Integration of Mechanical Load on Steam Expander

Investigation of how a Mechanical Component can be Integrated into a System Consisting of a Steam Expander and a Generator

Master's thesis in Product Development

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Abstract

This master's thesis is performed in collaboration with Maston AB and Invencon AB. The thesis investigates, generates, and analyzes how mechanical load can be integrated on to a steam expander. Maston AB develops the steam expander and they are looking to widen the areas of usage of the product. This thesis explores the possibilities of connecting it to mechanical components and having the excess power go to a generator that is connected to the power grid.

The steam expander originates from a neglected Saab project in the 1960s. When the project was put to bed, the engineer Ove Platell continued the development on his own with the company Ranotor AB. The development was after that continued by his son, Peter Platell who led the development until recent years. Today Stefan Larsson Mastonstråle of Maston AB recently joined forces to further develop the steam expander and have been making major progress.

The study explores the integration of mechanical load, using a water pump and a generator as a case study, which is connected to the steam expander. The steam expander uses waste heat to run the pump and takes the waste power to a generator which is connected to the power grid. Our research suggests a concept that solves the issue of power distribution between the two components, in a way that minimizes waste. Potential drawbacks and limitations of the concepts are discussed and visualised. Alternative concepts are discussed as part of the research as well.

The thesis proposes a final concept employing a power distribution system based on mechanical and electrical components, ensuring the water pump receives consistent speed and torque while the excess powers the generator. The system consists of several components, including a steam expander, generator, couplings, bevel gears, clutch, toroidal CVT, and ECU, designed to achieve efficient power distribution and control.

The study's objectives consist of concept generation, component comparison, market accessibility assessment, generator selection, load variation impact evaluation, and parameter role identification. Limitations include a focused scope, prototype constraint, material selection overview, limited economic analysis, and exclusion of human factors considerations.

Ultimately, the thesis contributes to Maston AB and Ranotor's goal of reducing industrial heat waste and advancing renewable energy generation. The proposed concepts and reviews are expected to benefit a broader area, where the pump can be switched out for other components. Also connecting the generator to other components rather than the power grid is an option.

Keywords: CVT, PMSG, Steam Expander, Steam Engine, ECU, Step-less gearing

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We would also like to thank our near and dear for their support and encouragement both during the thesis as well as during our studies as a whole.

Thank you all for being a part of this journey and helping to make this thesis possible. We hope that this work can contribute to further discussion and research in this area.

William Bogeryd Andersson and Felix Jacobs, Gothenburg, May 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

CVT	Continuously various transmission
DFIG	Doubly-fed induction generator
ECU	Electronic control unit
PCM	Power train Control Module
PLC	Programmable Logic Controller
PMSG	Permanent magnet synchronous generator
TCU	Transmission Control Unit
VFD	Variable frequency drive
WRSG	Wound rotor synchronous generator

Contents

1 Introduction

1.1 Background

This is a master's thesis performed in cooperation with Maston AB and Invencon AB. The main task of the thesis consists of generating a concept of how mechanical load can be integrated into a steam expander that has been developed by Ranotor AB and Maston AB. The mechanical load in this project will consist of a water pump and a generator. The steam expander has its roots in a Saab project from the '60s and was developed to be used as a source of mechanical power in a car, but the project was decommissioned. One of the engineers, Ove Platell, decided to continue the work with the expander and formed the company Ranotor AB. Today the company is driven by his son Peter Platell, and he is still working on the development of the steam expander (Platell, 1976).

Recently, Stefan Mastonstråle and Maston AB have joined forces with Ranotor AB to develop the steam expander and are this project's primary contact person outside of Invencon AB. Invencon has for some time worked together with Ranotor to develop the steam expander and they are the ones that act as the main clients of the project besides Ranotor and Maston.

The steam expander has been tested in several different applications, and the potential areas of usage include an unlimited number of industries. This thesis will focus on usage in the industry, where it has the potential to take heat waste and use it to generate energy. The steam expander can be used to generate electricity or run mechanical components from the waste of larger machinery or vessels. This thesis will investigate the possibility of using it for both of these purposes at once. To drive mechanical components and use the extra power to sell electricity to the grid. For this to be possible, ideas on how to integrate this mechanical load on the steam expander drive shaft are vital. How to prioritize the loads to different components as well as what components to use to realize these ideas needs to be presented. Creating a gear or coupling system that can meet the requirements and wishes of a such product is the main task in the thesis.

1.2 Problem statement

The task is to deliver concepts of how mechanical load can be integrated into the drive shaft of the steam expander in combination with a generator. To conclude how to integrate different types of mechanical load into this system, a specific case will be made. The specific case will be using a centrifugal pump from Grundfos, which is one of the applications that stakeholders have shown interest in. What generator to use for this application is also an important aspect in this case. The generator can potentially be the current motor to the pump that Grundfos offers, as it has the potential to operate as a generator as well, or a separate generator can be bought to better fit the capacity of the steam expander. Maston AB has so far begun testing the steam expander's operate-ability at nominal speed and torque while being connected to a generator but has yet to do any other tests while it is connected to anything else. The task includes prioritizing the pump and letting the excess go to the generator. The steam expander will have a various power output over time, which creates challenges when connecting the components.

1.2.1 Research questions

In consensus between the authors, Invencon AB and Maston AB, these 7 research questions below will lay the ground for the research done in the thesis. The last two research questions are meant to provide a more in-depth look into the project.

<u>Research questions:</u>

- Generate concepts of how the pump can be integrated into the steam expander, and still use the access torque to generate electricity to the grid.
- Which are the realistic alternatives to connect the loads? What gears or couplings are relevant and how do they differ in terms of lifespan, efficiency, and cost?

- Are the components that are included in the final concept easy to access on the market or do they need to be specialized for the system?
- How can the loads be positioned to each other? How does it affect the outcome in terms of space, efficiency, and complexity?
- What generator types are most beneficial for the system to work out? Is it optimal to use the existing motor for the water pump as a generator, or perhaps the generator used by Maston AB for testing? What aspects are taken into consideration to determine which option fits the purpose?

Theory (in-depth) research questions:

- How do load variations and operating conditions impact the selection of the mechanical system for integration on the steam expander's drive shaft?
- What role do parameters such as rotational speed and torque play in the design and performance of mechanical connection systems for power transmission and to a generator?

1.3 Purpose

The master thesis aims to solve a critical aspect of mechanical load integration of the steam expander output. The goal is to provide Ranotor with solutions that will fulfill all the requirements and therefore be a useful part of getting their project forward toward the goal of reducing heat waste in industry. The aim is also to come up with a general conclusion that can be useful for the integration of mechanical load to the steam expander in general terms, which will be relevant for the integration of other products. The research is contributing to the broader goal of harnessing waste heat and generating electricity from renewable sources.

1.4 Objectives

The objectives of the thesis are to investigate and deliver solutions to the following:

- To generate concepts of how to connect the steam expander with a water pump and use the excess torque to generate electricity.
- To deliver a comprehensive comparison of relevant mechanical components for connection of the system and their advantages and disadvantages.
- To identify accessibility for the system's crucial components on the market.
- To analyze whether the existing motor of the water pump can be used as a generator or if integrating a new generator is a more favourable option.
- To analyze how load variations and operating conditions impact the selection of mechanical components.
- To identify the best placement for components to get the best results in terms of performance, complexity, and user-friendliness.
- To examine the role of parameters such as rotational speed and torque in the design and performance of mechanical coupling systems for power transmission to a generator.

1.5 Limitations

In the course of this master thesis, several limitations be needed for the research to ensure a focused and achievable scope. Firstly, the study will concentrate on specific mechanical components directly relevant to integration with the steam expander's drive shaft, omitting a broad exploration of unrelated components. There is a time constraint in a master thesis that will limit the depth of prototyping and testing. The main focus will be to generate concepts and do an evaluation of these. No full-scale prototype will be done.

The selection of materials for the mechanical components will be considered, but an in-depth examination of material properties and their impacts on performance is beyond the thesis's scope.

Economic considerations will be addressed to some extent in a feasibility analysis, but a detailed economic analysis, including cost-benefit evaluations and market considerations, will not be the primary focus. As far as more specific cost limitations go, the limit is high enough to not be a concern other than that the cost has to be reasonable and thereby not far exceed the cost of existing solutions or rather what should be expected of such a solution. Human factors such as user interface design or ergonomic considerations will also be outside the thesis's scope. These limitations aim to balance the depth of research with practical constraints.

2 Final concept

The final concept is illustrated in the flow chart in figure 1.

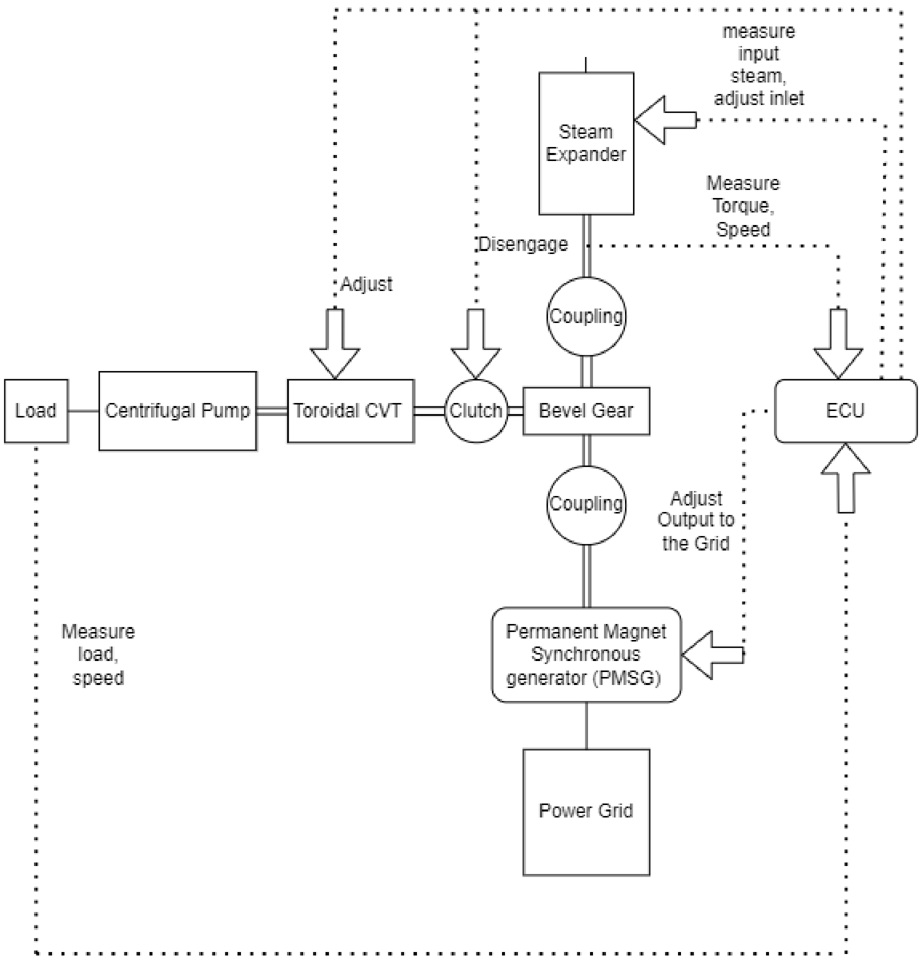

Figure 1: Full system flow chart

The system is constructed so that the varying loads and speeds created by the steam expander can be controlled. That way, the water pump gets the correct speed and torque and the generator gets the remainder. Essentially, it is a power distribution system based on mechanical physics that utilizes equilibrium. The way it works is that the steam expander and the generator are directly linked to each other through two couplings and therefore operate at the same speed. In the middle of the shaft between the two components sits a bevel gear which transmits power to a new shaft that leads to the water pump. The clutch is for disengaging the water pump from the system when not in operation and the toroidal CVT, which is Continuously Variable Transmission, adjusts the speed to make it optimal for running the water pump. The distribution of the steam expander's generated torque is adjusted by changing the generator's load. This load works against the torque generated by the steam expander and is adjusted continuously to ensure that not too much or too little is absorbed by the water pump. That way by changing both the speed (rpm) and torque, one can distribute the power that is coming from the steam expander in a controlled manner. The continuous adjustments and regulations are controlled by an ECU, which is an Electronic Control Unit, that receives input signals from the components marked in figure 1. It then adjusts the generator's load and gear ratio of the CVT based on the received data. Two rendered pictures of the final concept can be seen in figure 2 and figure 3, there are also more images to be seen in Appendix A-D. The difference between these two pictures below is that one has a protective casing around it and the other doesn't. One important aspect to have in mind is that these pictures show what the system could look like with the included components and not what it must look like. Redesigning it to fit a certain application is possible, as long as all the necessary components are included.

Figure 2: Render of the final solution

Figure 3: Render of final solution without the protective casing surrounding it

2.1 Components included

These are the components included in the final concept that are necessary for the system to work as intended. The water pump is in this section left out since the goal of the project is to create general solutions to the problem statement and the water pump is only a part of the case solution. The same goes for things like bearings and also the chassis and frame. All the components are a part of figure 1. Figure 4 shows the components mentioned below with numbers attached to them which represent their part ID which is written in the component's headings below. The components that don't have a part ID are either not mentioned below since they are not included in the general solution or they are not part of the CAD model like the sensors and ECU for instance.

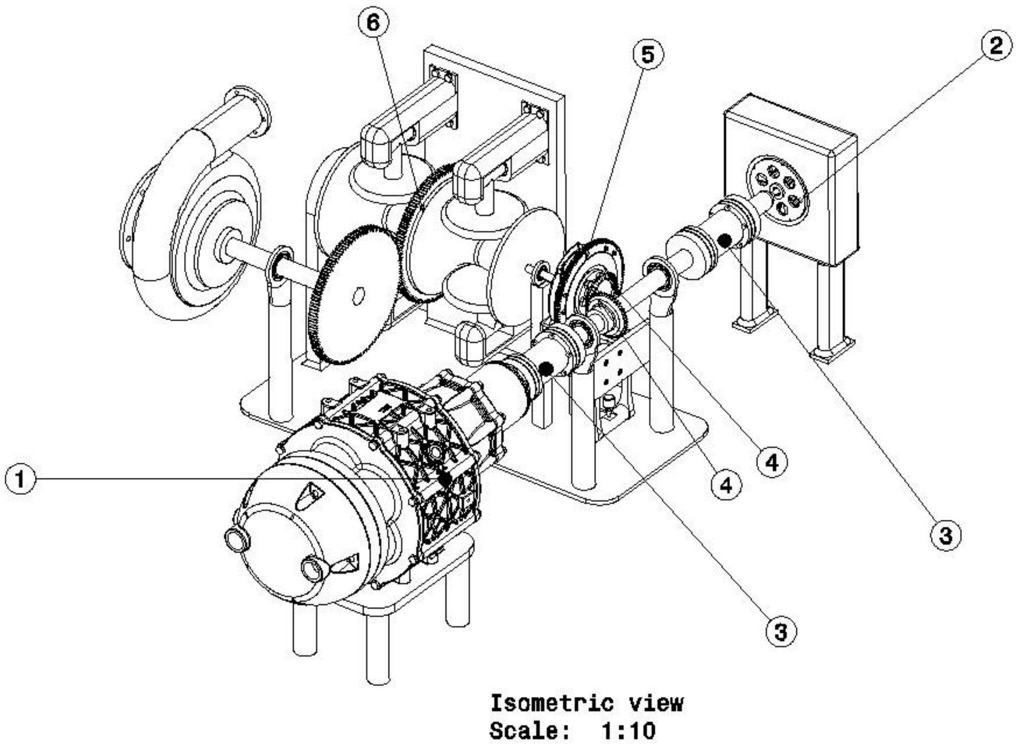

Figure 4: Drawing of final solution with part ID numbering of components mentioned in chapter 2.1

2.1.1 Steam expander (1)

The steam expander is what generates the input speed and torque into the system. Due to variations in the amount of steam entering the expander, the generated speed and torque might vary which the system must be able to adapt to. Safety measures such as safety valves will be put in place in case the steam pressure gets too high or too low for the system to operate properly. These safety measures along with general measuring of the generated speed and torque are controlled by the ECU.

2.1.2 Generator (2)

The generator generates electricity from the overflow of power that isn't used to run the pump. It is of the PMSG type (permanent magnet synchronous generator). What is special about this generator type is that it can adjust how much electricity it generates which thereby changes its load. This makes it manageable to control the power distribution and helps to achieve much higher efficiency and a lesser amount of losses.

2.1.3 Disc couplings (3)

These couplings connect the steam expander and the generator with the rest of the system. The couplings have built-in sensors for measuring certain data that could prove useful during operation when the system is used for certain applications.

2.1.4 Bevel gear (4)

The bevel gear is what distributes the power from the steam expander to the water pump. One wheel is fixed to the shaft connecting the steam expander and generator and the other is fixed to the clutch. The gear ratios between these could vary depending on the application. In the project case, the gear ratio has been set to 3:1. This is because the nominal input speed that the steam expander generates is 3000 rpm and the operational speed for the water pump is 980 rpm (about 3 times lower).

2.1.5 Clutch (5)

The clutch sits between the bevel gear system and the CVT. The clutch is a friction clutch similar to the ones used in cars with the difference being that instead of using a clutch pedal manually, the ECU engages and disengages the clutch. It does this by activating a hydraulic pump which moves a clutch fork against or away from the springs located in the clutch to engage or disengage the clutch. The purpose of using a clutch at this position and not a regular coupling or any coupling at all is because of the water pump. The water pump isn't supposed to be running continuously like the rest of the system but will instead be turned off and on somewhat regularly. Turning off the pump essentially is the same as the water pump's shaft not rotating and thereby not providing any power whatsoever. When the water pump is turned off, the CVT won't be required to do any work so to prolong its lifetime, turning that off as well would be preferable. Therefore, having a clutch that disengages the CVT and water pump when not in operation is needed for the system to work as intended.

2.1.6 Toroidal CVT (6)

The CVT variates the speed (angular velocity of the shaft) that is sent from the steam expander and then transmits the new speed to the water pump. This is done since the water pump is supposed to run at a certain speed continuously while the steam expander doesn't. The amount of variation is controlled by the ECU.

2.1.7 ECU

The ECU acts as the systems control unit. Throughout the system are several sensors that send information to the ECU which can as already mentioned be seen in figure 1. This information tells the ECU what the different speeds and torques are, which it then uses to calculate and regulate the system so that the system operates correctly. Other than regulating the loads and speeds, it also engages and disengages certain subsystems like the clutch and safety valves among other things. These ECU "outputs" can also be seen in figure 1.

3 Results

The final concept is one solution of how to integrate the pump into the system of a steam expander and a generator. In this solution, the solution uses a PMSG-type generator and a CVT (continuously variable transmission) drive in combination with an ECU to adjust and regulate both the torque and speed of the system. The CVT is used to regulate the speed, the PMSG-type generator regulates the torque, and the ECU tells the CVT and generator how much they should regulate. The reason for using a CVT is due to the step-less gear changes that it provides which allows for more fine tuning for the regulator and a higher efficiency compared to a normal gearbox for instance. By having a generator that can quickly adapt to changing driving conditions, the amount of generated current can be raised and lowered to control the amount of generated current that is let onto the power grid, thereby changing the torque that the generator applies to the rest of the system. In combination with the CVT, the drift of the pump can therefore be secured to have the correct amount of torque and speed.

The concept can be used to integrate other types of mechanical components as well, rather than just a centrifugal pump. Small modifications might be required depending on the type of load and in what industry it will be used. These modifications can include measuring the load a mechanical component drives with the ECU.

There are several options for couplings in the final solution, although Maston AB had been in contact with a supplier of couplings that had one solution aimed at connecting the steam expander directly to the generator. It was therefore decided to use that solution for both of the couplings in this project. This was a disc pack coupling, but other solutions would have been able to serve the purpose as well. The fact that Maston AB already has a supplier and design done, means that the cost, time, and complexity will serve as the base for the decisions. The differences in lifespans are small and would not outperform the other prosecutes of having the disc pack coupling.

The option of having the Grundfos integrated motor to the pump as a generator has been neglected. The motor can be used as a generator, but in case of high demand for versatility for shifting driving conditions, it is not optimal. If the Steam expander will be used in industries where a guaranteed steam rate and use of the pump will be constant, then the motor could work out as a solution. When the motor is used in this application it would be classified as a squirrel cage induction generator (SCIG) and they have the beneficial aspects that they are relatively cheap compared to other options. They also have a simple design and high efficiency during stable conditions. The decision not to use this generator is based on the fact that it cannot be quickly adjusted to various speeds and power, which is one of the main challenges with this thesis.

The decision to use a permanent magnet synchronous generator (PMSG) is to a high degree based on availability on the market and analysis of similar systems. In wind turbines of this size, PMSGs are the ones that are usually used. A doubly-fed induction generator (DFIG) was our primary choice. Still, it comes with extremely low accessibility on the market and a very high uncertainty when used in systems of this small scale, so the PMSG will be used instead, the main drawback is that it can't work within the same big span as a DFIG. However, it will be wide enough to serve the purpose of this system. The PMSG serves a big role in this system as it is not just a generator, it is also a part of the shifting for various driving conditions. The role of a substitute for a gearbox is as important as the role of an electricity generator.

While the regulation of power will be done by the generator, the regulation of speed will be done by a CVT. The decision to use a CVT is based on the step-less gear changes that come with it since the water pump is only allowed to operate within a certain speed range while in operation. What a step-less gear change means in practice is that instead of changing between gears with fixed gear ratios, a step-less gear change adjusts the gear ratio to any desired value within a certain range. This can be done while in operation which means that one could ideally have the pump run at a constant speed continuously even though the rest of the system doesn't. There exist different types of CVTs but for this system, the choice was made to use a toroidal CVT. The advantages of using a toroidal CVT are that it can withstand high amounts of torque, has a large range of gear ratios, and has seen multiple uses in practice within the automotive industry (cars, tractors, etc.). The downside with this type of CVT is that it is not as common as, for instance, the belt CVT which makes it more difficult to find suppliers but not impossible. There however is of course always the option of building one's own toroidal CVT which many car manufacturers are doing at the moment.

The ECU in the system will work to ensure the highest possible efficiency of the system by controlling the generator's generated current and the gearing done by the CVT, along with a few other things like connecting and disconnecting the water pump and CVT. The decision to use an ECU was based on the fact that different components in the system need to be electronically controlled. Compared to other types of control units, the ECU can do all the necessary tasks and can be easily implemented into the solution similar to how you implement an ECU into a car.

The choice of solution to distribute the speed between the shafts of the generator/steam expander and the pump is to use a bevel gear system. Its simplicity is its main advantage since there isn't any need for more complicated functions than transmitting a fixed amount of power. Why it was decided to use a bevel gear system specifically has to do with the placement of the system components with the pump being placed perpendicularly to the steam engine and generator.

The system components have been placed so that the water pump is situated perpendicularly to the steam expander and generator. The reason for this is due to the number of components and also spacing. It also happened to be the way that Maston AB wanted it to be placed. Having the generator placed opposite to the steam expander is how it would be placed without a third component and only requires 2 disc couplings to connect the two rather than a cardan coupling or some other variant. The perpendicular position of the pump is preferable since this gives easier access to the different components. If it were positioned in parallel, the bevel gear could be switched out with a normal spur gear or with a Schmidt coupling (Thomas, 2024b). The problem with this is spacing since one would have to take the size of the steam expander and generator into account when designing it which could end up limiting accessibility for maintenance. Also, if it were to be positioned alongside the generator, the generator would be limited to a maximum size. This could cause issues if one were to change the generator to a new one. The only upside to having the water pump positioned in parallel would be to lower the space that the system would take up.

4 Conclusions

There are several ways of connecting mechanical loads to the drive shaft of the steam expander. In the system of a generator and a steam expander, the choice of generator plays a vital role. We conclude that the easiest way to adjust the system to various driving conditions from the expander is by a generator and CVT, rather than an automatic gearbox, which was our initial thought. Generators that can adjust for various speeds and powers are key in our concept to keep the system in balance. The advantage of using generators of this kind is that multiple kinds of mechanical loads can be included in the system, which makes the concept modular and adjustable for many occasions.

All types of generators that can adjust the torque that acts against the gearbox can be used for this occasion as long as the generator allows the speed- and power span that are desired. Our research suggests a permanent magnet synchronous generator (PMSG), as the best solution if the expander will be used in occasions where the power input varies in big spans. If the expander will perform constantly near its nominal load and the power output to the pump is constant and never turned off, then a broad number of generator types would work.

To regulate the speed that the steam expander generates before it reaches the pump is as important as regulating the torque since the pump is built to run at a certain speed with some margin for fluctuations in input speed. The speed regulation unit therefore needs to be able to adjust the gear ratio while in operation and do so very precisely. This leaves out everything with a normally fixed gear ratio and the solutions that can't be as precise as required. Because of this, planetary gears, and more normal gearboxes that you can find in cars do not fit the final solution. This leaves the CVT as the only realizable solution that can fulfill the needs necessary for the system to work properly. One could use an electric transmission unit to regulate the speed as well but the losses are in this case high, the solution is expensive, and there are difficulties in finding existing solutions on the market that will fit the system.

The bevel gear system is used to distribute the power from the steam expander to the pump and generator. One bevel gear is fixed to the shaft situated between the steam expander and the generator. The other is fixed to the clutch that connects the shaft that transmits the power to the CVT. What essentially happens then is that the generator and steam expander rotate with the same speed and the CVT input receives the speed coming from the bevel gear system which are lower than the speed from the generator.

The couplings and the clutch are used to connect the different components within the system. There are a total of two couplings and one clutch. The couplings are located between the steam expander and generator with a shaft in between them that links the two. The clutch sits between the bevel gear system and the shaft that connects the CVT and thereby the pump. Deciding where to have a coupling and where to have a clutch had to do with what was most appropriate to have at each placement. The pump for instance will at certain times be turned off and on again, which makes it more suitable to have a clutch there instead of a coupling. That is because it takes a lot longer to disconnect and connect a disc coupling compared to simply turning a switch or pressing a button which then disconnects the clutch with the help of hydraulics and a clutch fork. The steam expander and generator on the other hand are not supposed to be disconnected in this way, which therefore makes it unnecessary to have a clutch at these locations. For that reason, it was decided to have couplings at those locations instead.

The cost of the system is one major disadvantage. As it stands the system would be more expensive and more complex compared to just having the steam expander connected to a generator and having the pump with the integrated pump motor as a separate system. As it is easy to sell and buy to and from the power grid, this complex system will be slightly less optimal for usage in industrial applications. However, this product has the potential to be profitable for usage in other applications, such as ships, or bigger non-rigid places, as they don't have the same opportunity of connecting generators to bigger power grids to sell it.

5 Method

5.1 Literature study

The literature study will deepen our knowledge of relevant components and techniques. Components that can be directly involved in a potential final solution are deeply investigated, while some components that are relevant to the project background are mentioned on an elementary level. The study includes the following parts:

- Modern steam expander technology
- Ranotors steam expander
- Grundfos centrifugal pump
- Generator types
- Regenerative Variable Frequency Drive (VFD)
- Alternative gears, coupling, and clutches
- Electrical components
- Simulation and finalization

Modern steam expander technology
The study includes an investigation of modern steam expanders to explain why and where steam expanders are used, relevant, and important in today's society. The positive aspects and prospects of the technology are presented in this chapter.

Ranotors steam expander
A review of how Maston's steam expander works and how it can be used. The positive aspects of the technology and its potential applications are part of the study. A description of its function and the characteristics and capabilities of the engine, such as size, weight, electrical power, voltage, and electrical current.

Water pump
The thesis discusses the pump type that will be used, which is a centrifugal pump from Grundfos. The pump is described by its function and area of usage. One model of the pump type is selected, analyzed, and described. The aim is to generate solutions on how to integrate load on the steam expander in general, but after recommendations from Maston AB, water pumps in the industry are one demand that they have, so the main case study that will be performed will therefore be of a water pump. The selection of pump type, supplier, and model is based on recommendations by Stefan Larsson-Mastonstråle, the contact person for this thesis. The review of the water pump will spawn realistic alternatives of how the pump can be connected. Different criteria will come along with the choice of pump and potential areas of usage. The aim is to generate solutions on how to integrate load on the steam expander, and this thesis will specifically study how to connect water pumps to the steam expander. Therefore the water pump is one vital part of the literature review.

Generator
The generator is another part that should be integrated into the steam expander. The purpose is that the generator should make use of the waste that is not needed for the water pump and thereafter generate electricity from this "waste power". The literature review will spawn into generator alternatives that are possible for this purpose. One option is to use the existing motor of the pump as a generator, and another option is to connect a separate generator for this purpose. If a separate generator is decided to be the best decision, there will be a selection of a specific type if there is one solution universal for multiple occasions.

Regenerative Variable-Frequency Drive (VFD)
A regenerative VFD is an external part that can be integrated into a generator if needed. If included, a specific model of VFD will not be picked and the thesis will not include a comprehensive study of how a VFD is working or how it is connected to the generator, although a short explanation will be provided. However, the selection of a generator will take into consideration whether it is compatible with a VFD or not. Some generators have an integrated VFD when they are bought.

Alternative gears, couplings, and clutches
Several alternative gears, clutches, and couplings will be investigated in the literature review. The choice of which coupling or gear is included in the report is a combination of many aspects. The competitor analysis and patent search are a part of the thesis and generated a few potential gear and coupling alternatives to the literature list. Furthermore, contact with key persons at Chalmers University gave us further alternatives.

The research of the gears/couplings consists of several key aspects. Examples of these are electrical characteristics, mechanical characteristics, environmental conditions, signal and data transferable, connection type, maintenance and service, and safety.

The alternatives that will be investigated:

- Standard planetary gear
- Planetary gear with a bevel gear wheel.
- Friction disc clutch
- Standard spur gear
- Cardan coupling and disc couplings

Electrical components
Some electrical components are investigated as they are part of potential solutions to automatic transmissions, or regulation systems. The components have been selected from the competitor analysis and other illustrations of how a potential solution can work out. When new components have been discovered, they have been added to the literature review. The literature review includes what kind of relevant components can be used, how they work, and their ups- and downsides.

The electrical components that will be investigated are the following:

- Transmission control unit (TCU)
- Sensors and tracking of input data

5.2 Patent search

In the patent search, the primary objective is to find patents related to couplings and gears, with a main focus on planetary gears, CVTs, and gears with one priority output. Modular gear systems will be investigated, to later create systems that can be useful for driveshafts of different sizes and with different power requirements, as there is a wish to be able to substitute the mechanical loads for others. One aspect of the search is to identify solutions for distributing torque and rotation speed to several shafts, which makes patents of gears with three shafts relevant. To perform the search effectively, two databases will be used: Espacenet and Google Patents.

The screening and filtering process will be performed by the judgment and valuation of the researchers. Patents will be evaluated based on their relevance to the study and their potential possibility for the researchers to use as inspiration in the concept generation phase. The documentation of the selected patents will include relevant images and explanations of the concepts. Each patent will be analyzed to make sure it is suitable for our research purposes. Following the analysis of relevant patents, conclusions will be drawn regarding the most relevant solutions for our research objectives. The strengths and limitations of the patents will be discussed and be a part of the information to conclude.

5.3 Competitor analysis

The competitor analysis will explore what already exists on the market. It is done to gain a further understanding of what already exists on the market and how the already existing products can help in the development of this new product. Because the goal is to help with the concept generation, the scope of the analysis will be limited to only finding ways to transmit rotational speed and torque from the input to the two outputs. Also with the possibility of only having one output. Being able to regulate the transmission to each shaft is also within the scope of the analysis, so finding solutions where this is either possible or there is a possibility to use an external regulation unit is needed. Because of this, finding applicable regulators is also within the scope if at least one of the analyzed transmission units is not able to do that by itself.

The search for competitors will be done within the gearing industry alongside the regulator-manufacturing industry. Since its purpose is to provide inspiration and help educate on what can be done, it doesn't necessarily have to be specifically applicable to the industry that the project is centred around. Instead, the key functions are what's important. This means that a product used in the car industry could very well be included in the analysis since the key functions can have many applications, including those relevant to the project. Meetings together with existing manufacturers will be held and compared to the patent analysis, this will likely give the best understanding of what is possible and also of what is being done within that market/industry today to potentially solve similar issues.

5.4 Concept generation

From the information gathered in the literature study, a requirement specification and a flow diagram will be constructed. This is done so that the product functions and limitations can be identified, thereby creating a clear understanding of what is to be created in the project before concepts start to be generated.

Following this, idea generation will begin and methods like brainstorming will be utilized. The generated product concepts and sub-solutions (a solution for a specific function) will then run through the elimination matrix, after which new concepts and sub-solutions will be generated and tested in the matrix. This will be repeated until a satisfactory amount of concepts and sub-solutions are generated and made ready for the next step.

An elimination matrix is done to sieve away concepts that will not be able to fulfil the requirements, even with some modifications. In table 1, the layout is visualized. When one option does end up with several "-", the concept can be seen as clearly worse than the others, and will thereafter be eliminated.

Table 1: Elimination matrix

Criteria	**Option A**	**Option B**	**Option C**
Criterion 1	+	-	+
Criterion 2	+	+	-
Criterion 3	-	+	+

The next step in the process is the morphological matrix which aims to combine the generated sub-solutions into product concepts, resulting in the elimination of stand-alone sub-solutions. These new product concepts will then run through the elimination matrix again but this time not as stand-alone sub-solutions but as complete product concepts.

When working with the morphological matrix, it is important to divide the systems into multiple subsystems, to be able to combine sub-systems from different full concepts to provide many new alternatives. In table 2, you can see a matrix with 3 options for 4 different design variables, all these can be combined, which means that a total of 12 solutions exist rather than just 3 solutions, thanks to the division into smaller subsystems. (Johanesson, 2013)

Table 2: Morphological matrix

Design Variable	Option 1	Option 2	Option 3
Material	Plastic	Metal	Wood
Size	Small	Medium	Large
Color	Red	Blue	Green
Shape	Round	Square	Triangle

5.5 Concept evaluation

In the evaluation phase, the created product concepts will go through a few evaluation processes. This is done to show which product concepts are superior to the others and will end up becoming the finalized alternatives once prototyping, testing, and further designing are done.

The first step in the evaluation phase is to create a Pugh matrix that compares the concepts with each other with the help of a rating system. Several iterations will have to be done so that a proper evaluation will be made. Once this is done, concepts will start to be removed (those with the lowest score) due to other concepts being better according to the Pugh matrices.

In table 3 an illustration of the method can be seen. In this case, there is a reference solution, which usually is the most ordinary one, and then you compare the other solutions to this reference and put a "+" when it is better or a "-" when it is worse. This method should not be used to make radical decisions, and no concept should be removed if it is not significantly worse than the others. It is mainly used to remove ineffective solutions, that still fulfil all criteria but won't be realistic for a final solution. (Pugh, 1981)

Table 3: Pugh matrix

Criteria	Baseline	Option 1	Option 2
Criterion 1	0	+	-
Criterion 2	0	+	+
Criterion 3	0	+	-
Total	0	3	0

The remaining concepts are then taken into one or many Kesselring Matrices that will help determine which remaining concepts are the best overall solutions to the project. This is done by ranking each concept individually instead of comparing them. A similar rating system is used and gives a set of points to each concept. Several matrices could potentially be done to modify the rating system and thereby see if it's possible to get different results.

In the table 4 below, one simple design of the idea of a kesselring is stated. All the criteria in ranked on a scale of 1-10 and then the performance is also ranked on a scale of 1-10 for each concept. The score is then calculated by taking the importance*criteria score and then adding all the points together to the result section. (Johanesson, 2013)

Table 4: Kesselring matrix with results

Criterion	Importance	Option 1	Option 2	Option 3
Criterion 1	7	3	5	4
Criterion 2	5	2	4	5
Criterion 3	9	5	7	8
Result		76	118	125

If the remaining concepts by this stage are still more than desired due to difficulty in the ranking of concepts in the previous stages, other methods will be utilized. One method is to try to further develop each remaining concept to get a clearer picture of the workings of the concepts. Once this is done, the concepts are again run through the Kesselring Matrices, or potentially through a much simpler 'Pros and Cons' list that could be created depending on the difficulty of evaluation. Another method is to do a feasibility analysis which can also help in eliminating concepts.

6 Theory

6.1 Modern steam expanders

The modern steam expander, just like the old ones, utilizes the Rankine cycle to create power, both mechanical and electrical. The Rankine cycle is the cycle for heating a fluid so it reaches a vapour state (preferably supercritical) and then cooling it down and compressing it to its initial state before heating it again, repeating the cycle (Sprouse-III & Depcik, 2012). Utilizing the Rankine cycle is an effective way of making use of heat energy to create mechanical power or electricity, which is what a steam expander is used for. There are different ways to utilize the Rankine cycle in terms of when heating occurs, how much it is heated, and so on. The traditional Rankine cycle for instance has two variations, reheat, and regenerative (Sprouse-III & Depcik, 2012). In the reheat variation, the steam does not expand fully to the desired pressure but is instead sent back to the evaporator for reheating where it then reaches the desired pressure level. The advantage of using the reheat Rankine cycle is the increased quality at the expander exit due to less moisture which increases the lifetime of the turbine expanders. The regenerative variation uses the heated vapour to partially preheat the condensed vapour at low temperatures before it enters the boiler. This lowers the amount of heat added at low temperatures, increasing the mean effective temperature of heat addition while enhancing the cycle efficiency. See figure 5 for further illustrations of the different Rankine cycles. The figure was taken from (Sprouse-III & Depcik, 2012).

Historically speaking, the Rankine cycle has always been a core part of steam expander technology ever since it was first introduced, in a very primitive manner, around 2000 years ago (Peterson, 2014). It is also used in many other ways to generate power such as in the burning of coal in coal plants, nuclear fission reactors, and in internal combustion engines. While the steam expander has somewhat gone out of fashion after the Industrial Revolution, there are still areas where they are used. Its main use is in steam turbines which could be found in many types of power plants such as nuclear power plants and coal power plants (French, 2024). Although steam turbines are not steam expanders per definition, they utilize the Rankine cycle like a steam expander does work and create power similar to how a steam expander does it with the difference being that a steam turbine is used to generate electricity while a steam expander typically generates motion. Ranotor's steam expander is built to generate both electricity and mechanical energy.

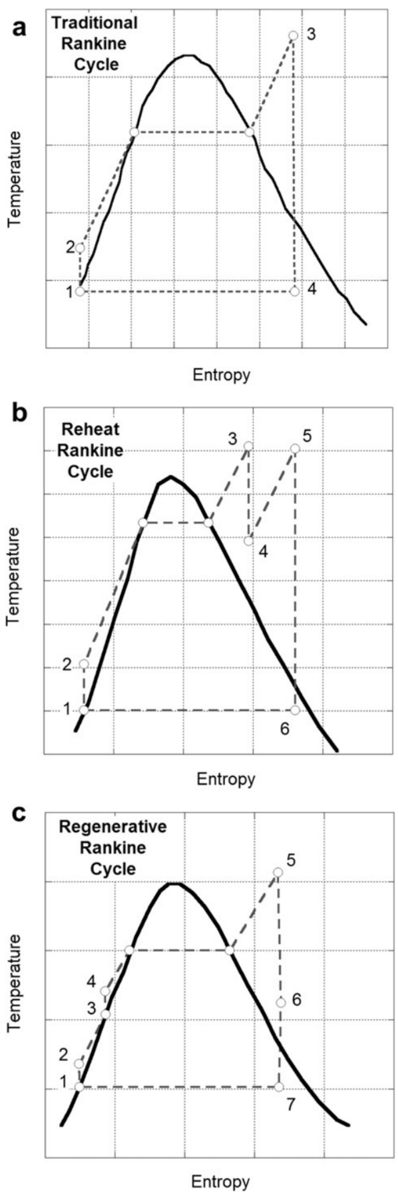

Figure 5: Different versions of the rankine cycle

6.2 Maston AB's steam expander

The steam expander is a compact engine type that is well-suited for oil pumps, water pumps, and hydraulic engines. The engine is an axial piston engine type, which means that there are several pistons mounted on a wobble disc, which is angled towards a normal plane which means that all the pistons are positioned in different positions in each cylinder stroke. The pistons are put under various steam pressures and are pushed down to the lower part. This movement forces the crankshaft to rotate, and that is how the torque is generated. In figure 6, the design is illustrated (Jonsson & Granquist, 2008).

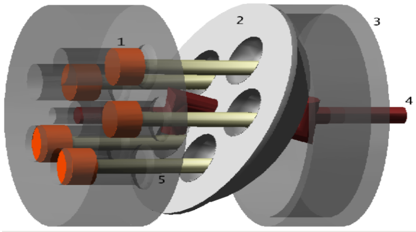

Figure 6: Axial piston inside the steam expander

A significant aspect of the steam expander is that it is oil-free, which proves advantageous when used in environmentally critical fields, such as in agriculture. Consequently, the presence of an oil lubrication-free coupling/gear stands as a wish to meet these specific requirements, to not disqualify the coupling solution to some fields.

Within environmentally sensitive sectors, such as agriculture, the importance of minimizing potential oil contaminations becomes particularly important. Steam expanders, designed without the need for oil lubrication, effectively address this concern. therefore the choice of an oil-free coupling not only supports the operational reliability and long-term performance of the steam expander but also offers a significant environmental advantage. The engine also relies on 100 percent water lubrication. (Mastonstråle, 2024)

The engine, which is illustrated in figure 7 operates on an AC power supply of 400 V and has an amperage of 110 A. The dimensions of the steam expander are 1000x650 mm and the weight amounts to approximately 500 kg. The steam engine has a shaft diameter of 40 mm. (Mastonstråle, 2024)

With this capacity, the engine will convert thermal energy to electrical power with high efficiency. The compact design with the size of 1000x650 mm makes the engine versatile for several applications. With a robust design, it is constructed to handle demanding work conditions and offer a reliable performance. The weight of 500 kg makes the engine relatively lightweight which makes it easy to transport and install.

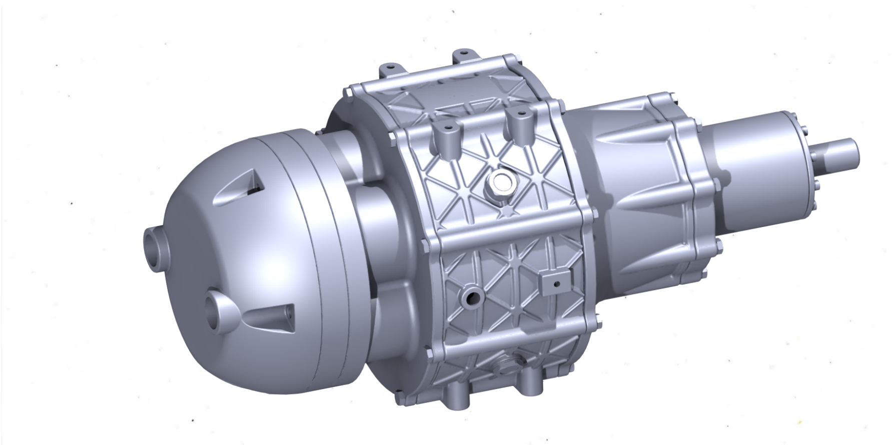

Figure 7: Steam expander

The steam expander represents an advanced technological accomplishment and is specified as an axial machine with 5 cylinders, and with a cylinder volume of 1.2 Liter. The engine can produce up to 1200 kW at its peak output level. With a speed interval reaching from 1000-10,000 rpm, this axial machine enables adaptability and efficiency for several different applications. At its peak loading, the engine can generate a torque of up to 3600 Nm. This capacity contributes to its ability to handle various workloads and maintain stable performance under various operating conditions.

It should be noted that the specified peak output of 1200 kW can be considered an indication of the steam expander's maximum capacity under high load conditions and may be particularly relevant for temporary power production requirements.

The nominal output from the steam expander will be 100 kW at 3000 rpm. The expander can regulate the steam inlet, and therefore it is possible to make sure that the steam expander does not increase drastically in power. Although, in this application, it might be preferable to use all heat waste that is possible.

6.3 Centrifugal pump

The water pump that will be used is a centrifugal pump from Grundfos, and has been selected on recommendation from our contact person for this master thesis, Stefan Larsson Mastonstråle.

A centrifugal pump is a pump that uses a rotating impeller to push a liquid radially outwards into a circular chamber or diffuser. This raises the pressure of the liquid thanks to the centrifugal forces generated by the impeller. This pressure in the liquid then pushes it out through the outlet. (Qazizada, Sviatskii, & Božek, 2016). This pump is somewhat sensitive to variations in pressure and the continuous flow of liquids. If the pressure drops at the outlet of the pump, it's more difficult for the pump to retain pressure within the pump which means that the pump won't be able to push the liquid forward. If the flow of liquid into the pump is disrupted, a sudden drop in pressure due to air pockets, for instance, cavitation could occur which breaks the pump. A centrifugal pump is mainly used to move thinner liquids such as water, acids, and certain oils.

In figure 8 the selected model of the centrifugal pump is illustrated. The model has been selected by recommendations from our contact person at Ranotor, and is called Grundfos "NK 350-350/388-352 AA1F1SBESBQQETW5". The pumps are used in several applications, with certain areas standing out for their importance. Water treatment, fertigation, and dosing are some areas of usage. Which plays an important role in agricultural practices. Other usage areas are groundwater management, frost protection, cooling and heating systems, wastewater treatment, etc. In table 5 relevant data on the pump can be found. (Grundfos, 2024b)

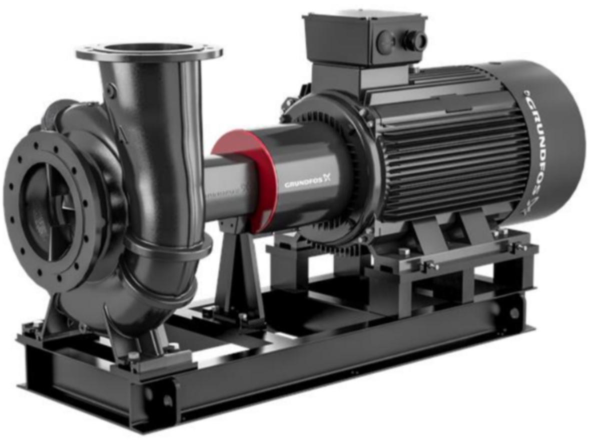

Figure 8: Grundfos, centrifugal pump

Table 5: Pump and motor specifications, selected centrifugal pump

Pump Data	
Pump speed (based on)	980 rpm
Rated flow	1202 m^3/h
Actual impeller diameter	370 mm
Nominal impeller diameter	350 mm
Shaft diameter	60 mm
Shaft length (part available for mounting of coupling)	110 mm
Net weight	1440 kg
Gross weight	1570 kg
Materials (Pump)	
Pump housing	Ductile iron
Impeller	Stainless steel
Shaft	Steel
Motor Data	
Range of ambient temperature	-15 - 40 °C
Rated power	45 kW
Power factor (Cos phi)	0.85
Rated speed	980 rpm
Rated full-load torque	148-439 Nm
Locked-rotor torque	200-200%
Breakdown torque	210-200%
Motor efficiency at full load	93.7-93.7%
Motor efficiency at 3/4 load	93.7-93.7%
Motor efficiency at 1/2 load	92.7-92.7%
Net weight	510 kg
Motor shaft diameter	75mm
Motor shaft length	140mm

6.4 Generator

The choice of generator that should be part of the system is between several alternatives. Inspiration from similar fields has been considered when looking over the alternative generators that can be used, specifically generators that are used in wind turbines are relevant for us, as the generator shall be able to operate during various drive conditions. The generators used in this field can in general be divided into two main categories, *Asynchronous (induction) generators* and *Synchronous generators*. Together with a regenerative variable frequency drive, any type of three-phase generator can be connected to the electrical grid, although all generator types have certain attributes, that need to be selected to best fit the purpose of this certain project. The case has two options when it comes to generators, one is to use the motor that is sold together with the pump as a generator, and the other option is to buy a separate one.

As the input from the steam expander varies, there is an advantage of having a generator that can constantly change the force on the gear system to have the system in balance. This means that as the expander increases from its nominal condition, the output from the generator should increase, and in the same way, when the power input decreases the output from the generator should decrease. So one possibility is to have sensors that measure the torque and speed output from the steam engine, and then the generator adapts to that output to keep the system balanced. This means that the power input to the generator will be calculated by this equation:

$$P_{\text{motor}} - P_{\text{Pump}} = P_{\text{Generator}} \tag{1}$$

The are 4 main generator types that are investigated and that are relevant in this application.

- Squirrel Cage Induction Generator (SCIG)
- Doubly Fed Induction Generator (DFIG)
- Permanent Magnet Synchronous Generator (PMSG)
- Wound Rotor Synchronous Generator (WRSG)

Squirrel Cage Induction Generator (SCIG)
The existing motor can be used as a generator and would then be a SCIG-type. The main advantage of SCIG is its mechanical simplicity. It has a simple design which makes it robust and reliable, which results in low maintenance criteria and lower cost for service. This type of generator also generally has a high efficiency, which means it can maximize the mechanical overload to convert it to electrical energy. SCIGs are generally stable and reliable during nominal conditions and constant rotational speed.

SCIG consumes reactive power, which means that usage of reactive power compensation, or that power is taken directly from the grid. Although a SCIG cannot adjust the amount of reactive power compensation and is therefore dependent on external components to provide it. Another issue is when connecting to the power grid, SCIG can generate high initial currents, which may cause voltage disturbances in a weak grid. SCIG may have a low power factor at full load, which can result in penalties from power utilities or requirements for compensation with capacitors. (Ackermann, 2005)

Doubly Fed Induction Generator (DFIG)
The main advantage of a DFIG is that it allows variable speed over big speed spans. This type of generator can also adjust the reactive power and decouple the control of active and reactive power by independently controlling the rotor excitation current. It can also generate reactive power to the stator via the grid side if it is needed for voltage adjustments. It can also use voltage control to produce or reduce the reactive effect to match the quality of the grid if it is connected to a weaker grid.

The backside of this generator type is the cost, the higher the span of rotational speed that is required, the higher the cost. Another cost issue is the need for a slip-ring, which both increases the manufacturing cost as well as the maintenance cost. DFIGs often have very complex regulation mechanisms that require higher knowledge from the users, manufacturers, and designers. It also requires accurate measurements and controls to ensure optimal operation. (Ackermann, 2005)

Permanent Magnet Synchronous Generator (PMSG)
PMSG can self excite which enables operation with high efficiency and power factor. The efficiency is higher than for induction machines as the excitation is done without any energy consumption. A PMSG can generate power during variable rotational speeds and can adjust quickly to changing demands.

The cost of the materials to permanent magnets is expensive and the manufacturing phase is complex, which increases the total cost for this type of generator. This type of generator also requires a power converter to adjust the frequency and the voltage to fit the power to the grid, which also increases the cost of the system. This type is also sensitive to temperature changes and can lose its magnetic properties during high temperatures. (Ackermann, 2005)

Wound Rotor Synchronous Generator (WRSG)
WRSGs offer stable operation, both during normal conditions and during variations. It is also easy to connect to the grid, as the stator windings are directly connected to it, this means that the rotational speed is directly controlled by the frequency of the grid. This type of generator does not require any reactive power compensation, which means that no extra components are needed. WRSGs also usually have a long lifespan with high reliability.

This type of generator is often very big and heavily constructed, which can lead to some issues during service and maintenance as well as installation. The gearless design requires a power converter to handle the power of the whole system, which increases the cost and the complexity of the system. Another backside is that this generator type is adjusted to the frequency from the grid, and can therefore have problems with adapting to varying operational conditions. (Ackermann, 2005)

Grundfos motor as generator

The option of using the integrated motor from Grundfos as a generator works by having the steam expander apply a torque on the drive shaft of the pump motor, which forces the motor to operate as a break. When the motor is used as a break, it can be used to convert the mechanical energy to electrical energy. In table 6 the data from the motor is visualized (Grundfos, 2024a).

Table 6: Motor specifications

Motor Data	
Range of ambient temperature	-15 to 40 °C
Rated power	45 kW
Power factor (Cos phi)	0.85
Rated speed	980 rpm
Rated full-load torque	439 Nm
Locked-rotor torque	200-200%
Breakdown torque	210-200%
Motor efficiency at full load	93.7-93.7%
Motor efficiency at 3/4 load	93.7-93.7%
Motor efficiency at 1/2 load	92.7-92.7%
Net weight	510 kg
Motor shaft diameter	75mm
Motor shaft length	140mm

An advantageous aspect of using this pump motor as a generator lies in its flexibility during periods when the steam expander remains inactive due to a lack of steam generation. In such scenarios, if there is still a demand for the pump's operation, the pump motor can make a transition to function only as a motor. This adaptability ensures the constant functionality of the pump when there is no immediate need for the motor to operate as a generator. This creates a more efficient and reliable system for the usage of the pump as it can deliver under various operational requirements. This double capability secures the overall reliability and versatility of the system, allowing it to adapt to different demands and ensuring a more robust performance under various conditions.

The disadvantageous aspect of using the motor as the generator is that it will not be able to match the power generation from the steam expander at its maximum, even when the pump is running at its full capacity. This will lead to a waste of the opportunity to fulfill the main goal of generating electricity from the heat waste in the industry. Whether the steam expander will be operating at its full capacity or not depends on the industry.

6.5 Regenerative VFD

A regenerative VFD (variable-frequency drive) is utilized to capture excess energy that would otherwise dissipate as heat and feed it back into the grid. A standard VFD is employed to regulate the speed of an electric motor by adjusting both the frequency and voltage. During normal operation, a motor generates a certain amount of energy when braking or when the load decreases. Rather than allowing this surplus energy to be lost as heat, a regenerative VFD can reclaim and store it. When the motor of the pump acts as a generator, the regenerative VFD converts the excess energy into direct current (DC), stores it, and subsequently converts it back into alternating current (AC) to feed it back into the electrical power system. Regenerative VFDs prove advantageous in applications where load braking is common and where there is an opportunity to recover and utilize the generated energy. This results in increased energy efficiency and reduced energy consumption (Mitra, Ramasubramanian, Gaikwad, & Johns, 2020).

By employing this technique, it becomes feasible to connect both Ranotor's steam expander, a water pump, and subsequently a generator capable of varying in speed and torque. This effectively addresses the issue of having the steam expander drive both a water pump and provide electricity, thus maximizing the steam expander's potential. The selection of a VFD and the method of connecting a VFD are beyond the scope of the thesis and will not be further elaborated beyond this brief introduction

6.6 Coupling/clutch alternatives

The choice of coupling alternatives is based on recommendations from our contact person at Ranotor, Stefan Larsson-Mastonstråle, and our supervisor, Kjell Melkersson. Since the solutions to the problem of integrating mechanical load can vary a lot, it's not certain that the couplings mentioned below are to be used in the final solutions or any solutions generated during the duration of this project for that matter.

6.6.1 Disc couplings

A disc coupling consists of two hubs and sometimes has a centerpiece in between that is attached with bolts or screws. By tightening the bolts/screws, friction is created between the two discs, and this is where the momentum will be transferred. These type of couplings works well for high-speed applications but are more delicate than the average coupling and can be more easily damaged if misused (Mägi, Melkersson, & Evertsson, 2018). There exist some alternative variants of disc couplings, for instance, SKFs OK coupling (SKF, 2024), but their functionality is more or less the same. Other similar couplings are the more elastic couplings like grid couplings whose purposes are the same but can sustain more variations in terms of misalignment due to the elasticity (Thomas, 2024a).

6.6.2 Friction disc clutch

A friction disc clutch works by having a flywheel connected to the input shaft, a pressure plate that is screwed together with the flywheel, and at least one thinner friction disc that sits between the flywheel and pressure plate and is connected to the output shaft. The pressure plate is accommodated with springs that push against the friction disc, which allows for motion to be transferred due to the created friction. By adjusting these springs with a clutch fork can a user disengage the clutch, which in practice means that the springs can be moved so that the springs and the friction disc will no longer be connected so that no motion can be transferred. The purpose of this kind of clutch is to be able to transfer high amounts of torque and to detach or declutch the clutch. For this reason, it's widely used as clutches in cars for instance. It's designed so that a slip momentum occurs when torque is created and is raised gradually, creating a smooth transition when clutching (Mägi et al., 2018).

This clutch could be used in a solution where for instance, there is a gear connecting all of the shafts involved and one wants to be able to detach one of the components i.e. the pump when it's not in operation so that the steam expander and generator can work alone. It could also be used to attach it again, both when not in operation and when in operation, similar to shifting a manual car.

6.6.3 Centrifugal clutch

A centrifugal clutch works by transferring torque and speed through friction. Blocks that are somewhat loosely connected to the input shaft come in contact with the output shaft due to centrifugal forces as seen in figure 9 down below. The way it works is that the blocks are pressed against the output shaft due to centrifugal forces generated by the rotation of the input shaft, which creates friction (Mägi et al., 2018). This type of clutch can be used as an automatic clutch because of the centrifugally based relation between the input and output. By utilizing springs as seen in figure 9, one can create a relation where the clutch declutches at low speeds and clutches at high speeds. The clutching/declutching speed can be adjusted by changing the tension of the springs and by calculating the centrifugal force generated at a certain speed. Due to the automatic clutch mechanism, the clutch has several applications when one doesn't want the driveshaft to always be rotating, for instance on scooters and chainsaws during idling. Since there is no need for a separate clutch mechanism to be implemented, manufacturers of different machinery can save both space and costs.

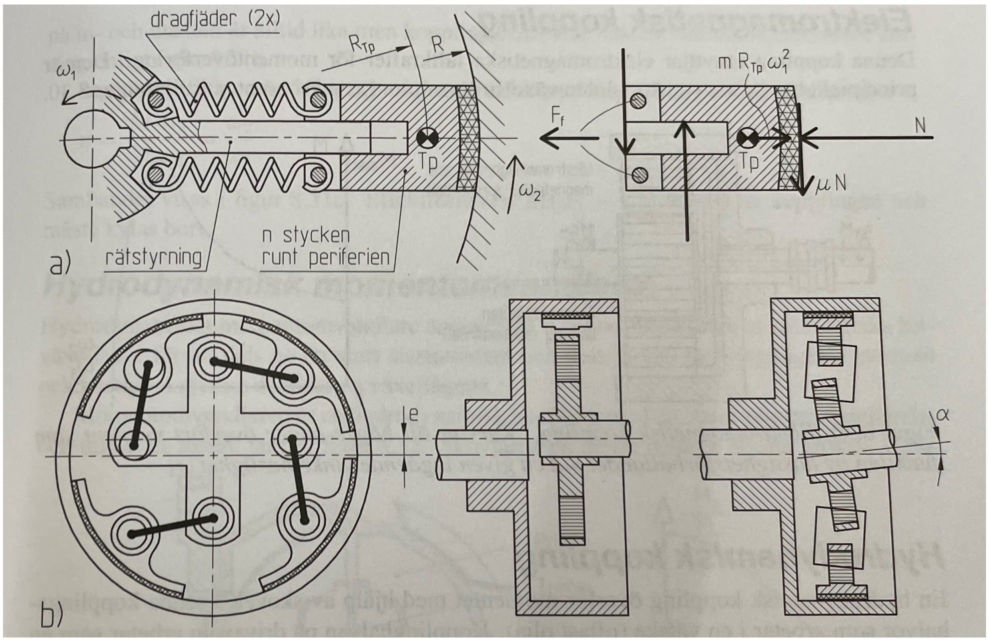

Figure 9: Workings of a centrifugal clutch

6.7 Gear alternatives

The gears mentioned below are the gears that will be used when generating solutions. The choice of gear alternatives is based on recommendations from our contact person at Ranotor, Stefan Larsson-Mastonstråle, and our supervisor, Kjell Melkersson. Similar to the coupling alternatives, the gears mentioned don't necessarily have to be part of any generated solution if it's realized further down the line that the gear alternative doesn't align well with what the final solution will eventually end up becoming.

6.7.1 Standard planetary gear

A planetary gear or epicyclic gear consists of a ring gear, a sun gear, planet gears, and a planet carrier. The shafts are attached to the sun gear and the planet carrier. Figure 10 shows the workings of the gear (Mägi et al., 2018). A planetary gear can be used in different ways since you can choose between three different shafts of the gear which are the sun gear, planet-, or ring shafts to be either outputs, inputs, or stationary. This means that you can have two inputs and one output or the other way around instead of one input and one output if needed. Planetary gears are frequently used to accomplish large speed reductions in a relatively small space (Marples-Gears-Inc., 2019). Some of the common uses of planetary gears are in robotic arms, hybrid vehicles, and turbine generators. The downside with planetary gears is that they may sometimes have a relatively low efficiency compared to simpler gear systems, although the opposite could at times also be true. Planetary gears come in many shapes and sizes, both in terms of how much they reduce but also in their overall design. One example of this is differential planetary gears which use bevel gears so that the shafts don't need to be co-aligned.

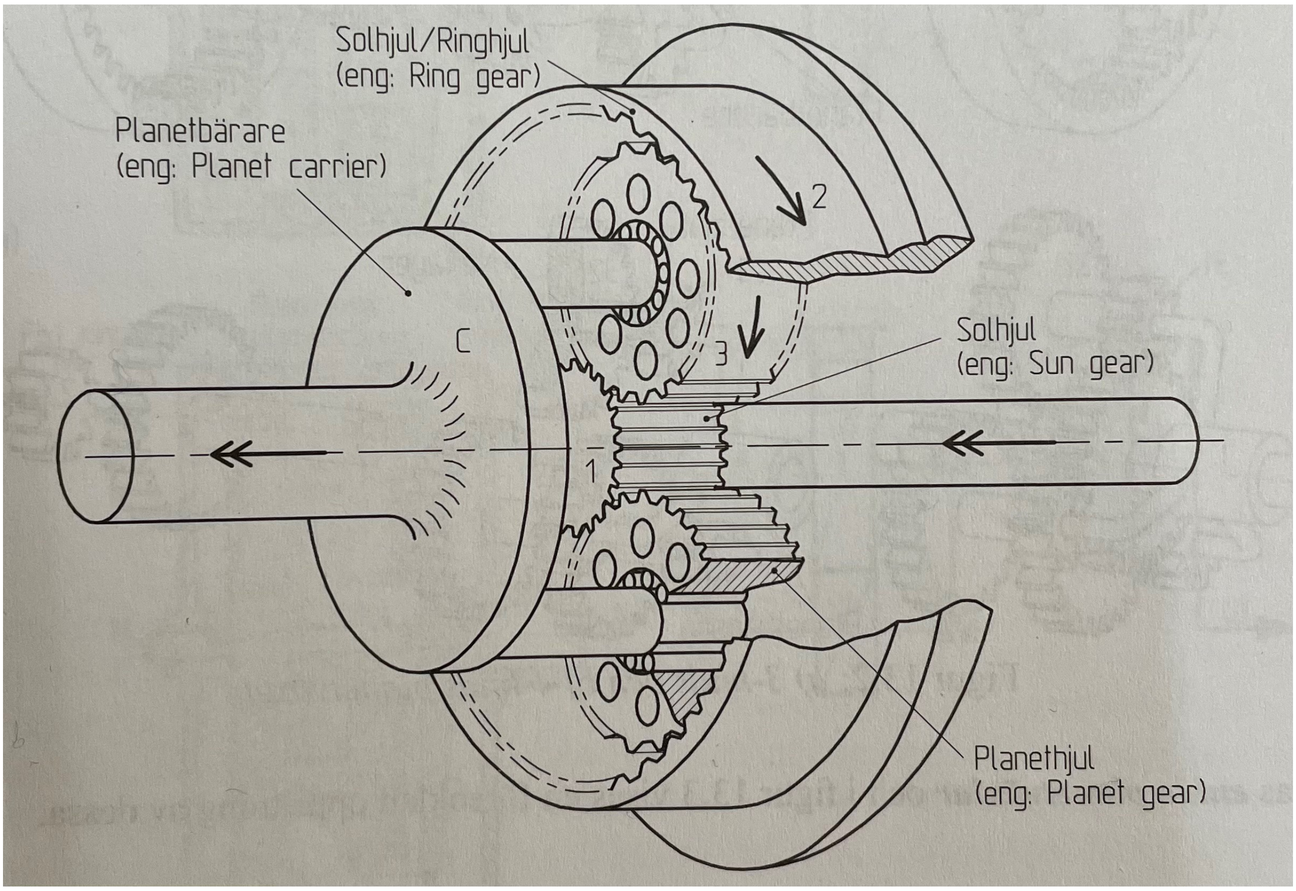

Figure 10: Three-wheeled planetary gear

6.7.2 Differential gear

A differential gears definition is that the mean value of the two sun gears' speed is equal to the planetary carrier's speed. This means that one output shaft could rotate at a different speed than the other if needed. See figure 11 where the elements of a differential gear are plotted (Mägi et al., 2018). This makes this type of gear useful in cars where the wheels on each side will have to move at different speeds when the vehicle is turning to not cause the wheels to skid or lose traction. The way it all works is that rotation is transmitted from the drive shaft to the ring gear. The ring gear, which is attached to the case, then transmits this rotation to the differential side gears by having the transmission go through the case (planet carrier) and differential pinions (planet gears). The differential side gears (pinions) which are attached to the output shafts therefore start to rotate which makes the output shafts also rotate. If for some reason one output shaft is forced to rotate quicker than the other due to external factors, similar to turning a car, the differential pinions will start to rotate relatively to the side gears and thereby compensate for the differential speed between the side gears, hence the name of the gear (Britannica, 2024) (Mägi et al., 2018).

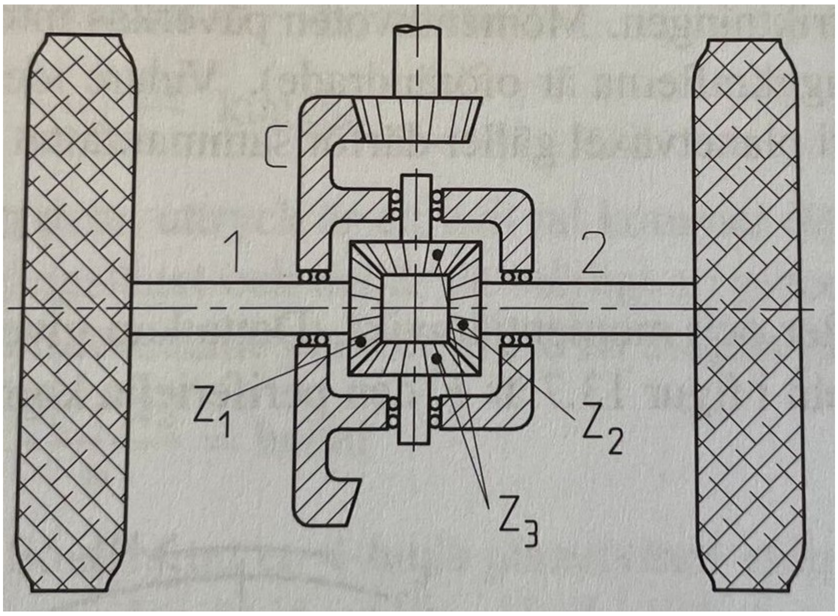

Figure 11: Workings of a differential gear

6.7.3 Standard spur gear and bevel gear

The simplest form of gear transmission. The input shaft is attached to a gear. This gear is in contact with one or more gears and the torque and speed are transferred from the gear with the input shaft to the other gear or gears. The difference between a spur gear and a bevel gear is that the bevel gear has its teeth situated at an angle compared to the spur gear so that the transmission is translated along that angle. For instance, if the teeth of the bevel gear are at a 45-degree angle, then the transmission is translated at a 90-degree angle (Mägi et al., 2018).

6.8 Continuously Variable Transmission unit

A solution to the problem statement might include a continuously variable transmission unit (CVT). These types of units are used to change the gear ratio continuously between two components without having to change gears step-wise, like in an ordinary gearbox. A typical application is in snowmobiles where it transmits torque and speed from the engine to the drive shaft, lowering the max speed and raising the torque when the snowmobile reaches high speeds (Ostieguy, 2021). A common model of a CVT is the pulley-based CVT. It has two pulleys and a belt or chain attached to it, this is what is commonly used in snowmobiles for instance. However, there exists a wide range of models such as mechanical, electric, hydraulic, and maybe even more (Mägi et al., 2018).

6.8.1 Toroidal Continuously Variable Transmission unit

The toroidal type of CVT uses friction to transfer torque and speed with the help of discs and rollers, with the rollers being situated between two toroidal-shaped discs. The discs and rollers are attached to the input shaft, which is then used to decide the gear ratio. If one wants to transmit high torque, it is possible to attach another pair of discs and rollers on the other side of the output. This type of solution for transmitting high torque was used in the tenth generation (1999-2004) Nissan Cedric (Silvestro, 2018). For this project, using a variable transmission like this is useful for getting more specific gear ratios which might be needed if one wants the pump speed and torque to be a specific value all the time. It can be used in combination with a gearbox. A downside with CVTs using friction disks is that there is a need for a traction fluid film which goes against the wish of not having to use any other fluids than water, which is the case with the steam engine. The lifespan of CVTs also tends to be lower than that of a regular transmission unit like those found in regular cars, a unit that utilizes gear change by literally changing gears instead of being step-less like the CVT is.

Other types of CVTs that use friction to transfer torque and speed do exist as well. The principle behind those CVTs is the same as the principle behind a toroidal one. It is therefore possible to use those kinds of CVTs as alternatives to a toroidal CVT, some of them having a rather similar design as well. Examples of alternative couplings are:

- Flat disc traction drive
- Single ball traction drive
- Orbital mechanical adjustable speed drive
- Beier variable-ratio gear
- Ball-ring CVT (i.e. The NuVinci CVT)
- Planetary cone CVT (i.e. the RXC drive developed by Nidec)
- Friction cone CVT

See figure 12 for further understanding of how a toroidal CVT works in practice (Verbelen, Derammelaere, Sergeant, & Stockman, 2018)

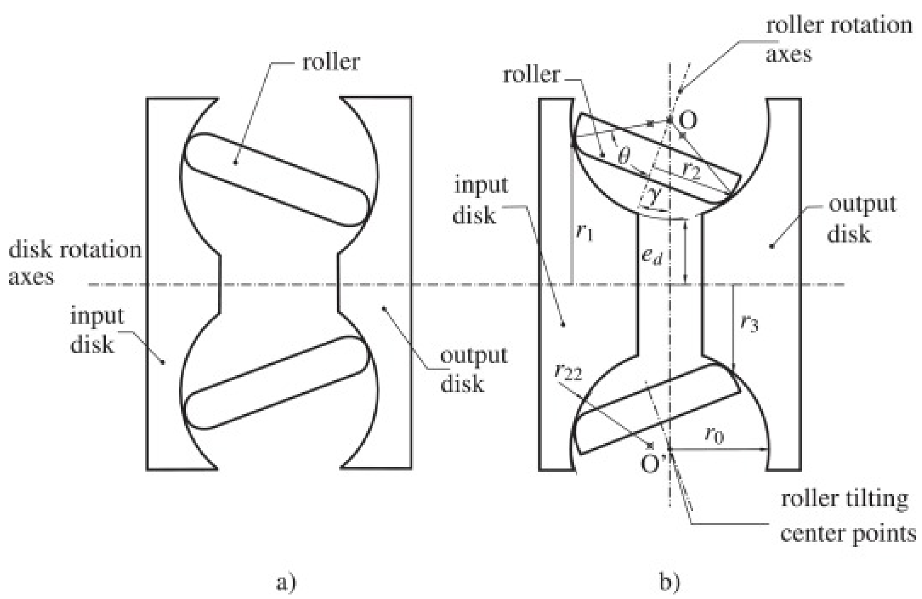

Figure 12: Toroidal Continuously Variable Transmission unit

6.8.2 NuVinci planetary CVT

The NuVinci CVT or CVPT (continuous variable planetary transmission unit) is a planetary gear that has a built-in CVT mechanism. This invention has mainly been used for gear transmission in bikes by the company that invented the CVT, now owned by Enviolo. The product's gear ratio range and max torque are relatively low and therefore not directly applicable to the project's solution. However, the concept in itself could greatly help reduce the size of the solution, so utilizing the theory behind the invention and adjusting it to suit the solution's needs could prove useful and a noteworthy endeavor.

The invention has two planetary discs on each side, one connected to the input and one connected to the planetary gear. Between these discs are balls, giving it a similar look to a ball bearing. These balls rotate along with the discs due to friction at a certain angle which then gives the gear ratio. The balls each have a steel rod going through them which then decides the angle at which they operate. See figure 13 for further information about the NuVinci CVT (Enviolo, 2024).

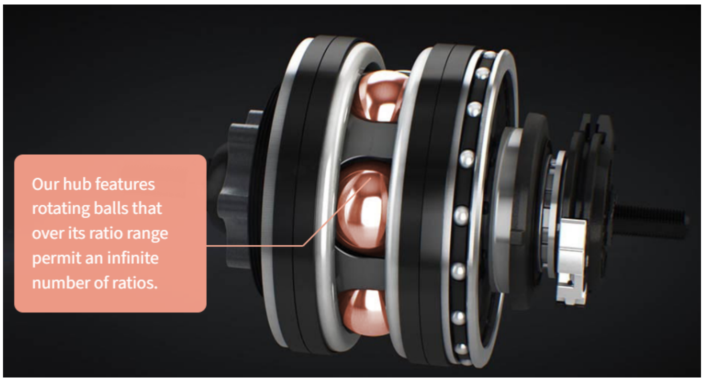

Figure 13: The NuVinci CVT

6.8.3 Orbital mechanical adjustable speed drive

The Adjustable Speed Drive (ASD) is a commercial version of the patented Milner CVT. It has a traction variator that is similar in design to a ball bearing. The planet balls inside the traction variator have four-point contact with the variable geometry which gives the ability to handle high torque and high speeds. The speed and torque are transferred to or from the planet balls by roller followers that are located between the balls and mounted on a rotating carrier (Orbital-Traction, 2024a).

The technology has been developed and refined over five years through equity funding and over a dozen Small Business Innovation Research contracts with the Department of Defense. The company now has several platform products thanks to this development (Orbital-Traction, 2024b).

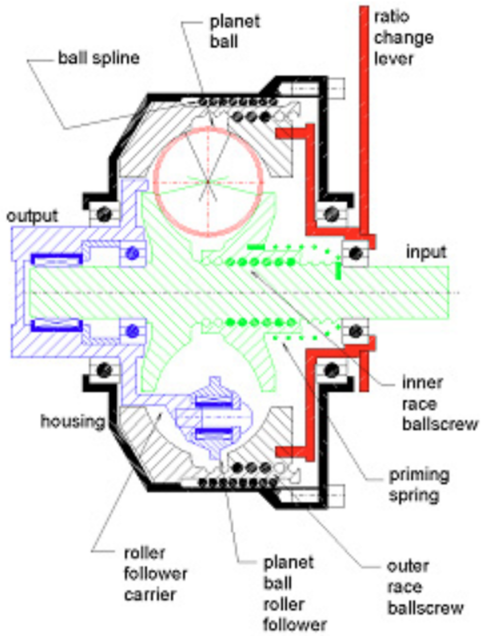

Figure 14: The orbital mechanical adjustable speed drive

6.8.4 RXC drive

The RXC Drive is a type of CVT that utilizes a ring and a cone friction power train. It consists of an input disc, a set of planetary cones, a control ring, a cam disc, a pressure control cam, and an outer casing assembly. It is constructed to be used for industrial applications and to withstand the conditions that come with it. For instance, there is a built-in cam mechanism that adjusts to the environment downstream and can withstand a heavy amount of shock load. The drive comes in different sizes to handle motor power ranging from 1/4HP - 20HP, and a nominal output torque spanning 15 - 130,000 in-lbs (1.695 - 14,688 Nm). The speed range of the drive is 0 - 800 rpm.

The drive was developed by the Nidec Drive Technology Corporation which is a Japanese manufacturer for motors and drives that are used within industrial applications. Nidec Corporation is the world's largest manufacturer of brushless DC motors (NIDEC-DRIVE-TECHNOLOGY-CORPORATION, 2019).

6.9 Electrical components

6.9.1 Control units (TCU, ECU, PCM)

A control unit is a type of computer within a system that receives and sends out electrical signals from and to other components. These types of control units are mainly found in cars and are there to control the workings of the car. All of the different units fill different roles within the system and it is important to distinguish these to find out if they can or cannot be used for this project's application. An ECU (engine control unit) mainly controls fuel injection and the timing of when the spark ignites (ECU-TESTING, 2024a). A TCU (transmission control unit) controls the shifting inside an automatic gearbox and is usually a part of the ECU (ECU-TESTING, 2024c). A PCM (Powertrain control module) is a combined engine and transmission control module and is in many ways the same thing as an ECU (ECU-TESTING, 2024b). This said, An ECU and PCM are more or less the same thing and a TCU is typically a part of the ECU. There exist other types of control units in the automotive industry but these are the relevant/applicable ones. The TCU compared to ECU and PCM seems to be the most relevant/applicable of the three types of controller, even though they all are very similar.

Transmission Control Unit (TCU)
A transmission control unit, also known as a transmission control module (TCM), is used to control electronic automatic transmissions, mainly in vehicles for different drive conditions. By using stored data on shifting characteristics, the TCU adjusts the gears for efficient and smooth shifting. TCU activates many sensors to monitor parameters that affect the shifting process. Which include the torque, speed, and pressure, when it is used in a vehicle. By continuously monitoring the system, the TCU can adjust the gear conditions to keep an optimal gear ratio. A TCU can be integrated into most automatic gearboxes, including torque converter gearboxes, CVTs, and double-clutched gearboxes. A typical TCU consists of several basic components including a central processor, in- and output interface, memory, sensors, and actuators. (Subaru, 2003)

6.9.2 Sensors and tracking of input data

Sensors that track the rotational speed and torque can be integrated into a gearbox, especially for automatic ones. The sensors can be a part of an electronic automatic shifting system, where the sensor tracks the data and transfers it to a regulatory system, which can perform the shifting. In many cases, these sensors are sold in combination with full systems of regulatory systems. (Futek, 2024)

Normally a torque sensor can be complex to integrate and therefore a potential solution is to measure the effect from the motor and the rotation speed as the torque can be calculated according to the formulas below.

$$P = \tau \cdot \omega \tag{2}$$

$$\tau = \frac{P}{\omega} \tag{3}$$

Therefore a multimeter to measure the voltage and the current, and thereafter calculate the effect, according to the formula below. (Smartsafe, 2023)

$$P = I \cdot V \tag{4}$$

6.9.3 PID controller

A PID controller is a type of controller that combines three different mathematical styles of regulating a signal and creates a control loop based on constant feedback loops. These constant feedback loops give the controller the error value e(t) which is the difference between the set-point value SP and the actual value PV. For instance, if a shaft is supposed to rotate with a speed of 1500 rpm but instead rotates at 1400 rpm, that means that SP=1500 rpm, PV=1400 rpm, and e(t)=100 rpm. The controller then tries to regulate the signal by having e(t)->0. It does proportional (P), integral (I), and derivative (D) calculations to decide how to regulate the signal and change the necessary values within the system (B. Thomas, 2018).

6.9.4 PLC

A PLC (Programmable logic controller) is a type of computer that uses input signals to calculate logical algorithms which give an output signal that is then sent to the relevant component. There exist many different variations of PLCs and the design is of a modular type which gives the user the option to design the unit to perfectly suit the PLC's intended application, both in terms of its function and in more concrete terms like its size. The user configures what each input and output are and how many they are. Programming the PLC is done on a PC, where the script describing what the PLC's functions are is made. The user also programs what output goes with what input and how they relate to each other with the help of algorithms and other mathematical functions. In its simplest form, these inputs are typically something like a sensor's yes/no signal or a physical button that turns something on/off. An algorithm for one of these inputs could for instance be something like, if something is in front of sensor x, then start operation x. More complex algorithms and functions exist like those based on time, several inputs or outputs, and so on. Typical uses of PLCs are in manufacturing like on a production line where a PLC would control a robot and potentially also the line in which the product to be manufactured rolls in and out (Wayand, 2020).

6.9.5 Hydraulic control system

Electrohydraulic motion control in its basic form, is a control system that controls the flow of a hydraulic fluid into a system to achieve, for instance, circulation for things like heat transfer or to move something like the arm of an excavator. The way it works is that electrical signals tell several components within a system (pumps, impellers, other types of engines) to both pump and not pump the hydraulic fluids to certain places in certain directions at certain speeds and times (Nachtwey, 2019).

6.9.6 Pneumatic control system

A pneumatic control system works similarly to how a hydraulic system works with the biggest difference being that air is moved within a system rather than hydraulics. The way it works is that compressed air is pushed into a system of pipes, tubes, and cables and controls the movement of mechanical components with the help of cylinders (and pistons), actuators, valves, and other components that control the movement and pressure. The compressed air is generated by a compressor and the air is stored within a storage tank. Pneumatic systems are generally regarded as safe, cost-effective, and reliable. This is because no sparks or heat is generated, can create big amounts of force if necessary at different places at the same time, and aren't affected by changes in temperature or humidity. They are also resistant to shock and vibration. The cost-effectiveness comes from it generally being less expensive compared to other systems because fewer components are needed, easier to install, and relatively easy to maintain. Pneumatic systems are used within a wide array of industries, ranging from braking systems in cars, trucks, and planes to medical and food packaging to manufacturing and construction (Fluid-Controls-Limited, 2024).

6.10 Lubrication

Ranotors steam expander is oil-free, which makes it optimal for usage in environmentally critical fields, such as in the agriculture industry. Automatic gearboxes have a demand for lubrication which can make the gearbox less attractive in some applications. The task of the thesis is to come up with concepts of how load can be integrated into the steam engine drive shaft, therefore other applications than only the specific case are worth taking into consideration to make the gearbox modular and easy to adjust for other industries, such as agriculture.

There are alternatives on the market that can be of relevant use. One of them is mineral oil. The usage of mineral oils has the advantage that they are easily decomposed if there is leakage. This lowers the impact on the ecosystem, which is extra relevant when it is used in environmental critical applications. The life span of this type of lubrication is usually shorter than the traditional options, which of course puts higher maintenance costs and effort by the workers in an industry where the steam expander will be used. Although the cost of the mineral oils is often lower than the traditional ones. The main issue with mineral oils is the quality, synthetic oils outweigh the mineral ones, especially when operating in high temperatures and under rough conditions. (Rader, 2024)

6.11 Connection to power grid

For companies that want to sell electricity to the power grid, it comes with several regulations. The frequency and voltage need to be at stable, constant levels with only small variations. The following regulations are relevant for the frequency:

- The facility must comply with the requirements to remain connected within the following frequency intervals:
  - At least 30 minutes within the frequency range 47.5 – 49.0 Hz (EIFS 2018:2, 3 kap §1)
  - Unlimited within the frequency range 49.0 – 51.0 Hz (EIFS 2018:2, 3 kap §1)
  - At least 30 minutes within the frequency range 51.0 – 51.5 Hz (EIFS 2018:2, 3 kap §1)
- The facility must remain connected to the grid and operate during frequency change rates up to 2.0 Hz/s (EIFS 2018:2, 3 kap §1)
- The facility must reduce its active power when the frequency exceeds 50.5 Hz (EIFS 2018:2, 3 kap §2)
- The setting value for the static factor is 8
- Output power from the facility should be reduced by a maximum of 3.0 percent per Hz at frequencies lower than 49.0 Hz (EIFS 2018:2, 3 kap §4)
- Automatic reconnection of the facility should only occur within the frequency interval 47.5 – 50.1 Hz:
  - Reconnection should occur only after the grid frequency has remained within this interval continuously for at least 3 minutes (EIFS 2018:2, 3 kap §7)
- The facility must comply with the requirements for increasing output power at automatic reconnection according to:
  - < 49.9 Hz – Output power increase rate not limited (EIFS 2018:2, 3 kap §8)
  - 49.9–50.1 Hz – Output power increase rate is a maximum of 10 percent of nominal output power per minute
  - > 50.1 Hz – No increase in output power occurs
- The lowest active output power (in kW) that the facility can be regulated down to during over-frequency should be reported

(Energiföretagen, 2020)

7 Implementation

7.1 Requirements specification

The Criteria for the requirements specification are generated from the literature study and in discussion with Ranotor. The requirements for the gear consist of wishes and demands from the water pump, the generator/motor, and the steam expander, which are the 3 mechanical loads that are relevant to the case. In table 7, the full list of all the requirements and specifications is illustrated.

Table 7: Transmission specifications

Steam expander full capacity		
Manage torque from the steam expander shaft	500 Nm	Demand
Manage torque from the steam expander shaft	3600 Nm	Wish
Manage work from the steam expander shaft	40-200 kW	Demand
Manage work from the steam expander shaft	1,200 kW	Wish
Manage rotation speed from the steam expander shaft	1,000-5,600 rpm	Demand
Manage rotation speed from the steam expander shaft	1,000-10,000 rpm	Wish
Steam expander to water pump distribution		
Distribute a constant torque from the steam expander to the water pump	439 Nm	Demand
Distribute a constant work from the steam expander to the water pump	45 kW	Demand
Distribute a constant rotation speed from the steam expander to the water pump	980 rpm	Demand
Transmissions from the steam expander to generator/motor		
Should be able to transmit the remaining torque from the steam expander	0-1000 Nm	Demand
Should be able to transmit the remaining torque from the steam expander	0-3600 Nm	Wish
Should be able to transmit the remaining work from the steam expander	40-200 kW	Demand
Should be able to transmit the remaining work from the steam expander	0-1,200 kW	Wish
Should be able to transmit the remaining rotation speed from the steam expander	1,000-5,000 rpm	Demand
Should be able to transmit the remaining rotation speed from the steam expander	1,000-10,000 rpm	Wish
Additional requirements		
Ambient temperature	-15 - 40 degrees	Demand
Protective housing	Yes	Demand
Removable protective housing	Yes	Wish
Lifespan	5 years	Demand
Lifespan	25 years	Wish
Pump placement	90° from the expander to one side	Demand
Decoupling	Yes	Wish
Easily accessible components	Yes	Demand

As the gear will work as a transmitter in several directions, the requirement can be rather confusing. The first three demands are related to the steam expander's maximal capacity. The gear should be able to resist this power, and divide it both to the pump and the generator at once or only direct all the power to the generator. The rotation speed has a very big value span, which means that a versatile gear is needed.

Requirements 7-9 are related to the water pump. These are the demands that the pump needs to fulfil to be running, and the data matches the capacity of the motor that Grundfos usually sells together with this pump. In this case, this is the power, speed, and torque that the gear needs to be capable of providing from the steam expander to the pump.

Requirements 10-15 are demands for the gear to be able to provide all the power, speed, and torque that are not needed for the pump. One option should also be to have the pump turned off, and then the gear should provide the generator with the full capacity of the steam expander. What exact capacity the steam expander can provide will depend on its application.

The criteria 16-20, there are more quality-related requirements. The lifespan of the gear has been set to a minimum of 5 years, which is a realistic goal, but there is also a wish of 25 years which to some degree will be determined by factors that can not be affected from the design perspective, mainly how and in what environment a customer decides to use it. Protective housing is one demand, that will increase the lifespan of the gear, no material requirements have been stated, although there is a wish that the gear should be oil-free, which affects the material choices. The demand for ambient temperature is stated to match the pump and generator data.

Criteria 21-23 are wishes and demands that were given by Maston AB during a study visit. This includes the pump placement which they want to lay at 90° from the steam expander and the generator, as illustrated in figure 15. There is no demand for the system to be decoupled, although it remains a wish. During their production phase, they have had a problem with finding components that fit their system, so they would prefer if all including components for our system were easy to gain access to.

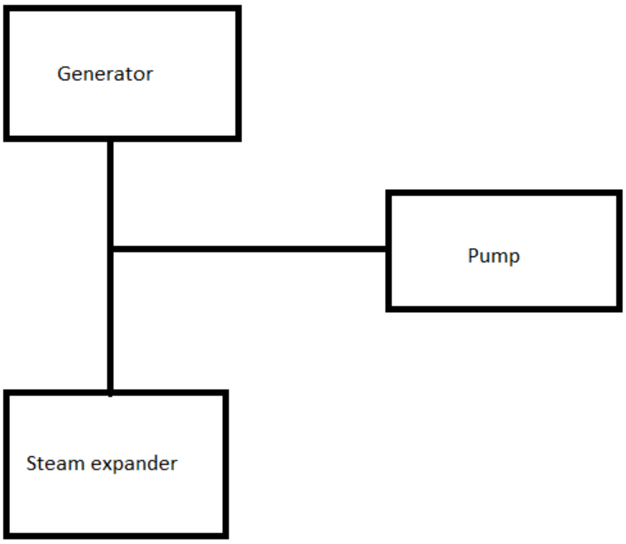

Figure 15: Pump placement

7.2 Concept generation

The overall solution will consist of several different parts working together to act as a solution to the problem statement. Since the overall solution includes many different sub-solutions, a functional diagram was constructed to help show what needs to be included in this solution. The functional diagram can be seen in figure 16. The input shaft in the figure is what is connected to the steam expander. The output shafts are connected to the pump and generator respectively. Each box in the figure represents a function or solution or something that gives/receives a signal to/from a regulation unit. The gearbox represents a protective housing, the text in the figure below the gearbox heading explains what happens inside the gearbox. The clutch mechanisms are there so that the shafts can be disconnected from the gearbox if needed or to regulate some of the momentum (effect) generated if it's higher than what the pump and generator can handle. The regulation units are there to regulate the speed and momentum that comes from the steam expander. They are all linked with each other so that communication between the units is possible. The power distribution transmits the power from the input to the two outputs. The headings below provide further information regarding these functions.

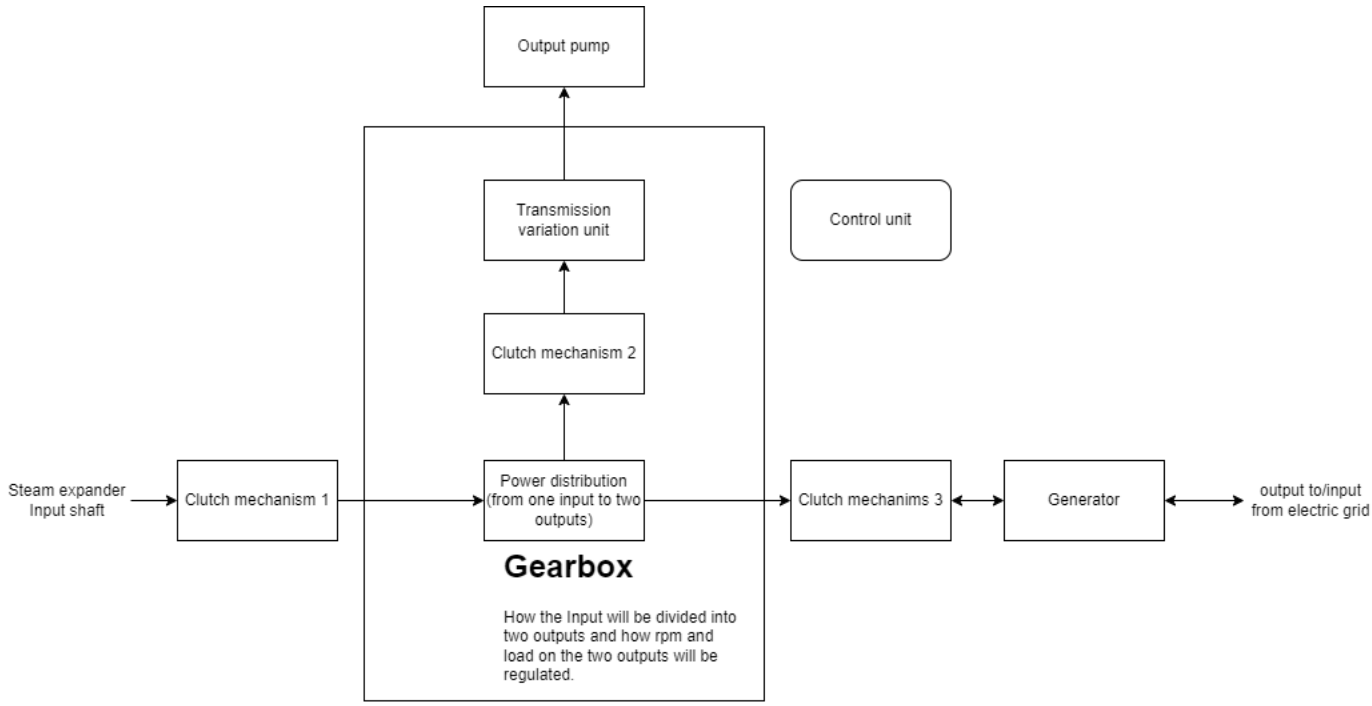

Figure 16: Functional diagram of the overall solution

7.2.1 Clutch mechanism 1-3

The functional diagram in figure 16 includes 3 clutch/coupling mechanisms, all of which come with their requirements. It is desirable to use the same clutch for all 3 applications, although it is not considered to be a demand. The clutches/coupling needs to enable diameters of different sizes to be connected.

Clutch mechanism 1 needs to withstand the power from the steam expander and is therefore the clutch with the most strict constraint. The maximum output of the expander is 1200 kW, 10000 rpm speed, and 3600 Nm torque. The nominal output of the expander is 100 kW, 3000 rpm, and 318 Nm. The generator that will be chosen for the system will not have the capacity of various power between 55-1200 kW, and therefore the expander will be limited to not come up to its maximum input power. This means that the clutch mechanism is not required to reach up to the full capacity of the steam expander for any longer periods.

Clutch mechanism 2 is seated at the output from the gearbox towards the pump. The biggest challenge with the clutch is when the engine starts, as that is where the biggest damage can occur. This clutch has lower demands of what it needs to resist compared to the other two, as it only works with the constant power to the pump of 439 Nm torque and a speed of 980 rpm. One wish for this clutch is that it can disconnect the pump from the system to send all the power from the expander directly to the generator during periods when the pump is not needed to run.

Mechanism 3 is similar to the first one, as in some periods the clutch will withstand the full capacity of the steam expander and in other periods there will be no force put on this clutch at all.

The clutch alternatives that have arisen from our brainstorming session can be seen in table 8.

Friction disc clutch
Friction Disc clutches are easy to find and are a standard choice when manual clutching and declutching are needed within a system. There exist multiple options on the market that fit the requirements of the project solution. In figure 17 one model from CUMATIX AB is shown. It is built to be used in industrial applications can handle very high torques and is easy to clutch and declutch.

Table 8: Clutch alternatives

Clutch alternatives
Friction disc clutch
Disc coupling
Torque converter
Centrifugal clutch

Figure 17: Friction disc clutch

Disc pack coupling
Maston AB has been in contact with a supplier of clutches, R+W, and they have recommended a disc pack coupling to connect the shafts. Although their solution is recommended when connecting the steam expander to the generator directly. This solution is still relevant for this case, especially when connecting the gearbox with the input shaft, as the torque and speed are the same in that case. A drawing of this coupling can be seen in figure 18

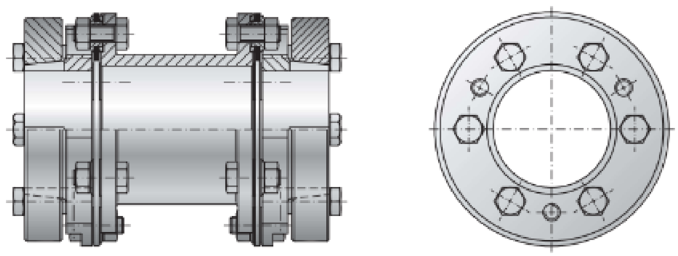

Figure 18: Disc pack coupling

This solution can be connected to shafts with a diameter between 35mm and 85mm. It also has a maximum capacity of 5200 Nm, which means that it can leverage under full capacity. It is also noticeable that Grundfos has a disc coupling when they connect their motor with their pump in their integrated solution, so it is a proven concept at least for output 2.

Torque converter
Torque converters offer some advantages when connected to a gearbox. One benefit is their ability to

provide smooth and gradual power transfer from the engine to the transmission, which helps reduce wear and tear on gearbox components, particularly during starts from low speeds. This smooth power transfer results in less stress on the transmission and can contribute to a longer lifespan for the overall system, although the component itself has a quite short lifespan.

Torque converters act as a form of overload protection for mechanical components connected to the engine. By allowing some slippage between the engine and transmission, they can help prevent damage in potential situations where the engine output exceeds the capacity of the gearbox.

There are also drawbacks to using torque converters. The biggest one is that torque converters serve to increase the transmitted torque during low output speeds which is not optimal for the project solution. However, if one were to use another type of fluid coupling, then that problem might be avoided. Another limitation is their inefficiency compared to direct mechanical coupling systems. Due to the fluid coupling mechanism within torque converters, there can be a loss of power during transmission. This inefficiency can be particularly clear in applications where precise power delivery is important.

Torque converters may introduce complexity and additional cost to the system. They require fluid and hydraulic systems for operation, which adds components and maintenance requirements. Additionally, designing a torque converter to withstand the specific speed and torque requirements of a given application may necessitate custom manufacturing, increasing both cost and lead time (Rudolf Lysholm Alf, 1933).

Centrifugal clutch
Centrifugal clutches might be a good option as they are of the type "soft start clutches" which means that they lower the risk of a rough start from low speed to very high speed, which can limit the tear on components in the gearbox. It also works as a protection for overload for the mechanical components that are connected to the engine. It is unusual to find centrifugal couplings that can withstand the speed and torque that are relevant for this system, and there is therefore a high risk for special orders that will make the system more expensive and less accessible for manufacturing.

7.2.2 Regulation unit

The regulation unit is needed due to various inputs from the steam expander, but still needs a constant flow to the pump, this means that the gear needs multiple speed rations. There is a need to track the input by some kind of sensor and thereafter have the gearbox regulated to fit the current condition. The shifting can be done in many ways and including many components and our brainstorming sessions have come up with several alternatives, as can be seen in table 9. Note that combining different units from the tables below is a possibility and that some units don't work as standalone units but instead need to have other components added to them. Sensors of different kinds are included in the solutions that utilize electrical signals to function.

Table 9: Regulation unit

Regulation unit
PID controller
Control unit (TCU, ECU, PCM)
PLC
Hydraulic control system
Pneumatic control system
Mechanical/electric control system

PID controller
A PID controller can be used to regulate the different variables affecting the solution when in operation. It is widely used within the industry today and there exist many different applications for it. A PID controller compared to a PLC or an ECU for instance is different since it represents a different approach to control

systems. A PLC for instance relies on its input and output variables and makes the logical calculations based on them. A PID controller on the other relies upon the feedback loops that are generated and makes regulations accordingly. This means that a PID controller works well where continuous control is needed like when regulating flow, speed, or pressure while a PLC works great when there are a lot of on/off signals like when running a production line or other manufacturing processes.

Control units (TCU, ECU, PCM)
It could be possible to find a sort of combination control unit of all of the three control units mentioned in the heading that is applicable for this purpose, especially since there are far fewer data inputs that need handling compared to that of a car. How these units work more specifically is that they receive input signals from their many sensors and based on the input signal send out output signals to the relevant components (in a combustion engine for instance, a sensor sends a signal to the control unit when the piston is at a certain position and the control unit sends a signal to the spark plug to start ignition). It works similarly to how a PLC works but there exist differences which are further described under the next heading.

PLC
Due to the modular nature of a PLC, it is possible to make use of one that is specifically modified to regulate the workings of a project solution. Compared to the controller, a PLC is much more robust and the technology behind it is more mature. A PLC is also easier to maintain because of its modular design and is known to never break apart. On the other hand, PLCs tend to be rather expensive compared to a controller. Unlike a controller, a PLC cannot be embedded into the solution in the same way. Instead, it works as a separate component, likely situated on a rack and connected to the components of the project solution by cable. While this leads to easier maintenance, it increases the overall size of the complete solution.

Hydraulic control system
This could be useful to move certain components to be able to regulate the outputs which is necessary to meet the demands that were put on the project solution. The focus of this solution is the movement of a control rod or piston which is then attached to something else on the solution which helps regulate the output, similar to how you move an arm on an excavator. Hydraulic systems can work with high loads but there are risks of leakage and other failures. It is also uncertain how this solution fairs in comparison to other control systems like pneumatic systems or mechanical systems.

Pneumatic control system
Pneumatic systems could prove useful to help with gear changes and so on. The downside is that there must be room for a compressor and an air storage tank. The size of these doesn't necessarily have to be that big but still requires to be taken into consideration. Compared to hydraulic systems, this solution is both cheaper and easier to maintain and possibly the better solution although that is yet to be seen after considering other factors and what implementations that will be needed.

Mechanical/electric control system
Mechanical control systems exist pretty much everywhere when there is some kind of motion involved. There exists a wide array of systems so the content of this section will only mention those applicable to the project solution. Those solutions could for instance be to utilize small asynchronous motors to move pistons, gears, shafts, and so on. Other solutions could instead be purely mechanically based where for instance if some error occurs, then a spring jumps loose which releases a component that causes the mechanism to shut down.

7.2.3 Power distribution

Mechanisms to distribute the power from the steam expander input shaft to the output shafts, with the correct distribution division. As explained previously, the distribution between the shafts will not be at a constant value but will instead differ regularly. It is therefore necessary that it is possible to achieve this with the distribution unit that will come to be used in the final solution. It is not the job of this unit to change the distributional value but rather allow for other components in the system to create this change in distribution. The table 10 shows the generated ideas for how this distribution could be achieved.

Table 10: Power distribution

Power distribution
Differential gear
Bevel gear
Electronic distribution
Planetary gear

The reason why the regular spur gear or a variant of that, like a toothed belt, wasn't included was that the pump would have to lay parallel to either the steam expander or the generator. This could prove problematic since the generator and steam expander could vary in size due to wanting to have the possibility of making more general solutions from the solution of this case. This is the reason why it is desirable to have the pump placed perpendicularly. It also provides more space for maintenance. Therefore, it was decided beforehand to not include the spur gear or any possible variant as a possible sub-solution.

Differential gear
By using a differential to this system the power can smoothly be divided between the pump and the generator.

Bevel gear
A simple design consisting of a bevel gear system can be very cheap and simple to construct, it also has great potential to quickly respond to changing driving conditions from the steam expander. Compared to the alternatives, it can have problems with keeping efficiency on the levels that are required to not destroy the pump.

Electronic distribution
The way this distribution works is that electricity is generated from the input and directly transferred to the output shafts, basically making it a combination of a generator and two electric motors. It works as a distribution unit and a transmission unit simultaneously since the unit can do both by simply regulating the flow of energy. Although this solution has its advantages with fewer components being needed in the overall solution, it also has its disadvantages. This is further explained when describing the transmission.

Planetary gear
One advantage of using a planetary gear is that it has very low wear over time. Planetary gears are very efficient and can leverage a uniform power distribution over time. The design of a planetary gear needs accurate design as small errors in placement or size can affect the whole system negatively. Also, the compact design of a planetary gear makes the heat dissipation more complex. This then raises the price of the gear. It would also be necessary to include something like a cardan coupling or a bevel gear set since the gear allows for an axial distribution which is only desired for one of the outputs while the other is positioned perpendicularly to the input shaft. (Collins, 2017)

7.2.4 Transmission variation unit

This mechanism will enable transmission from the gearbox to the water pump and adjust the torque-speed relation to meet the requirements of the pump. Our brainstorming session has given us several concepts that are listed in table 11. The power requirements of the pump are that the pump runs at a torque of 439 Nm +-10% and a speed of 980 rpm +-10%.

Table 11: Transmission variation unit

Power transmission
Toroidal CVT
Belt CVT
Automatic gearbox
Electronic transmission
Planetary CVT
RXC drive

A recurring problem with most of these solutions is that they can't control the speed ratio and torque transmission individually without having to suffer losses in energy. This is because that would require a complete variable energy distribution and transmission which is not possible to do mechanically with gearing without suffering losses since the momentum for instance is based on the system's equilibrium and if the steam expander is accelerating or decelerating in power. There are however ways to work around this which is further explained in the implementation chapter.

Toroidal and belt CVT
The usage of a CVT enables a continuous and step-less adjustment of the gear ratio to optimize both the torque and the speed due to the physical relation between speed and torque. A CVT has the potential to keep a high efficiency over time, as it can quickly adapt to changes in running conditions. CVTs are usually more expensive to manufacture and maintain than other types of gearboxes. Complex systems also increase the risk of potential errors and increase the need for maintenance or reparation. A CVT's lifetime tends to be half that of a normal gearbox.

RXC drive
The RXC Drive is designed to work in environments similar to the working environment of the project solution. Unfortunately, the low-speed range ultimately will need to increase if not a change in gear ratio occurs before and after the drive. This however does not necessarily lead to an issue since gearing could be included both before and after the drive due to the rest of the system solutions. Therefore, this could end up proving to be a possible sub-solution for this project (NIDEC-DRIVE-TECHNOLOGY-CORPORATION, 2019).
Automatic gearbox
The automatic gearbox solution aims to work similarly to how the CVT does except that it won't be a step-less change in gear ratios but instead will require a set of gears. It is a simpler solution than the previously mentioned CVT and a more stable and reliable one. On the other hand, there are major disadvantages to this solution as well. One is that it requires many different gear sets to be able to deliver a speed and momentum to the pump that is always within its operational range. Another disadvantage is that it will rarely be able to deliver the optimal speed and momentum to the pump due to the gear ratios being fixed. If implemented, the gearbox will very much resemble that of a car but with many more gears (Nice, 2000).

Electric transmission
This solution is the same as the electronic distribution solution since the only thing you need to do to create a variable transmission is to adjust how much is transmitted to each shaft. One advantage of having an electronic transmission is that it is very flexible in terms of adjustment and regulation. By electronic adjustment, the gear ratio and torque can be constantly changed and adjusted to the driving conditions. It is at the moment the only transmission solution that can adjust both the torque and speed ratio individually. It is on the other hand a complex systems that require specific competence and resources to design, implement, and maintain. The system would also be much more expensive than the other mechanical concepts and have a lower efficiency due to losses that occur when transmitting the energy from the input to the outputs compared to a mechanical solution.

Planetary CVT
One of the biggest advantages of a Planetary CVT is that it allows a very compact design to handle step-less gearing in a tight space. On the other hand, a Planetary CVT is difficult to design with a big ratio, compared to other gearboxes. This can make it difficult to have the correct gear ratio that is needed for the final solution.

7.2.5 Protective housing

Protective housing is needed around the gearbox to prevent dirt from getting into the gear, it is also a safety issue to avoid people getting their hands or fingers in dangerous places. There is a wish that the protective housing should be easy to dismantle to make the gearbox easily accessible for reparations or maintenance. During the brainstorming session, it was decided that this part would be designed after all the other decisions were taken, as it is difficult to design something that does not waste any space and fits all the alternative concepts for other parts.

7.2.6 Generator

The concept generation of generator types has its ground in research of relevant techniques and contact with potential suppliers. The four investigated techniques are the following ones.

- Squirrel Cage Induction Generator (SCIG)
- Doubly Fed Induction Generator (DFIG)
- Permanent Magnet Synchronous Generator (PMSG)
- Wound Rotor Synchronous Generator (WRSG)

One of the research questions is whether the existing motor that is integrated with the Grundfos water pump would be able to serve as a generator. As the area of application for the steam expander will vary, the answer of whether it can or not, won't be definitive for all situations. The generator that will be recommended in the case study will have its starting point that the expander will be delivering close to its nominal power output, but with small variations.

One of the main advantages of having the pump motor serve as a generator is that it will be able to work as a motor during times when the steam expander will not reach up to the 45 kW that is required for the pump to run. The option with other generator alternatives would be to decouple the pump and send it all to the generator or simply just turn off the full system. Grundfos motor would work as a Squirrel Cage Induction Generator (SCIG). The main drawback of the SCIG is that it has a constant rotational speed, which is not ideal for varying input from the expander. In applications where the expander could operate constantly with stable power generation, this type of generator would be ideal.

Doubly Fed Induction Generator (DFIG) is another potential solution. This technique is to a high degree used for wind turbines and allows the system to work despite various speeds. The main drawback with this technique is that most suppliers only produce generators of this type for more powerful applications, often up to 5-6MW, but some less-known suppliers can deliver these as well. They are usually used in wind turbines where the system can look like the illustration in figure 19 (Runcos, Carlson, Sadowski, Kuo-Peng, & Voltolini, 2006)-

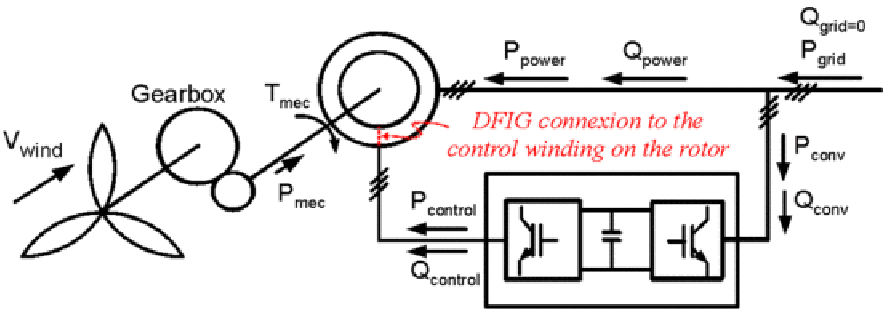

Figure 19: DFIG for wind turbine

A Permanent Magnet Synchronous Generator (PMSG) is often used in wind turbines because of its self-exciting properties, which enable drives with high power factor and efficiency. The efficiency in a permanent magnet machine is higher compared to an induction machine as the excitation happens without energy consumption. The materials used to produce a PMSG are rather expensive and difficult to work with during production. The system does require a power converter to adjust frequency and voltage, which also entails a higher cost. The main advantage is that power can be generated at any speed to fit the current conditions.

It is possible to connect the generator to a control unit to regulate the electricity that is generated by the power grid. The torque from the generator back towards the gearbox can therefore be controlled. It is possible to have the generator optimized for maximal power generation, which can be optimal during periods when the pump is disconnected. In figure 20 the system is illustrated. (Ackermann, 2005)

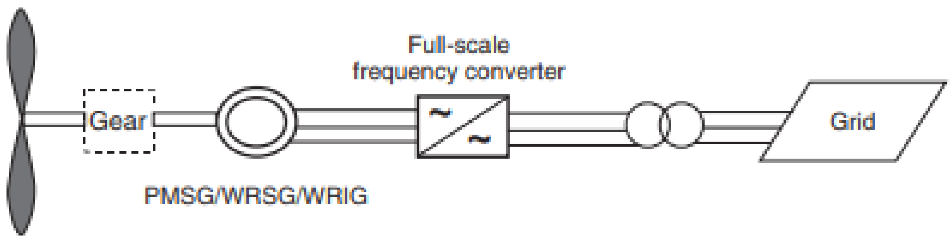

Figure 20: PMSG

The wound Rotor Synchronous Generator (WRSG) can be a good solution for generators with various speeds and powers, as it adapts to changing driving conditions by adjusting the torque from the rotor. This means that the voltage can remain constant when the speed decreases/increases. Normally these generators are more complex, and require more competence for both installations as well as for maintenance. An illustration of a WRSG system for a wind turbine can be seen in figure 21 (Tleis, 2008)

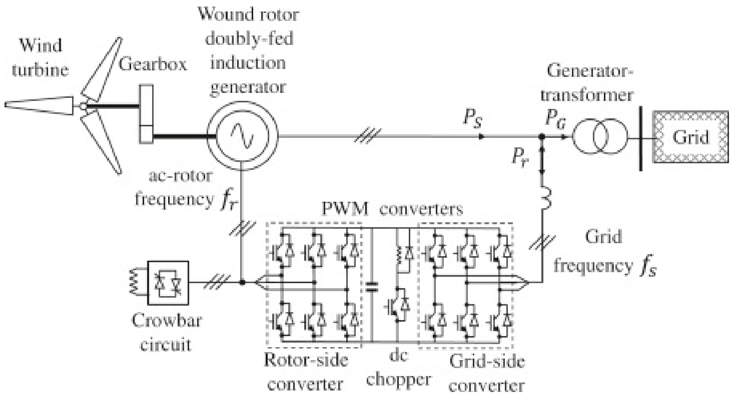

Figure 21: WRSG

The WRSG is not as quickly adaptable to changing driving conditions compared to the PMSG and the DFIG. The power span that it can operate under is usually lower than for the DFIG and PMSG as well.

7.2.7 Pump

Due to the choice of pump, a certain load will be applied to the system which will add to the system's overall torque load because of the system equilibrium. The load from the pump is 439 Nm. Also, a variation unit will have to be able to change the ratio coming from the steam expander so that the right amount of both torque and speed is sent to the pump. This is what the Transmission Variation Unit aims to achieve and the regulation units placed throughout the system will decide what that ratio will be at a certain time.

8 Evaluation

The concept evaluation compares the sub-concepts with each other to give a comprehensive decision basis for when the full concepts should be developed. There is possible that some sub-concepts are preferable for their task, but more difficult to combine with other parts of the full system, which makes them less preferable.

8.1 Clutch/coupling mechanism

We have 4 qualified concepts of potential clutches, including friction-, disc-, centrifugal clutches, and the torque converter. The alternatives will be evaluated by a Pugh matrix and find what solution/solutions are optimal for the system. The preferable option would be to use the same clutch type for all 3 shafts, but there is an option to use 3 different as well.

Table 12: Pugh matrix - clutch

Criteria	**Disc Coupling**	**Friction Disc Clutch**	**Centrifugal Clutch**	**Torque Converter**
Connects shafts of different diameter	0	0	0	0
Lifespan	0	-	-	-
Cost	0	+	+	-
Withstand high rotational speed	0	0	0	0
Withstand high torque	0	0	-	0
Grip	0	+	-	+
Wear and tear	0	-	-	-
Heat dissipation	0	+	-	-
Fast reaction for speed/torque changes	0	-	0	-
Sum	0	0	-4	-4

As can be seen in the Pugh matrix in table 12, both the torque converter and the centrifugal coupling are worse alternatives compared to the other two. It is also noticeable that they underperform in key criteria such as withstand torque and fast reactions to changing conditions. Therefore these options have been eliminated for further investigation.

A total of three couplings are needed for the system, 2 of them have similar criteria, and the last one has the wish of being possible to dismantle. Maston AB has been in contact with a supplier of couplings for the connection of the generator and steam expander, for another project, and it was decided to go with that solution for our clutch mechanism 1-2, which means that the disc coupling is our choice here. For clutch mechanism 3, this solution is not optimal as it is difficult to disengage. The friction disc clutch fulfills all the other criteria and will therefore be the solution for clutch mechanism 3.

8.2 Generator

The evaluation of the generator options consists of an elimination process, to see whether any of the options do not fulfil the requirements of the system. Thereafter a Pugh matrix to see whether any of the generators were a worse option than the others, and then finally a Kesselring matrix to perform a full evaluation of the remaining options.

Firstly, it can be seen that the SCIG as a generator type is a less good option as the possibility to change the speed is limited. What could have been advantageous could have been to use the existing motor for the Grundfos pump, which would have been a SCIG, although one can see that the capacity of using it as a generator, even when the pump is switched on is too low. The capacity of the motor as a generator is at 45 kW and the pump also needs 45 kW, which means that when the steam expander is running at its nominal power, 100 kW, the system would require a break and therefore waste energy. Therefore the squirrel cage induction generators are not a preferable option for this application, and therefore it has been eliminated for further evaluation.

The remaining three options are evaluated by a Pugh matrix to review whether any of the options is significantly worse than the others. The Pugh matrix is illustrated in the table 13 below. The DFIG has been set as a reference for the other two options.

Table 13: Pugh Matrix for generator options

Criteria	**DFIG**	**PMSG**	**WRSG**
Easy access on market	-	+	0
Capacity of shifting speeds	+	0	0
Simple design	0	0	0
Cost	-	0	0
Easy to regulate	+	0	-
Easy to connect to the grid	0	0	0
Total score	0	+1	-1

The three options do perform evenly, although the DFIG is best when it comes to performance. Still, the issue with this generator type is that it is very complex and not cost-effective when working with these small power spans. The DFIG is the most popular choice for wind turbines with capacities of 1-6MW, which is significantly higher than the requirements for this application, there are no DFIGs available on the market in this size, and a specially manufactured one can have unknown issues and be rather expensive. The DFIG might be a useful solution, but it comes with a high uncertainty, and therefore the decision to move on with the other concept is taken.

The choice of generator therefore stands between a wound rotor synchronous generator and a Permanent magnet synchronous generator. Both alternatives are possible to use for this application, but they both have their ups and downs. PMS generators usually can work in a higher span, which is one of the most important criteria for the project, as it will maximize the amount of waste heat that can be utilized. The PMSG also has a faster reaction time to adapt to changing driving conditions.

The generator decision depends very much on the circumstances for the specific application, but for this case, the project group seek an ideal solution that is as universal as it gets, and therefore the PMSG will be used.

8.3 Distribution unit and transmission variation

The distribution unit and transmission unit are put together in one evaluation as they are dependent on each other. Some concepts for power distribution are better suited with some concepts for transmission variation. The criteria for the distribution can be seen in figure 14, and a Pugh matrix can be seen in figure 15.

Table 14: Power distribution criteria specification

Transmission criteria	**Description**	**Priority**
Endure rotational speed	8000 rpm	Demand
Endure rotational speed up to 10000 rpm	10000 rpm	Wish
Lifespan	5 years	Demand
Lifespan	20 years	Wish
Components requiring special orders	Not allowed	Demand
Easily distributable in two perpendicular directions	Yes	Demand
Resistant to shock during startup	Yes	Demand
withstand ambient temperature	-20° to 40°	Demand

Table 15: Pugh matrix - power distribution

Criteria	**Bevel gear**	**Differential gear**	**Planetary gear**
Resist speed	0	-	0
Resist torque	0	0	+
Lifespan	0	-	+
Precision when the torque is around 350Nm	0	0	0
Distribute load according to wishes (perpendicular)	0	-	-
Simple design	0	0	-
Fast reaction for speed/torque changes	0	0	+
Sum	0	-3	+1

As the Pugh matrix demonstrates, there are small differences in the ability to reach the demands and wishes for the power distribution part. All solutions would be able to serve their purpose, and therefore investigation of what solutions fit to what transmission unit will take place. The transmission unit is also considered to be a more complex component in the full system, and therefore the final concept there is prioritized over the final concept for distribution.

The idea of using an automatic gearbox was removed because the full system would need too many shifts. Also, progress was made along the way, on the generator front, and therefore an automatic gearbox became unnecessary. Also due to the gear ratios being fixed, there would be a power waste from the expander during periods, which is not optimal in this application as the main idea is to reduce the waste of the total system. This solution would also be significantly more expensive than the others.

After evaluating the advantages and drawbacks of the electronic transmission solution, it is apparent that while it offers unparalleled flexibility and adjustability, its complexity, cost, and lower efficiency compared to mechanical alternatives make it less practical for implementation. Therefore, the decision to explore alternative transmission solutions that offer a better balance of performance, cost-effectiveness, and feasibility for the desired application.

The continuously variable planetary transmission is also one alternative that is removed from further investigation because there is no current solution on the market that can handle the torque requirements and that has enough high gear ratios. It would require extensive reconstruction of the solutions that exist today, it would be expensive and time-consuming as well as unpredictable.

The RXC drive was a product that was found on the market, this type of product is made for smaller applications and would require a special design for our applications. The product is not commonly used and it is considered to be too unreliable to base our solution on this technique.

With these four concepts eliminated, the toroidal CVT and the belt CVT are our remaining concepts. The ovulation will therefore be between the two transmission units and the three distribution units, which means that a total of 6 concepts remain. For this, a Pugh matrix was performed, In preparation for this stage, names were given to the different concepts based on their attributes. These names will have the type of CVT at the beginning of the name and the type of distribution unit at the end of the name. The concepts with a toroidal CVT have the first name "Toroidal" and the ones using a pulley-based CVT have the name "Belt". The concepts with a differential gear will have the last name "Diff", the ones with a bevel gear will have the name "Bevel", and the ones with a planetary gear will have the name "Planetary". The first Pugh matrix was done with the concept named "Belt-Diff" as the reference element, which is the pulley-based CVT with a bevel gear as the distribution unit. The criteria used in the matrix are a combination of wishes and some demands. The reason why demands are included and not just wishes is because there are risks of failure in those areas and lowering these as much as possible helps with raising the robustness of the solution, thereby making it easier to design the whole process. The Pugh matrix is illustrated in table 16

Table 16: Pugh matrix for generator options

Criteria	**Belt-Diff**	**Belt-Bevel**	**Belt-planetary**	**Toroidal-diff**	**Toroidal-bevel**	**Toroidal-planetary**
Correct speed and load regulation	0	0	0	1	1	1
Rotational speed endurance	0	1	1	0	1	1
Torque endurance	0	0	1	1	1	1
Lifespan	0	1	1	0	1	1
Manufacturing capability	0	0	-1	-1	-1	-1
Easy to maintain	0	0	-1	-1	-1	-1
Shock resistance	0	0	1	1	1	1
Thermal endurance	0	0	0	1	1	1
Cost	0	1	-1	-1	0	-1
Modularity	0	1	0	0	1	0
Total score	0	4	1	1	5	3

When analyzing the results, it is rather obvious that the concepts with the bevel gear are superior as well as the toroidal CVT. However, the planetary gear did get a rather decent score as well. Keeping this in mind, a new Pugh matrix was constructed but this time with the "Toroidal-Planetary" concept as the reference element, which is the toroidal CVT with a planetary gear distribution. The results from this next Pugh matrix are shown in table 17. The reason why this concept was chosen was due to it being very different from the previous reference "Belt-Diff", hence giving a wider picture of which concepts are better compared to the others.

Table 17: Pugh matrix for generator options

Criteria	**Toroidal-planetary**	**Belt-bevel**	**Belt-planetary**	**Belt-diff**	**Toroidal-diff**	**Toroidal-bevel**
Correct speed and load regulation	0	-1	-1	-1	-1	0
Rotational speed endurance	0	0	0	-1	-1	0
Torque endurance	0	-1	-1	-1	0	0
Lifespan	0	-1	-1	-1	-1	1
Manufacturing capability	0	1	1	1	1	1
Easy to maintain	0	1	1	1	1	1
Shock resistance	0	-1	-1	-1	1	-1
Thermal endurance	0	-1	-1	-1	0	0
Cost	0	1	1	1	1	1
Modularity	0	-1	0	-1	-1	-1
Total score	0	-3	-2	-4	0	2

After analyzing both matrices and their results, it was decided to remove the concepts "Belt-diff" and "Belt-planetary" from the list of potential project solutions. This is due to them receiving a low score in both of the two matrices. The other concepts either scored well in both matrices or one of the matrices, meaning that it is yet unclear whether they should be removed or not. This is especially true since this method of evaluating different concepts only shows how they compare to each other without giving it any proper scoring so to speak. The four remaining concepts, which are Belt-Bevel, Toroidal-Diff, Toroidal-Bevel, and Toroidal-Planetary will therefore be further evaluated in a Kesselring matrix.

A Kesselring matrix is performed to do a final evaluation of what system that are most beneficial for the system. The Kesselring matrix included the same criteria as the Pugh matrix. The weighting was based on how important the different factors were for the system's functionality. The weighting of the demands is ranked higher than most of the wishes since lowering the risk of system failure is viewed as more important than for instance making the design more modular or cheaper. The Kesselring matrix is shown in figure 22.

Kesselring matrix											
		Solutions									
Criteria		**Ideal**		**Belt-Bevel**		**Toroidal-Diff**		**Toroidal-Bevel**		**Toroidal-Planetary**	
Name	**W**	**v**	**t**	**v**	**t**	**v**	**t**	**v**	**t**	**v**	**t**
Correct speed and load regulation	5	5	25	4	20	4	20	5	25	5	25
Rotational speed endurance	5	5	25	5	25	4	20	5	25	5	25
Torque endurance	5	5	25	4	20	5	25	5	25	5	25
Lifespan	3	5	15	3	9	4	12	4	12	4	12
Manufacturing capability	4	5	20	5	20	3	12	4	16	3	12
Easy to maintain	3	5	15	4	12	2	6	4	12	3	9
Shock resistance	3	5	15	3	9	4	12	4	12	5	15
Thermal endurance/resistance	3	5	15	4	12	5	15	5	15	5	15
Cost	2	5	10	4	8	2	4	3	6	2	4
Modularity	1	5	5	4	4	3	3	4	4	4	4
Total		50	**170**	40	**139**	36	**129**	43	**152**	41	**146**
Rank					3		4		1		2
Decision		The final solution will be the Toroidal-Bevel									

Figure 22: The Kesselring Matrix

After the process of making the Kesselring matrix, one could conclude that there were two solutions that best suited the system. These were "Toroidal-Bevel" and "Toroidal-Planetary" with the former being slightly better. Therefore, it was decided that the solution to move forward with would be the "Toroidal-Bevel", both because of its higher score but also because the design of bevel gears compared to planetary gears is a lot simpler which saves time in the design process.

8.4 Regulation unit

To select the regulation unit for the system, the differences between the PID regulators and control units need to be clear, to control their suitability for this application. The PID regulator regulates the system based on continuous feedback loops, which give relevant information to the system to keep the performance at optimal conditions. The control unit takes signals from sensors and can handle multiple processes at the same time. If there is a need to regulate multiple processes at the same time, a control unit is optimal. In our case, it is optimal if the same regulation unit can be used both for the generator and the CVT at the same time.

After investigation, it was discovered that the most common type of control system for CVTs is a hydraulic system, which for us, therefore, is a preferred solution as it requires less development to fit in a regulation system for our purpose, Therefore the pneumatic/electric control system has been eliminated from further evaluation.

A combination of a PID regulator and a simple control unit might be useful, especially if it is needed to connect to a bigger centralized control system.

Decision
By doing further research, it has been discovered that the most common type of control system for CVTs uses an ECU to help control and regulate the variation in a CVT. It was therefore decided to use a unit like the ones used in other CVTs. Examples of these are the DENSO TEN control ECU (Murakami, Fukamachi, & Miyazaki, 2019) and the power-split CVT controller (ECU) for a tractor (Savaresi, Taroni, Previdi, & Bittanti, 2004). Another reason why an ECU was chosen was because one could potentially be able to control other functions within the system as well. For instance, to switch on/off the pump and clutch/declutch when that happens. It is also possible to adjust the generator with this device.

8.5 Simulations and finalization

A Matlab code for simulating the full system was performed, although, with assumptions of characteristics of the steam engine, which made the result very unreliable, a decision to leave this code and results out of the report was made due to this. Although some conclusions can be drawn from the code that we made, independent from the motor characteristics. The ratio of the CVT will not be close to the allowed span, which means that it can operate with high efficiency and reliability. The generator is the main factor regarding what limits the operation of the full system. A generator that can operate in a higher span is possible to add to the system without changing the possibility of using a CVT. A generator that could match up towards 1000 kW output from the steam expander would roughly be the limit for the usage of CVTs of this type, compared to drives of 140 kW which this thesis looks into.

8.6 Full system

After making all the different matrices for both sub-solutions and complete solutions, the most suitable solution was discovered. This solution includes:

- A disc coupling between the steam engine shaft and the gearbox to connect the system to the steam engine.
- A disc coupling between the generator shaft and the gearbox to connect the generator to the system.
- A friction disc clutch between the pump and the gearbox to connect the pump to the system with the possibility to disconnect the pump if not in operation.
- A hydraulic control system that is operated by an ECU to regulate the CVT and generator and also to control other functions such as disconnecting and reconnecting the pump when not in or in operation.
- A bevel gear system that distributes the torque and speed from the steam engine to the pump and generator.
- A Toroidal CVT that variates the transmission to the pump by changing the rotational speed to the correct value for the pump.
- A Permanent magnet synchronous generator that adjusts the torque that acts against the system to keep the system in balance.

Except for the components mentioned above, components such as protective housing should be included. Although the design of such protective housing would depend much on the area of usage and need for maintenance, and are therefore overlooked in detail. Some illustrations of how it can look can be found in

Appendix A-D.

For the ECU to work, one would need to program software to ensure that the ECU can perform its tasks. No such programming is done during this thesis. Instead, equations and instructions explaining how and what is to be coded into the ECU have been constructed. The reasoning behind this is that a software developer should be able to construct a functioning software based on the information provided in this thesis. The equations and instructions are written down below.

Variables used in the equations:

- Angular velocity of the steam expander shaft = ω_S and the torque = $M_{\mathrm{v,S}}$.
- Angular velocity of the generator = ω_G and the torque = $M_{\mathrm{v,G}}$.
- Angular velocity in to the CVT = $\omega_{\mathrm{CVT,in}}$ and the torque = $M_{\mathrm{v,CVT,in}}$.
- Angular velocity out from the CVT = $\omega_{\mathrm{CVT,out}}$ and the torque = $M_{\mathrm{v,CVT,out}}$.
- Angular velocity of the pump = ω_P and the torque = $M_{\mathrm{v,P}}$.
- Gear ratio of the bevel gear system = $i_b = \frac{\omega_S}{\omega_{\mathrm{CVT,in}}}$
- Gear ratio of the CVT = $i_{\mathrm{CVT}} = \frac{\omega_{\mathrm{CVT,in}}}{\omega_{\mathrm{CVT,out}}} = \frac{M_{\mathrm{v,CVT,out}}}{M_{\mathrm{v,CVT,in}}}$

For the ECU to be able to regulate the system while in operation, it needs to control two things. One is the gear ratio i_{CVT} and the other is the generator load that should be equal to the torque $M_{\mathrm{v,G}}$. It is important to keep in mind that the equations that control the two variables are dependent on each other so they will have to work together to get the desired values. Control codes are also needed for the system to operate so that things like the clutch disengage in the right moment. Equations and instructions used for programming the software are:

- CVT gear ratio = $M_{\mathrm{v,CVT,out}} = 439Nm$, $\omega_{\mathrm{CVT,out}} = 980rpm$,
  $=> i_{\mathrm{CVT}} = \frac{\omega_{\mathrm{CVT,in}}}{980} = \frac{439}{M_{\mathrm{v,CVT,in}}}$
- Generator load = $M_{\mathrm{v,G}} = M_{\mathrm{v,S}} * \omega_S - \frac{M_{\mathrm{v,P}}}{i_{\mathrm{CVT}} * i_b}$
- Have a safety shut down button available.
- If the generated power by the steam expander is <85 kW, disengage the clutch.
- When the pump-stop button is pressed, disengage the clutch.
- When the pump-start button is pressed, engage the clutch. Don't engage if the generated power by the steam expander is <85 kW.
- If the generated power is >185 kW, start regulating the flow of steam by opening the safety valve(s). If the generator is not a PMSG-type generator, the amount of generated power could be different.

More equations than the ones that are mentioned do exist and can be calculated. However, they won't be necessary to calculate since the information provided isn't of any real use or those values are already measured by sensors that are placed throughout the system.

9 Discussion

The thesis suggests one concept of how load can be connected to the system of a steam expander and a generator. Instead of using an automatic gearbox to allow multiple driving conditions, we suggest that the generator that is adjustable for multiple speeds and powers is chosen, this is particularly a great choice for the project as it enables multiple mechanical components to be included in the system rather than just the centrifugal pump. An automatic gearbox would have required more adjustments to enable the switching of components. It is also noticeable that a gearbox would be very complex to design to divide the power between the two components during shifting driving conditions from the steam expander.

The CVT in the system acts as the speed regulator to ensure that the pump is driven at its optimal speed. Among all the different alternatives and options for regulating the speed, using a CVT seemed to be both the simplest and most effective solution. It also seemed to be the most efficient option as well. The other options included an automatic and manual gearbox, a planetary gear that could change its ratio, an electronic transmission, a gearbox with a differential, a differential and brake, etc. The joint issue with these optional solutions, and the CVT too for that matter, except the electronic transmission is that they only distribute speed while not taking torque into account which is either gained or lost when the speed is lowered or raised. The electric transmission solution solves this issue although it comes at a cost since there are losses to take into account along with the required size since that would essentially be a combination between a generator and an electric motor. In the end, the issue was solved by having the generator control the distribution of torque, which meant that this solution could solely focus on regulating the distribution of speed. As for most of these optional solutions, one would need to invent something new or at least something rather complicated. To avoid reinventing the wheel, it was decided to find a solution that was rather simple but still had great performance. This is then what resulted in the final solution which was a CVT. The choice of CVT type wasn't exactly straightforward since the technology is still rather fresh and far from mature which means that there are a lot of different variants on the market with some manufacturers developing their unique type of CVT which they then try to sell (like the RXC drive for instance). It was eventually decided that the more mature models were preferable to use since they had been tested in practice a lot more than the other models. Those models left in consideration that weren't as mature were still considered due to extensive data provided by the manufacturers and from other sources which gave a clear picture of what the solution could do and what it was good for. Then from the process of elimination, the toroidal CVT was chosen. What made the toroidal CVT stand out from the other remaining solutions was its ability to withstand a high torque while still being able to have a high rotational speed. Since the amount of developers is limited within the CVT bracket of the market, developing one's own CVT to fit the needs of the product solution would seem like a possible option if the resources are at hand. This could prove beneficial in the long run since there does exist a demand for good working CVTs out there. As the technology keeps evolving and finding new uses in different industries, one could assume that the technology behind the toroidal CVT would be a good idea to keep developing as it has many advantages other than giving the user the perfect gear ratio but can, for instance, lower emissions in cars among other things. This however is nothing more than just a thought and is outside the scope of the project.

To distribute the power throughout the system, it was necessary to have some kind of distribution unit. The decision to use bevel gear came from a similar mindset as the choice of the speed regulation system where one would not need to reinvent the wheel and instead keeping it simple was likely to be the best option. Since the distribution was gonna be fixed, there was no need to have a solution that would be able to do anything else such as a differential that works great when you have two shafts moving at different speeds and a planetary gear that would give an unnecessary amount of speed/torque reduction/increase or the other way around. For that reason, a simple gear-to-gear distribution ended up becoming the solution. The option therefore came down to either using a spur gear system or a bevel gear system. Due to the pump's positioning, the bevel gear system was chosen.

The system that we have generated consists of three couplings/clutches. The couplings that connect the steam engine to the bevel gear, and the generator to the bevel gear are of the same design. This part was generated by a company that Maston AB has been in contact with and does serve the purpose of another project where the steam expander is directly connected to the generator. It is therefore designed to withstand the same powers as those that will be reached in this project when the pump is disconnected. Other alternatives were investigated although the decision to keep the existing one was made to save time and simplify the future work.

One friction disc clutch was designed to fit in the system between the bevel gear and the CVT. This clutch has the advantage that we can disconnect the pump and just have the steam expander connected to the generator. The reason for picking the friction disc clutch (or friction clutch) was because it is rather compact and easy to operate since you only need to push a button to disconnect the clutch. There also exist many different versions on the market for different applications which means that it can be chosen to fit a certain application. Compared to, for instance, the centrifugal clutch, the friction disc clutch can be disconnected at any given point in time which the centrifugal clutch can't since it would only disconnect once the steam engine is turned off and then reconnect once it is turned on again which isn't ideal. as for a normal coupling, one would also need to turn off the steam expander to disconnect the pump and CVT which would take up time and therefore not be efficient enough.

The mechanical component that is connected to the system is, in this case, a centrifugal pump, but it should be possible to switch out for other mechanical components, with some small modifications. The area of usage of the system when the pump is connected is mainly for cooling, but can serve other purposes as well. Some mechanical components will drive various loads while others have a constant load. If the load varies, there is a need to measure this load with the ECU to adjust the system for the correct driving conditions.

The choice of generator type comes with some ups and downs. For a long period, we were set to use a doubly-fed induction generator, as it was the generator type that would best fit the concept idea. However, these generators are usually not manufactured on such a small scale as capacities around 100 kW. So recommending this type of generator would come with high uncertainty as it is unclear whether it will be efficient in this application or not. This type of generator is usually used in wind turbines with a power range of 1-6MW. In smaller wind turbines Permanent magnet synchronous generators are usually used, and it is also the generator type that we recommend for this application. Both the DFIG and PMSG have the advantage that they are possible to adjust by an ECU. They can also easily be connected to the power grid. In that way, the generator can adjust the current that is left to the grid and lower and upper the electricity generation to match the power generation from the steam expander. When the current is lowered, the torque that is applied from the generator towards the bevel gear in the system decreases, and when the current is increased the torque also increases. By then the generator is not only serving the purpose of generating electricity to the grid, but it also works as a shifting for torque distribution to keep the water pump at its needed driving conditions.

The PMSG is also a much cheaper option compared to the DFIG, which also was a factor to consider when making the decision. One of the research questions was to decide whether the motor that is connected to the Grundfos pump would be a suitable option or not. The choice of generator depends very much on the area of application for the steam engine, and also the needs of the pump in the specific industry. For applications where the waste heat and need for the pump are constant, there is no need for a complex generator that can handle various speeds. In that case, no CVT would be needed either, rather just the simple bevel gear would be required for this system. There can also be applications with small variations of heat waste, and then it is probably more cost-effective to adjust the inlet to the steam expander to keep the power stable. In those cases, the motor to the water pump could be used as a generator, or any other generator type. Although our case study has the starting point that the steam expander is used in applications with a big variation of waste heat and need for the pump, and in that case a generator that can operate at different speeds and in a big power span is optimal.

The steam expander has a nominal output of 100 kW but has a peak output of 1.2 MW. A generator that can operate at powers between 0-1.2 MW is unrealistic, therefore we aim to have the system working with some variations, around 40-120. This would mean that the generator could work when the pump (power of 45 kW) is operating, and then have a power generation of 55 kW. It would also be able to have a total power generation of when the pump is switched off, of the 100 kW at nominal drive, but with some extra margin.

The generators that are discussed in this report are generators that are suited for various speeds and powers. In cases where the driving conditions are more reliable, there are plenty of other generator types that could be relevant, although they are not a part of this report.

The steam expander comes with many uncertainties, as the product still is in its development phase. There are no known motor characteristics, which means that we have made assumptions and found other products for our simulations. We do know the expected nominal drive (100 kW), although we also know that the expander can operate at higher levels with its peak output at 1200 kW. Having a generator that can operate in a power span of 0-1200 kW is unrealistic, so for the project, we have designed a system that fits during nominal conditions of the steam expander but still allows for variations.

As it stands today, it will be significantly cheaper to have two systems, one consisting of a steam expander and a generator and another one consisting of a centrifugal pump together with its original engine, compared to the system that we have created, as it is easy to sell and buy electricity to and from the grid.

During the coming decades, it is likely that the usage of electricity will increase and it is unlikely that the electricity production will increase fast enough to reach the demand. The possibility of great increases in energy costs exists and is worth taking into consideration when analyzing the profitability of this system. An increased number of small units with renewable energy can also create an unbalanced and unpredictable system, which can be the subject of political discussion and can result in increased legal requirements in the future.

10 Final words

This thesis provides a concept of how mechanical load can be integrated into a system of a generator and a steam engine. This concept is one idea of how to solve the issue with various conditions for the steam expander, although all components need to be slightly adjusted to fit into the specific applications. The concept that we have generated is set to be used in applications with heavily various conditions, whether when the expander is used in more stable situations, there are more cost-effective and reliable solutions that can be considered.

The progress that has been made should serve as inspiration for further development, where some components can be improved or adapted to the specific purpose that they shall serve. The main advantage of the concept that is generated may lay a decade ahead, as changes in society as laws-restrictions or energy crises can occur and increase the profitability of a such product.

Further development of this thesis would be to calculate and improve the cost efficiency of this concept, as it stands today, there are solutions of different kinds that would be cheaper and more reliable than this certain system. Our work has been performed without knowledge of how the engine characteristics could look, so the system as a whole has not been tested with specific components and products. Instead, most of the analysis is done from assumptions or with consideration taken to similar products on the market. Simulating realistic driving conditions can be performed if one case study of a specific industry where the steam/heat waste flow is known or can be predicted.

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Appendix

A Render of final solution without the protective casing

Figure 23: Render of final solution without the protective casing surrounding it from a different angle

B Render of final solution in CATIA

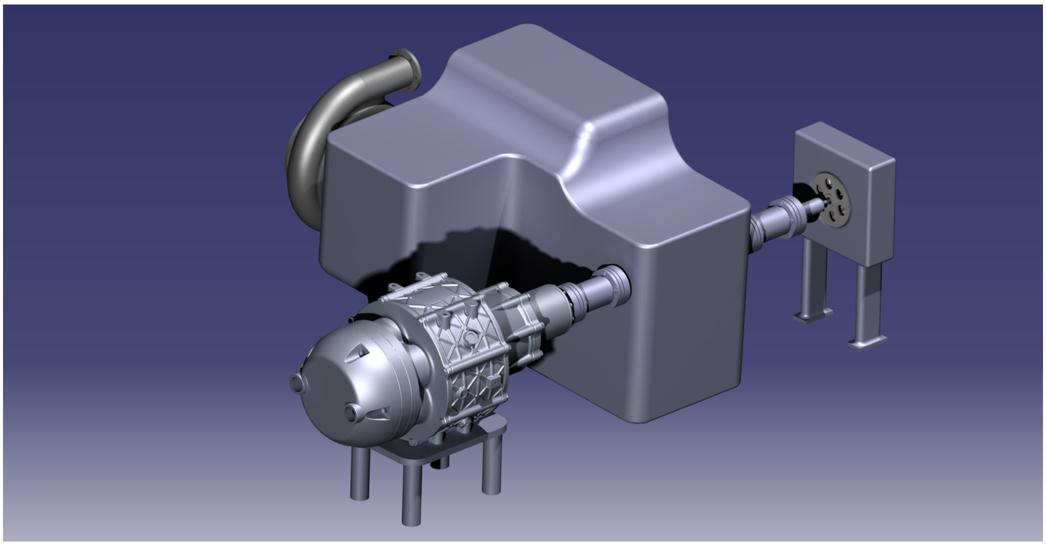

Figure 24: Render of final solution in CATIA

C Render of final solution in CATIA without the protective casing

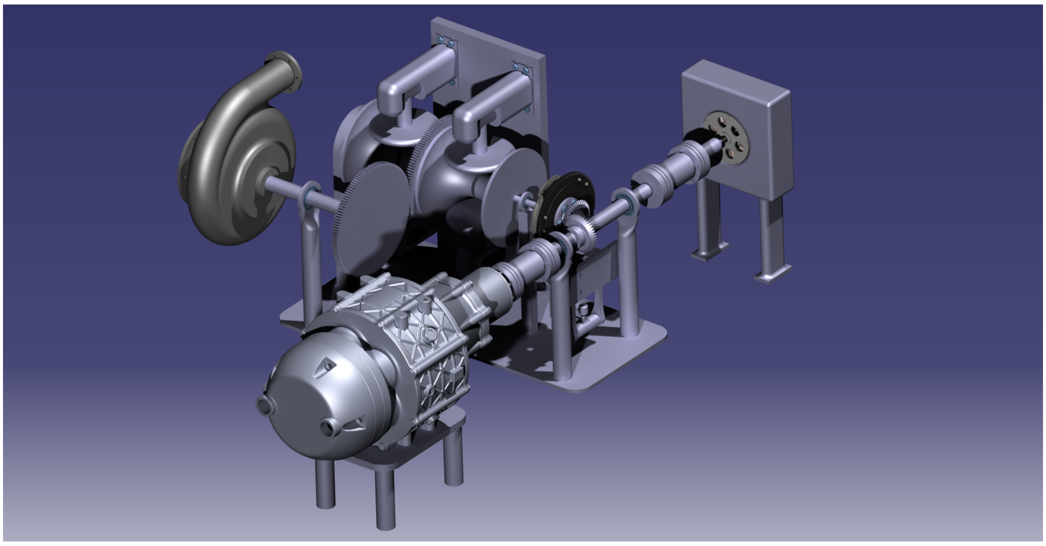

Figure 25: Render of final solution in CATIA without the protective casing surrounding it

D Render of final solution in CATIA without the protective casing, different angle

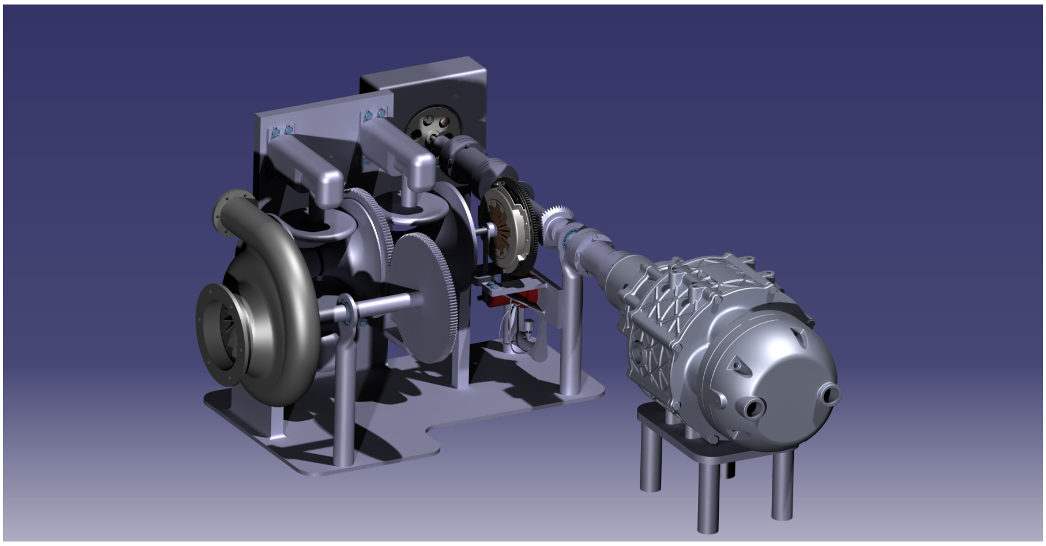

Figure 26: Render of final solution in CATIA without the protective casing surrounding it from a different angle