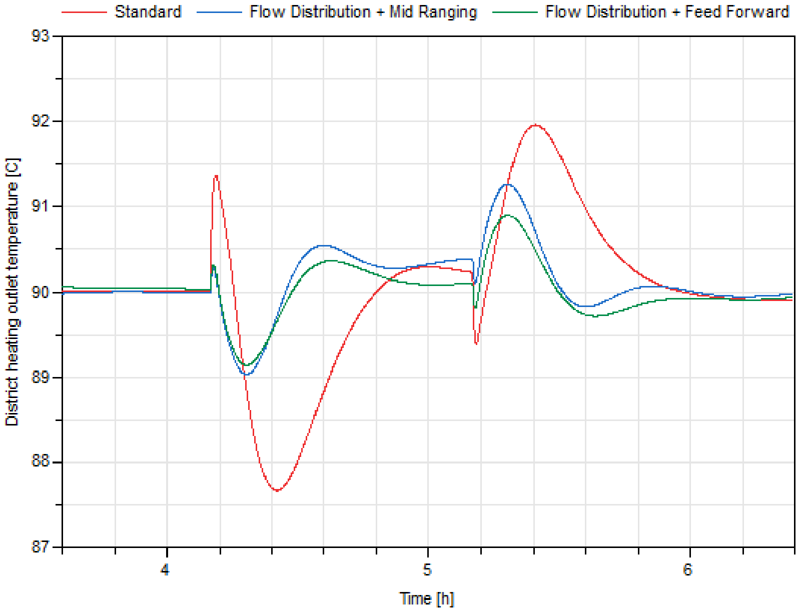

Figure 4.21 District heating temperature flow distribution control strategy

Lastly, figure 4.21 displays the response from the district heating network. The simulations show that the new configuration of the turbine together with the additional control strategies is able to improve the temperature deviation compared to the standard case. The initial temperature rise is almost eliminated. This is possible since the inlet valve does not need the change its opening as much and, thus, the total steam flow at the end of the turbine is almost unchanged. Additionally, the feed forward strategy seems to be slightly better than using mid ranging and a dynamic set point for the direct condensation valve. The deviation in outlet temperature for the feed forward strategy is less than 1 ºC throughout the step change.

4.7 Combined turbine flow distribution steam extraction and mid-range direct condensation valve control

The results from the final simulation can be seen in figures 4.22-4.24. The figures show results from electricity production, steam net pressure and district heating temperature. Overall, the performance of the system is greatly improved on the steam net pressure and the district heating temperature does not deviate that much.

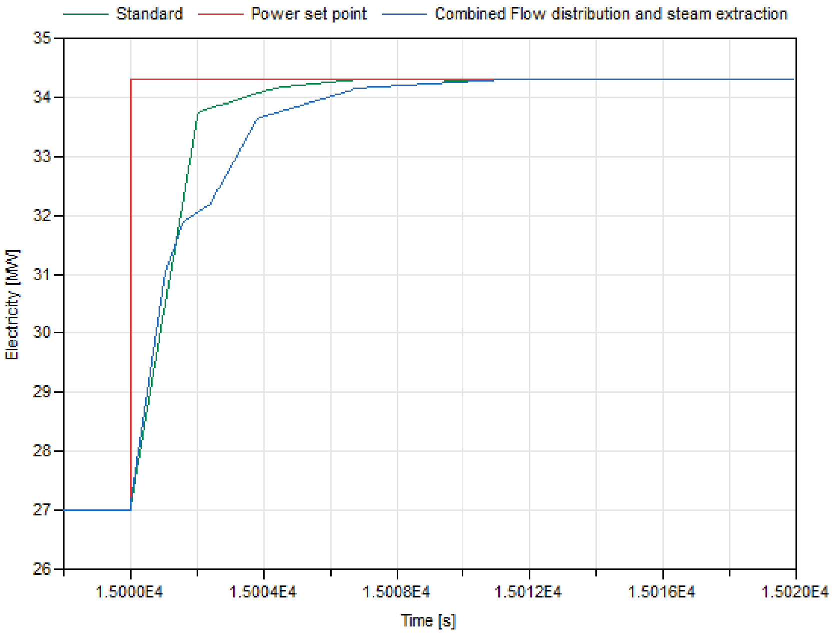

Figure 4.22 Electricity production combined flow distribution, turbine drain and mid-ranging control strategy

Figure 4.22 shows that the control strategy of first throttling the reduction valve and turbine drains and then opening the inlet valve is equally fast as the standard. They only differ by a couple of seconds when it comes to reaching the electricity set point, which is good. Furthermore, this shows the split range controller is working.

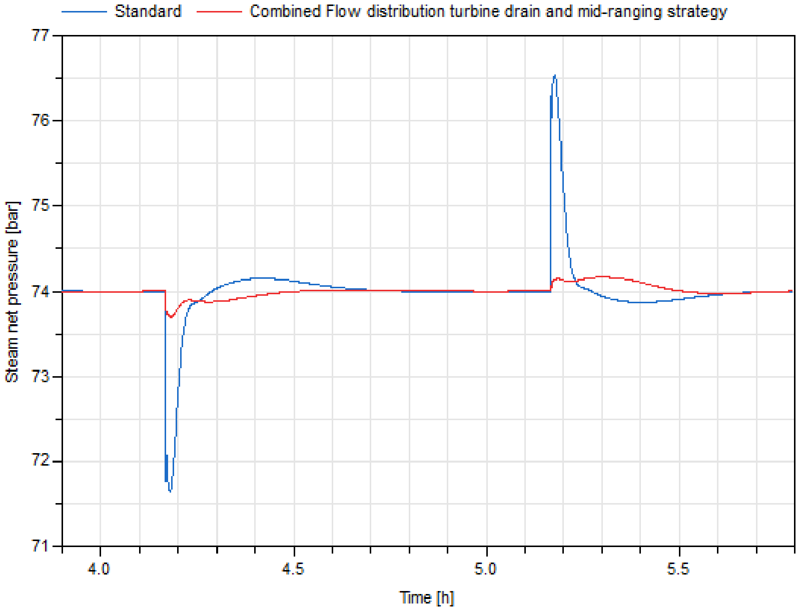

Figure 4.23 Steam net pressure combined flow distribution, turbine drain and mid-ranging control strategy

Figure 4.23 illustrates the response of the steam net pressure after a 7.3 MW step change in electricity production. The result shows that the control strategy is able to almost completely eliminate the pressure drop in the steam net compared to the standard strategy. This is a great improvement in performance.

According to figure 4.24 the deviation in district heating temperature is in the same magnitude as the standard control strategy only reversed. The response is the same as for the combined split and mid-range strategy, described in section 3.5, with a lower amplitude. Furthermore, the deviation in temperature can be explained by the same logic. Overall, the system performs quite well in terms of temperature deviation the amplitude is only around 2.5 ^{o}C.

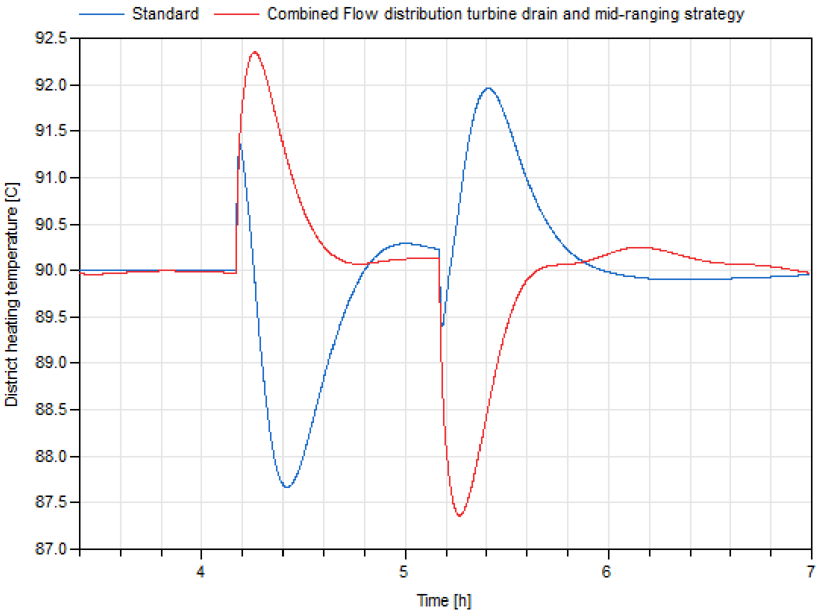

Figure 4.24 District heating temperature combined flow distribution, turbine drain and mid-ranging control strategy

4.8 Comparison of strategies

The strategies above show that the there are many possibilities to improve the performance of the power plant. Which strategy that is the best can be discussed. On the one hand, the feed forward strategy and mid ranging strategy have less deviation in district heating temperature compared to the split range strategy or the combined split and mid-range strategy. On the other hand, the split range strategy clearly outperforms the other in terms of the steam net pressure. Generally, in a power plant it is more important to minimize the pressure drop in the steam net since that can lead to boiler trips and equipment damage. The deviation of the outlet temperature of the district heating is generally not as problematic since there is often some type of accumulator tank before the water is pumped to the consumers. This further favors the control strategies that minimize the pressure drop in the steam net. A final factor that can be discussed is the difficulty of practically implementing the system and the potential complications for the operators in understanding the systems. Implementing the split, mid-range or the combined split and mid-range strategy requires trimming of more controllers, which can be hard to do and also a more complex system for the operators to understand. Implementing the feed forward does not require a change of the overall control system, no extra controllers need to be trimmed and it is less complex than the other which makes it easier for the operators. To choose which of these to implement, further information about the power plant and its staff is necessary.

Moreover, the two strategies of modifying the turbine to be able to change its flow distribution seem to outperform all the other control strategies. They have the best performance in terms of steam net pressure drop, where the combined flow distribution and steam extraction strategy almost eliminates the pressure drop. The deviation in district heating temperature is best for the simpler flow distribution strategy were the deviation is less than 1 ^{o}C and around 2.5 ^{o}C for the other. Based on the performance in steam net pressure these modifications should therefore be considered as an option. The problem with the strategies, however, is that they are hard to implement on an already existing plant since it requires the purchase of a new turbine if the old one does not have multiple inlets. For an already existing power plant it might be cheaper and easier to just implement one of the control strategies described above, since they do not require any major process modifications. Nonetheless, if a new power plant is to be built or the old turbines are being replaced consideration should definitely be taken in investing in these strategies.

Lastly, depending of the type of power plant, the electricity and heat demand, different strategies will be beneficial. If the plant for instance uses waste incineration as its fuel source most of the revenue comes from both the electricity and the amounts of burned trash. Hence, to maximize profits the plants want to have as high base load as possible, which means that it cannot deliver as much frequency control. If this is the case the best strategy might be using the split-range and only delivering the amount of frequency control that comes from throttling the drains. If the plant, however, has a surplus of trash compared to energy demand, the flow distribution strategy could potentially be even more beneficial since the plant can have a higher combustion rate for the same amount of electricity, whilst, still having the operational flexibility. Finally, if the plant uses another fuel source that has a cost associated with it the most profitable operation is often to produce as much electricity as possible per kg of fuel. This means that using a direct condensation valve to control steam net pressure is slightly counterproductive since you lose some potential produced electricity. If this is the situation, the best strategy could be to, (like above) run the plant at the highest possible base load and using the split-range control to throttle some of the preheating drains to deliver minor frequency control.

5. Conclusion

Overall, the results show that there are possibilities to improve the performance of the process by utilizing slightly more complex control structures or process modifications. Generally, using a feed forward improves the deviation of the district heating water as well as allows the process to run at a higher base load, whilst, delivering maximum frequency control. Furthermore, adding a primary air overshoot factor can slightly improve the recovery of the steam net pressure. Better performance of the district heating network can also be made by using the mid-range control strategy. Using a split range controller that first throttles two of the drains and then opens the turbine inlet valve, reduces the pressure drop in the steam net when increasing the load. Additionally, combining the split range and mid-range control strategy makes the district heating temperature recover quicker from the temperature increase caused by throttling the drains and still maintain the lower drop in the steam net pressure. In addition to the control strategies above, great improvements in terms of flexibility can be made by modifying the turbine to have multiple inlets and letting a split range controller manipulate the flow between them and the drains. These strategies have the overall best performance in terms of steam net pressure drop and is able to almost eliminate it if combined with throttling the steam extraction drains. The district heating temperature deviation can be reduced to under 1 ^{o}C if only a reduction valve is used to manipulate the flows between the turbine stages together with a feed forward to the boiler. These modifications are, however, probably harder and more expensive to implement on an already existing power plant since it requires new equipment but should, nevertheless, be considered when constructing a new plant.

Finally, in order to determine which of these that is the best for each plant, factors such as economy, difficulty of implementation, potential confusion for operators and whether or not it is more important to minimize fluctuations in steam net pressure or district heating temperature need to be considered.

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Title and subtitle

Improved control strategies for primary frequency control in Swedish combined heat and power plants

Abstract

A model of the Swedish power plant Mälardalen Energi, developed by Solvina AB was simulated in Dymola with different types of control strategies in order to evaluate if they could improve the operational flexibility of the plant and, thus, its ability to deliver frequency control to the Swedish power grid. Several different control strategies and process modifications were tested and compared to previous simulations done by Solvina. Overall, the results show that improvements could be done to the systems deviation in steam net pressure and district heating temperature by implementing a slightly more complex control structure or by modifying the system slightly. The simulations showed that implementing a feed forward on the already existing control structure would improve the deviations of the outlet temperature of the district heating network. Furthermore, implementing a split range control structure that first throttled the steam exhaust drains and then opened the turbine inlet valve, decreased the steam net pressure drop when increasing the production demand. Lastly, modifying the turbine with inlets at different pressures and letting a split-range controller manipulate the flows between them gave the overall best performance. Finally, several factors such as economy, performance, difficulty to implement and potential confusion for the operators need to be considered in order to determine which of the control structures that are the best.

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