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Power Management System for Offshore Crane

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Abstract

The main objective in this thesis is to control the power consumption of a lattice boom offshore crane in order to reduce frequency variations and prevent blackouts.

After studying how the electrically powered offshore lattice boom cranes works and are put together, a dynamic model of the power consumption for a crane was developed. By using the moment balance for the different systems on the crane (hoisting, luffing and slewing) the torque needed to drive the system at a given speed is calculated.

A model of a diesel generator was also implemented. This model was found in an technical article, and implemented mainly by using parameters for a 440kW diesel generator. Some of the parameters had to be found in other literature. These values are "typical values" for diesel generators, and may be the cause of that the modelled diesel generator has a relatively slow response.

Two datasets were received from National Oilwell Varco Molde AS (NOV) which shows total load in kW and the corresponding RPM of the diesel generator from an actual crane. The load sequences from these datasets were extracted in order to have realistic load scenarios for simulations.

The next step was to set up three different simulation scenarios in order to explore the advantages of feeding the measured load forward to the regulator of the RPM of the diesel generator. The first scenario was made by using the model of the crane with a sequence of different reference speeds for the speed controllers for the three systems on the crane. The two other scenarios are using the load sequences from the two datasets received from NOV.

After running these three simulation scenarios both with and without the feed forward and studying how this influenced the RPM of the diesel generator, the conclusion was that it reduced the variations of the RPM. The small variations were almost completely removed, while large variations in the load still caused peaks in the RPM even though they were reduced.

The large peaks still remained because of that the diesel generator has a limit to how fast it can increase its produced power. When the total load consumed by the crane has a large instant increase, the diesel generator does not manage to follow and in worst case, it blacks out.

Therefore this had to be prevented by limiting the rate of change of the load, so that it does not increase faster than that the diesel generator manages

to increase its produced power. In this project a MATLAB function is used to limit the requested load from the different speed controllers for the three systems on the crane. In addition to the rate of change, it also has to control that the total consumed load does not exceed the maximum load that the generator is able to produce.

When sharing the power between the different systems, the hoisting system has a 100% priority, while the luffing and the slewing system shares the remaining power available based on how many percent of their maximum power consumed they requests.

The effect of this limitation is shown by running a simulation by using the first simulation scenario. The reason for choosing the load sequence that is generated by running the crane model is that the loads for the different systems are available separately, whereas in the datasets received from NOV only the combined total load is available.

The conclusion is that the combination of the feed forward and the limitation of the requested load and the rate of change of the requested load, helps reduce the variations in the RPM of the diesel generator significantly. Thereby the variations in the frequency are reduced and an eventual power blackout is prevented.

Sammendrag

Hovedmotivet med denne oppgaven er å kontrollere kraft forbruket til en offshore kran, for å redusere variasjoner i frekvensen og for å unngå overbelastning som i verste fall fører til at kranens diesel generator kveles.

Etter å først studere og sette seg inn i hvordan disse kranen virker og er satt sammen, må en dynamisk modell av kraftforbruket til kranen utvikles. Dette blir gjort ved å sette opp momentbalansene for de tre forskjellige hovedsystemene på kranen(heis, bom-heis og sving), for så å regne ut hvilket moment som kreves for å kjøre de forskjellige systemene i gitte hastigheter. Det er også implementert en modell av en diesel generator. Denne modellen ble funnet i en teknisk artikkel, og er implementert hovedsaklig ved bruk av parametere for en 440kW diesel generator. Noen av parameterene måtte bli funnet i annen litteratur. Disse verdiene er "typiske verdier" for en diesel generator og kan være årsaken til at den modellerte diesel generatoren har en forholdsvis treg respons.

Det ble mottatt to datasett fra National Oilwell Varco Molde AS(NOV) som viser total last i kW og tilhørende turtall for diesel generatoren på en ekte kran. Last sekvensene fra disse datasettene ble hentet ut for å ha realistiske last scenarioer for videre simuleringer.

Det neste steget var å sette opp tre forskjellige simulerings scenarioer for å undersøke effekten av å mate frem lasten til regulatoren for turtallet på diesel generatoren. I det første scenarioet ble last sekvensen laget ved å bruke modellen av kranen som ble utviklet i dette prosjektet, ved å bruke en sekvens av forskellige referanse hastigheter for de tre forskjellige hastighetsregulatorene for systemene på kranen. I de to andre scenarioene ble last sekvensene fra de to datasettene brukt.

Etter å ha kjørt disse simulerings scenarione både med og uten å mate frem lasten til regulatoren for turtallet på diesel generatoren, ble det tydelig at denne funksjonaliteten reduserte variasjonene i turtallet til diesel generatoren. De små variasjonene ble nesten helt borte, mens de største toppene og bunnene i turtallet ble redusert.

Grunnen til at de største toppene og bunnene ikke forsvinner er at diesel generatoren har en begrensning på hvor raskt den kan øke drivstoffinnsprøytningen sin. Når lasten øker fortere enn drivstoffinnsprøytningen kan øke, resulterer dette i svingninger i turtallet og i verste fall at diesel generatoren kveles.

Måten å takle dette på er å begrense hvor fort lasten kan øke, slik at kraftforbruket ikke øker fortere enn den produserte kraften. I dette prosjektet er dette gjort ved hjelp av en MATLAB funksjon som begrenser kraften som hastighetskontrollerene til de forskjellige systemene på kranen spør etter fra sine elektriske motorer.

Når kraften skal fordeles mellom de 3 systemene på kranen har heis systemet 100% prioritet, mens bom-heis og sving systemene må dele kraften som er til overs basert på hvor mange prosent av maksimum kraft hastighets regulatorene deres spør etter.

Effekten av denne begrensningen er vist ved hjelp av det første simulerings scenarioet. Grunnen til at det er vist med dette scenarioet er at her har en kraft forbruket til de tre systemene på kranen tilgjengelig separat, mens i de to datasettene fra NOV er det bare total last som er tilgjengelig.

Konklusjonen er at en kombinasjon av å mate frem lasten til regulatoren av turtallet til diesel generatoren, begrense hastigheten på endringen av den forespurte kraften fra de forskjellige hastighetsregulatorene og å begrense den totale forespurte kraften fører til at variasjonene i turtallet til diesel generatoren blir redusert. Dermed vil variasjonene i frekvensen også reduseres, og en unngår at diesel generatoren kveles.

Preface

This is a master's thesis at The Department of Engineering Cybernetics at NTNU, in cooperation with National Oilwell Varco AS located in Molde. The master's thesis is a mandatory assignment of 30 credits for all master students during the last semester of their masters degree. The project is written during the spring of 2013 (15th of January - 10th of June).

It is worth noting that some small parts of this project is based on a project that was written during the autumn of 2012, by the same student. This project dealt with a constant tension functionality for the hoisting system of a lattice boom offshore crane, and was also in cooperation with NOV.

About National Oilwell Varco Molde AS

National Oilwell Varco is a huge supplier of equipment used when drilling for oil and gas. They offer a variety of products, such as drilling rigs and derricks, mud systems, control systems and equipment for handling drilling pipes. The department located in Molde currently has approximately 300 employees and their main products are winch systems, hose stations and offshore cranes.

Acknowledgements

I would like to express my gratitude to my supervisor Tor Arne Johansen for useful guidance, comments and help during this master thesis.

I would also like to thank Bernt Sandøy, head of the Automation department at National Oilwell Varco Molde AS for giving me te opportunity to work with this project and for providing the necessary information along the way.

Contents

Chapter 1

Introduction

1.1 Motivation

Model of Diesel Electric Generator and Power Consumption for the crane

A model of the diesel generator is necessary in order to explore how the management of the power consumption effects the diesel generator. If the model behaves like the actual diesel generator, one can find out which measures will work on the real one as well when managing the power consumption.

A model of the power consumption of the crane is also essential for this project in order to develop a Power Management System (PMS), a realistic model is necessary in order to create realistic load scenarios for testing the modelled diesel generator. The better the model is, the fewer changes and adjustments has to be made if the PMS eventually is implemented to a real crane.

Power Management System

NOVs offshore cranes usually does not have enough power to run both slewing, luffing and hoisting at full power at the same time. This is because it is not often that this is necessary and therefore money is saved by using a smaller power source. In this project the power source is a diesel electric generator, and a smaller one will save fuel consumption in addition to the cost of buying the generator itself. A smaller generator is also advantageous since the cranes are used on rigs and vessels, where there are limited space and the weight needs to be kept as low as possible.

When using a power source smaller than the potential maximum power usage, one have to control the power usage to avoid overloading the source. This is where the PMS comes in. The PMS must make sure that the power source does not get overloaded, while at the same time make the operation of the crane as smooth as possible and keeping the fuel consumption as low as possible.

As it is today, NOV already have a PMS which they are looking to improve. Therefore this assignment is given as a Master's thesis to a student in order to get a independent solution to a PMS from someone that was not a part of developing the system in use today. Hopefully this solution, or parts of the solution can be used to improve the one they already have.

1.2 Objective

The main objective in this project is to develop a model of the Power Consumption for an electrically powered offshore crane and suggest a PMS for this crane, but in order to do this there are several steps that has to be completed. The problem description given by NOV can be found in appendix D.

Find literature and earlier work on the subject

Literature about the same or approximately the same subject can be useful in order to get a picture of how a PMS system is usually put together. It can give an idea about how to best attack the problem and where the difficulties lies.

Investigate how the cranes work and are put together

To get a good understanding of how the cranes work and are put together is essential in order to get a good model of the power consumption of the cranes, which then again is essential to develop a PMS. This step includes getting familiar with the overall configuration of the crane. From the diesel generator, through the controllers and to the hook that is hanging by the wire from the boom tip.

Developing a model of the power consumption for the crane

A good model is essential in order to develop the PMS for the crane. This model has to be based on specifications and information provided by NOV.

There are some parameters that may differ from crane to crane. Such as the mass and length of the boom, length and thickness of the wire, number of turns for each layer of wire on the drum, size of the generator, the gear ratio and number of falls. All parameters shall be collected in a m-script in MATLAB, so that they can easily be changed if the model is to be used on a different crane.

Even though this model will be an approximation it has to include all the aspects that is important regarding the power consumption.

Suggest a control philosophy for the PMS

Based on the model of the power consumption there will be suggested a control philosophy.There is not enough power available to run every function of the crane at full power at the same time, therefore the control systems task is to avoid overloading the generator, as far as possible minimize the fuel consumption and make the operation of the crane as smooth as possible for the operator.

1.3 Outline of thesis

Chapter 2 - Power management systems

This chapter contains theory about PMSs in general. This theory is mainly gathered through literature studies. The theory presented focuses on minimizing frequency variations and preventing blackouts in a power system.

Chapter 3 - Lattice boom offshore crane

In this chapter, the lattice boom offshore crane is presented. The three main systems on the crane, hoisting, luffing and slewing. It is explained how they are powered and the necessary specifications are given.

Chapter 4 - Rules and regulations

In this chapter, the rules and regulations that affects the PMS from NS-EN 13852-1 [9] are presented.

Chapter 5 - Datasets

This chapter presents two datasets that were received from NOV. The datasets shows the total load and the corresponding RPM of an actual diesel generator. Note that there is an unknown regulation structure included in this system.

Chapter 6 - Model of diesel electric generator and power consumption

This chapter presents the model of the power consumption of the crane that is calculated in this project. The power consumption is found by developing a model of the complete crane, and using the moment balance for each system to extract the torque needed to move the different systems at given velocities.

Chapter 7 - Controlling the power consumption

This chapter handles the controlling of the power consumption. Based on the modelled diesel generator, measures are made to as far as possible reduce the frequency variations and to prevent power blackouts.

Chapter 8 - Conclusion

This chapter concludes the project, how good the solutions are and what could have been done better. It also suggests further work.

Chapter 2

Power management systems

When first used in the industry, the name PMS was used to describe the system that managed the automatic starting and stopping of generators depending of how big a load that was in use. Today the term PMS is also used for systems that controls and optimises the energy usage both by controlling generators and limiting the power consumers where this is possible and advantageous.

PMSs are a crucial part of the power and automation systems on for example oil rigs and marine vessels, where space is limited and the weight has to be kept at a minimum and thereby the power available is limited. The PMS can either be connected to the other control systems or it can be a independent system, but most often it is integrated in the control system or connected to it. The advantages of a PMS are many. Blackouts can be prevented, fuel consumption can be minimised, frequency variations can be reduced and the total weight can be reduced because in some cases there can be used a smaller generator when the power usage is properly managed. The PMS can also cause lower maintenance costs by reducing the number of faults and damage to the equipment. [10]

2.1 Blackout prevention

A power system that is powered by a diesel generator operates optimally at an approximately constant load. Because of the slow turbocharger dynamics the engine can be unable to respond to quick changes in the load, especially if these changes are big. A sudden large increase of the load will lead to a drop in frequency, and in worst case some of the consumers have to be disconnected or the diesel engine stalls. Small changes in the frequency are tolerated, but the rule of thumb is that these shall not exceed ±10% deviation from the nominal value. [1]

2.1.1 Feed forward

A diesel generator usually has a PID controller that regulates the RPM of the generator. The PID controller measures the deviation in the RPM of the generator from a drooped set-point and controls the fuel rack in order to reach this set-point.With no feed forward functionality the controller can only respond after the changes in the load has affected the RPM of the generator. This causes variations in the frequency, which is not desirable.

The feed forward gain can either be calculated based on the expected load based on signals from for example a joystick or other actuators, or it can be calculated based on measured load values. Based on either expected or measured load the appropriate fuel rack position can be calculated and this value is then added to the output of the PID controller. This will result in that the fuel rack instantaneously changes to a value that is close to what is necessary in order to produce enough mechanical power to match the consumed electrical power. This will result in a more stable rotational velocity of the diesel generator. [1]

2.1.2 Battery bank

One way to cope with the problems that comes with quick variations in the load is to have a large battery bank connected to the power system that can supply extra power during the load peaks.

An advantage of having a battery bank connected is that if the bank is big enough, it can be used to operate the crane if the generator stops and this causes a critical or dangerous situation. The disadvantages of this solution is the price of the battery bank the space required and the weight of the battery bank. Since these cranes are usually used on rigs and vessels, the space is limited and the weight has to be kept at a minimum.

2.1.3 Limiting the load

Another possibility is to simply limit the acceleration of the different functionalities of the crane in order to give the diesel generator time to catch up with the increase in the load. This solution will influence the speed at which the crane can be operated, and has to be implemented in a smart way in order to not be of annoyance for the operator of the crane. A system like this has to be developed either by calculation or by measurements from the actual crane, in order to know how large accelerations by one or more of the cranes functionalities the diesel generator can handle without the frequency dropping too much.

2.2 Minimizing fuel consumption

Minimizing the fuel consumption can also be a part of a PMS. This is most advantageous on power systems with two or more power sources. The fuel consumption can then be optimized because the fuel consumption is not linear to the power produced in a diesel generator. This can then be described as a optimization problem with the fuel consumption as the cost, and the load will be shared between the different generator by the combination that gives the lowest total fuel consumption.

There are some measures one can make to lower the fuel consumption a little bit even with only diesel generator. One of these are to low pass filter the measurement of the frequency of the generator so that disturbances does not influence the regulation of the fuel rack. The other is to, as far as possible limit the load so that the system never has to work in its least economic areas, but this will effect the performance of the power consumers in the system.

Chapter 3

Lattice boom offshore crane

3.1 Overview

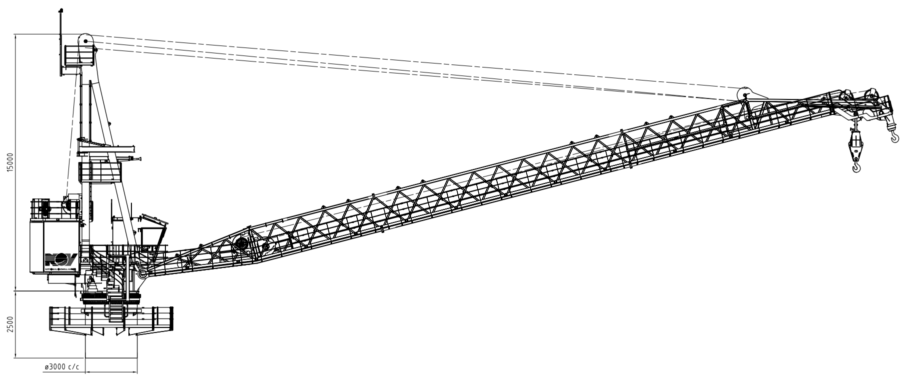


Figure 3.1: Offshore crane

The offshore cranes produced by NOV are called lattice-boom cranes. The crane itself is placed on a pedestal and is rotated by the slewing system. There is one boom that can be hoisted and lowered by the luffing system which consists of a winch located on top of the operators cabin, with wires that go through the top of the mast over the operators cabin and is connected to the tip of the boom. The main hoisting winch is located at the start of the boom right in front of the operators cabin and the wire goes through several sheaves upwards the boom and to the boom tip sheave where the wire goes down to the hook and block. [2] [8]

3.2 Main and whip hoisting system

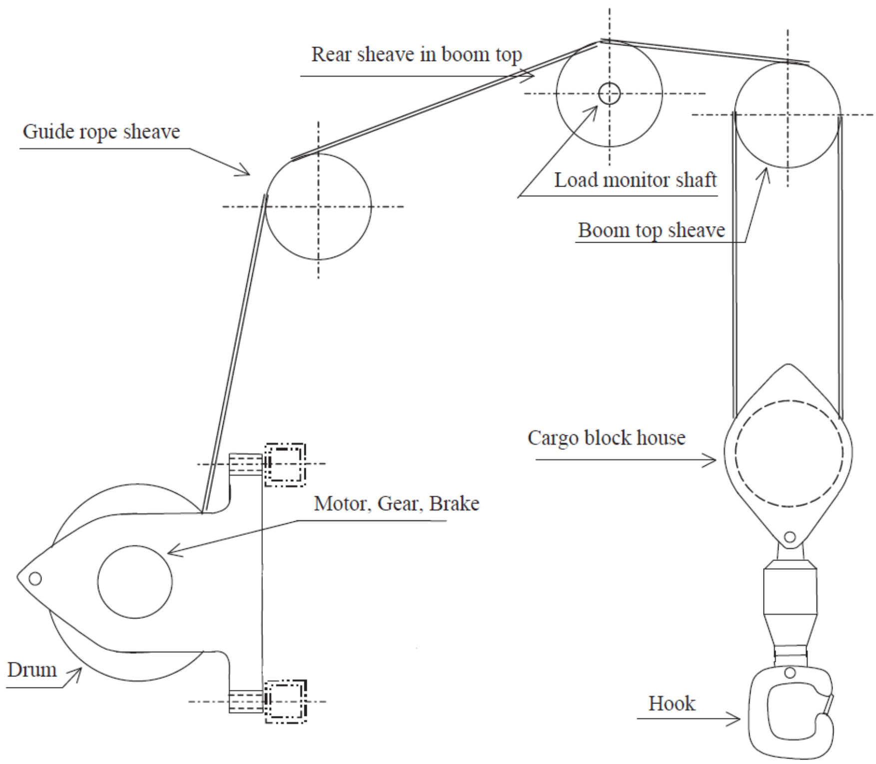


Figure 3.2: Hoisting system sketch

As shown in Figure 3.2, the hoisting systems are driven by an electric motor, which is connected to the winch drum through a gear with a given gear ratio. The wire is winded on the drum, goes up the boom through several sheaves and down to the hook and block from the boom tip sheave. The electric motor is controlled by the PLC which receives the input signal from the joysticks in the operators cabin of the crane.

There are two hoisting systems on most of the offshore cranes delivered by NOV. There is a whip hoisting system in addition to the main hoisting system, the main difference in these two hoisting systems is that the main hoisting system usually uses more falls than the whip hoisting system, which reduces the speed but increases the lifting capacity. The whip hoisting system is used for lifting light objects and the main hoisting is used when lifting heavy objects.

Both systems are powered by the same motors, but they have different total wire length, different weight of the hook and block and different number of falls. [2] [8]

Instrumentation

- Input signal from Joystick in operators cabin available in PLC.
- Output from PLC to electric motor.
- Load cell at the tip of the boom (Which measures the load in the hook).
- Angular position of winch drum (Which means that rotational acceleration, velocity and position of the drum are available measurements).

Specifications

- Approximately 2 seconds from 0 to maximum hoisting speed.
- Maximum speed 2m/s with 5000kg load.
- Maximum Power consumed 200kW (Approximately 1000Nm. Formula for transformation shown in equation 5.1)

3.3 Luffing system

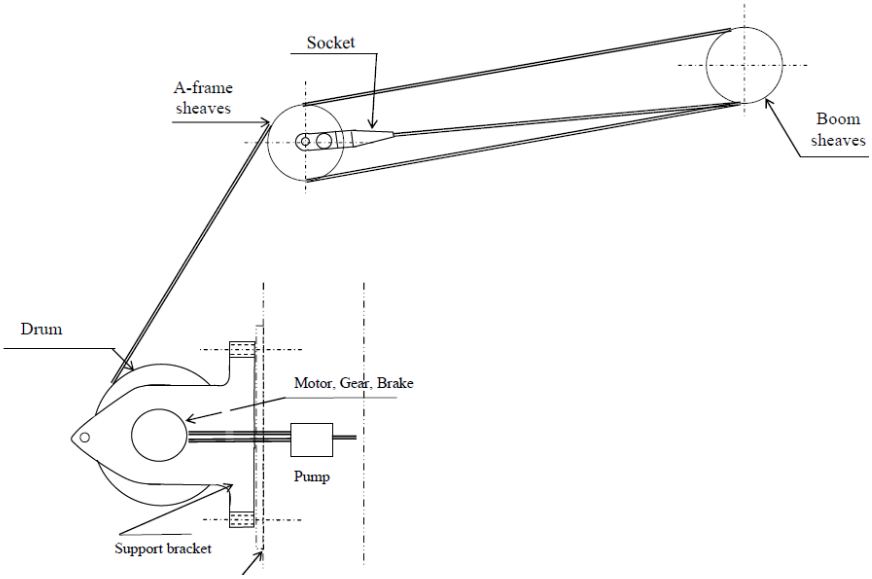


Figure 3.3: Luffing system sketch

The luffing system is the system that rises or lowers the boom of the crane. This system is similar to the main hoisting system, and consists of a winch on top of the operators cabin with wires that go through the top of the mast of the crane and to the boom tip. The boom of the crane operates within 15 - 85 degrees. The luffing system can move the boom from 15 to 85 degrees in 60 seconds at full speed, and the maximum outreach of the boom is approximately 50 meters [2].

Instrumentation

- Input signal from Joystick in operators cabin available in PLC.
- Output from PLC to electrical motor.
- Load cell at the tip of the boom (Which measures the load in the hook).

- Angular position of winch drum (Which means that rotational acceleration, velocity and position of the drum are available measurements).
- Angular position of boom (Which means that rotational acceleration, velocity and position are available measurements).

Specifications

- Approximately 3 seconds from 0 to maximum luffing speed.
- Maximum speed approximately 1°/s.
- Maximum Power consumed 200kW (Approximately 1000Nm. Formula for transformation shown in equation 5.1)

3.4 Slewing system

The slewing system is powered by two or three electrical motors, which are physically connected to the crane through sprockets [2].

Instrumentation

- Input signal from Joystick in operators cabin available in PLC.
- Output from PLC to electric motor.
- Angular position of boom (Which means that rotational acceleration, velocity and position are available measurements).

Specifications

- Approximately 4 seconds from 0 to maximum slewing speed.
- Maximum speed approximately 1°/s.
- Maximum Power consumed 100kW (Approximately 500Nm. Formula for transformation shown in equation 5.1)

3.5 Auxiliary system

The auxiliary system powers miscellaneous parts of the crane, such as emergency brakes, cooling systems etc. Maximum Power consumed is 50kW (Approximately 250Nm.Formula for transformation shown in equation 5.1)

3.6 Power system

NOVs offshore cranes have their own power supply in the form of one or two diesel engines. Some of their cranes are driven by electric winches and some are driven på hydraulic winches. In case of electrical winches, the diesel engine(s) are connected to a generator which then again powers the winches of the crane.

Electrical cranes are becoming more and more used. There are a few advantages with using electrically powered winches instead of hydraulic powered winches, such as better energy efficiency and the total weight and size are reduced compared to a hydraulic system with the same power. The electrical systems also require less maintenance than a hydraulic one, since there are no filters, o-rings etc. that has to be changed regularly. In addition, the electrical system produces less noise than the hydraulic systems.

The crane considered in this project is a electrically powered crane, powered by one diesel electric generator.

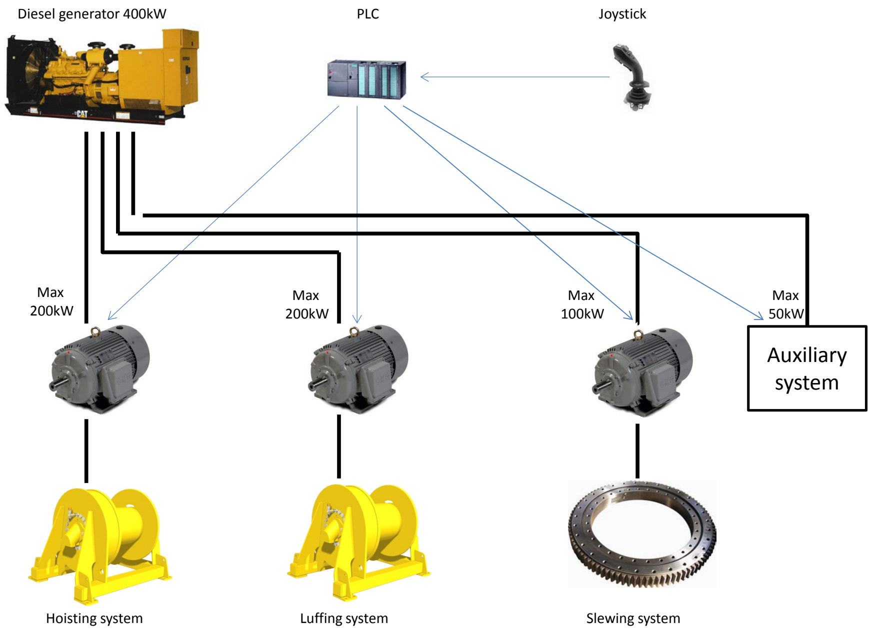


Figure 3.4: System sketch

Instrumentation

- Measurement of the load for the electric motors (This measurement has a slight time delay).
- Percentage measurement of load for the diesel engine (This measurement has a significant time delay).

3.7 Constant tension and heave compensation

3.7.1 Constant tension

NOVs offshore cranes have a Constant Tension functionality implemented. The meaning of a constant tension system is that the tension in the hoisting wire is held at a constant value by regulating the speed of the winch. This value is either set by the crane operator or it is chosen by the manufacturer of the crane.

A constant tension functionality is useful when hoisting or lowering items from or to a moving surface. For example when lowering a container from an oil rig to a supply vessel by using a offshore crane. It can be useful in numerous settings, but particularly out at sea with vessels and rigs that is always moving vertically because of the sea.

The constant tension hoisting mode is used when the load is in touch with the moving surface that it is hoisted from or lowered to. Without this functionality there might occur dangerous situations and damage to both the load and the vessel it is being hoisted from. For example if a heavy load is connected to the crane while placed on the deck of a vessel, and the vessel suddenly drops several meters because of a big wave, there will be a very strong jerk in the wire which can cause damage to both the crane and the load. Also the vessel can be damaged when the next wave comes and lifts the vessel so that the deck hits the load that is hanging by the wire. [4]

Another situation where the constant tension functionality can be useful is when hoisting or lowering items to or from the bottom of the sea by the use of a crane vessel. These operations are often done in the Oil and Gas industry when installing subsea equipment. This can be very expensive equipment, and it is therefore important avoid damage to it. In this case, there will be the crane that moves instead of the surface that the item is being lowered to or hoisted from, but the principle is the same. [8]

The constant tension functionality has to be taken into account when developing the PMS. The constant tension system has to have enough power to manage to function at the maximum speeds it is designed to. This means that the hoisting system must have enough power available for the constant tension functionality when this is activated.

3.7.2 Heave compensation

The Heave Compensation is quite similar to the constant tension functionality. The difference is that the Heave Compensation is used when hoisting or lowering, while the Constant Tension is used when the load is resting on the surface it is being hoisted from or lowered to.

The Heave Compensation is used when hoisting or lowering something out at sea where there often are waves that causes vertical movement of the rig or the vessel that the crane is mounted on. The Heave Compensations task is then to compensate for this vertical movement and keep the load moving at a fixed speed which is set by the joystick in the operators cabin. This technology allows the cranes to work in rough seas without risk of damage to people or equipment.

Similar to the Constant Tension functionality, the Heave Compensation also needs to have enough power available to run the hoisting winch at the maximum speeds that it is supposed to manage, to avoid dangerous situations and damage to equipment.

Chapter 4

Rules and regulations

4.1 Rules and regulations

There are lots of rules and regulations regarding the security of the offshore cranes. Among these regulations there also some that concerns a PMS. The most important regulations in *NS-EN 13852-1* that affects the PMS are summarized here:

5.3.3 Power requirements (From NS-EN 13852-1) [9]

"The crane prime mover shall be such that the full power demands of any loading and speed combinations associated with the various motions are compatible with the operations that the crane is designed for, such that;"

- a) A diesel engine shall not stall.
- b) A diesel engine shall not over-speed.
- c) An electric motor shall not overheat.
- d) The supply energy is sufficient (if power is supplied from an external source off the crane).

"If the crane does not have enough power for full speed to all motions at maximum load simultaneously, the speeds shall be reduced either automatically or manually according to rules of priority clearly stated in the operating manuals. Hoisting motion shall always have first priority.

The installed power shall not be less than the highest of the required power for:"

- 1) Full hoisting speed and 50% luffing speed, or
- 2) Full hoisting speed and 50% slewing speed.

5.4 Drive systems (From NS-EN 13852-1) [9]

"All main functions, e.g. hoisting, slewing, luffing shall respond to the controls such that minimum required speed is obtained from stand still within 2s from full activation of the control lever.

The controls of the main functions,hoisting, slewing, luffing folding and telescoping shall provide predictable smooth motions proportional to the position of the control levers and with insignificant hysteresis and zero band.

Control systems including multiple speed selection either manual or automatic shall always return to their safest condition with regard to stabilising the crane and the load, if any error occurs in the control system."

Chapter 5

Datasets

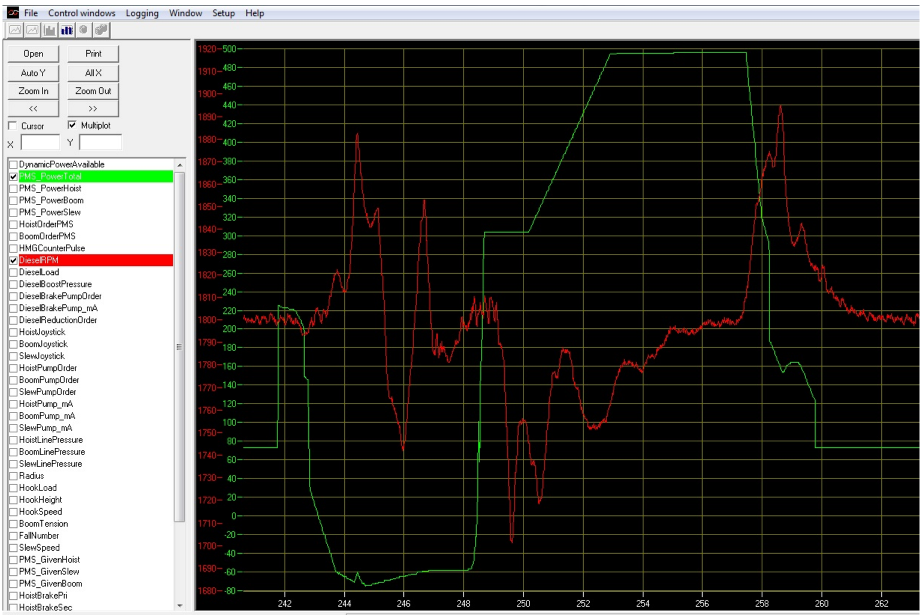


Figure 5.1: Dataset 1, shows the total load(Green) and the corresponding RPM(red) from an actual diesel generator

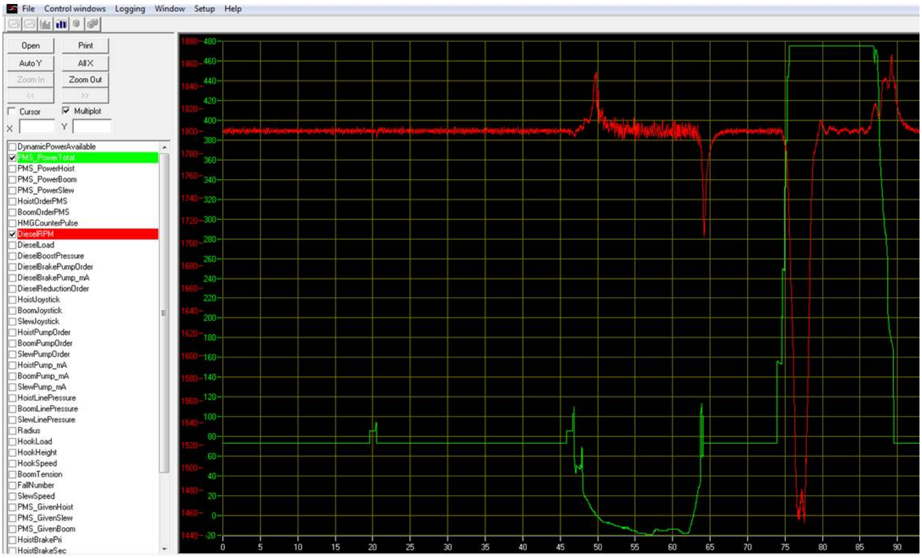


Figure 5.2: Dataset 2, shows the total load(Green) and the corresponding RPM(red) from an actual diesel generator

These two datasets were received from NOV. It is worth noting that there is an unknown regulation structure included in these datasets, as you can see especially in the first dataset, there are other factors than the load that influences the RPM of the diesel generator.

A digitiser is used to retrieve the load values from the plots, so that the load sequences can be used in MATLAB. Since they are retrieved by using a digitiser, the time axis for the sequences might be slightly shifted.

The array of values that are retrieved are converted from kW to Nm by using the formula shown below. After the conversion, the whole sequences are shifted in a positive direction so that all values are above 0.

$$T = \frac{P}{2\pi n} \quad where \quad n = \frac{1800}{60} \tag{5.1}$$

T	-	*Torque [Nm]*
P	-	*Power [W]*
n	-	*Rotations pr. second*

Chapter 6

Model of diesel electric generator and power consumption

The model that is made in this project is a model of the power usage for a complete electrically powered offshore crane. The movement and the dynamics of the crane are not prioritised, as it is the power consumption that is important. The main function of this model is to get the consumed power of the crane as a function of the signals from the joysticks in the operators cabin of the crane.

The hoisting, luffing and slewing systems are operated by the joystick in the operators cabin located on the pedestal of the crane. The joystick is connected to the PLC which is further connected to the electric motors that powers the different systems.

There are some parameters that may differ from crane to crane. Such as length and thickness of the wire, number of turns for each layer of wire on the drum, size of the electric motor(s), the gear ratio and number of falls. For this model, these parameters are collected from one of the electrically powered cranes that are delivered by NOV. All parameters are collected in a m-script in MATLAB, so that they can easily be changed if the model is to be used on a different crane.

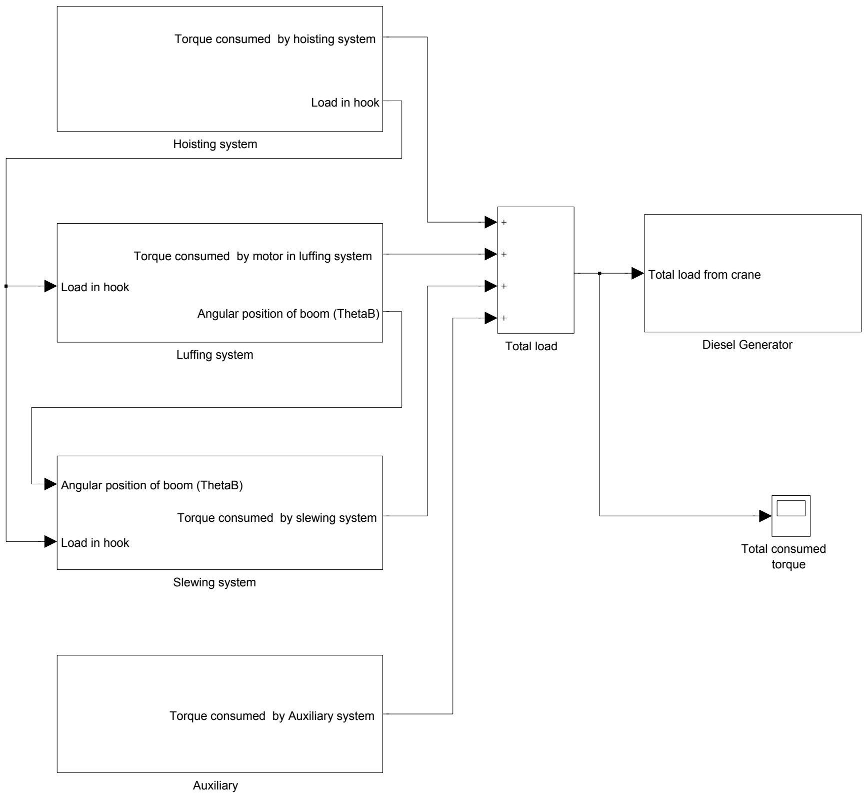


Figure 6.1: Crane Model Simulink Overview

Figure 6.1 shows an overview of the Crane Model Simulink diagram and how the different subsystems are connected.

6.1 Model of diesel electric generator

When modelling the diesel generator, the diesel generator model from the paper "*Transient power control in dynamic positioning - governor feedforward and dynamic thrust allocation*" by Aleksander Veksler (2012) [1], was used as a basis.

This model can be seen as a simplification of the diesel generator model in Xiros (2002) [11]. As Veksler writes in his article about the diesel generator model:

"It is cycle-mean in that all the state variables that are considered are averaged out through the combustion cycle, and it is quasi steady in thermodynamic parameters, which in reality are distributed and vary throughout those volumes. The benefit of this model compared to other models available in the literature is that situations when the engine experiences large load variations are represented with a fair degree of fidelity, while in most other respects the model remains fairly simple."

The model includes the dynamics that follows with large variations in the load, something which occurs in a power system for a crane. At the same time the model is not to complicated, so that the implementation does not take to much time.

The equations for this model are as follows:

$$AF = \frac{m_{a,0} + (1 - m_{a,0})\omega t}{F_r} \tag{6.1}$$

$$\eta_c = \begin{cases} 1 & AF \geq AF_{high} \\ \frac{AF - AF_{low}}{AF_{high} - AF_{low}} & AF_{low} < AF < AF_{high} \\ 0 & AF \leq AF_{low} \end{cases} \tag{6.2}$$

$$t_m = p_e = \eta_c F_r \tag{6.3}$$

$$\dot{\omega_t} = -\kappa_1(\omega_t - p_e) \tag{6.4}$$

$$P = P_r t_m \frac{N}{N_r} \tag{6.5}$$

$$H = \frac{\frac{1}{2} I (\frac{2\pi N_r}{60})^2}{P_r} \tag{6.6}$$

$$\dot{N} = \frac{(t_m - t_e)\pi \frac{N_r}{60}}{H} \tag{6.7}$$

AF	-	*Air-to-fuel ratio*
$m_{a,0}$	-	*Air flow without the turbocharger as fraction of the maximal airflow*
ωt	-	*Turbocharger rotational velocity*
F_r	-	*Fuel rack position*
AF_n	-	*Nominal air-to-fuel ratio on max turbocharger velocity*
η_c	-	*Combustion efficiency*
AF_{high}	-	*Air-to-fuel ratio at which full combustion is acheived*
AF_{low}	-	*Air-to-fuel ratio at which the combustion stops due to excessive in-cylinder cooling from the injected fuel*
η_c	-	*Combustion efficiency*
t_m	-	*Total mechanical torque from engine[Nm]*
p_e	-	*Rated BMEP [Pa]*
κ_1	-	*Decides how fast the turbocharger reaches steady state velocity*
P	-	*Current engine power output [Watt]*
P_r	-	*Rated engine power[Watt]*
N	-	*Instantaneous crankshaft RPM*
N_r	-	*Nominal engine RPM*
H	-	*Inertia constant of the engine*
I	-	*Moment of inertia of the rotating mass in the genset*

The values that are used for the different parameters for the model of the diesel generator in this project are mainly collected from a datasheet for a 440kW diesel generator received from NOV. The ones that could not be found there are collected from the book *"Robust control of diesel ship propulsion"* by Nicolaos Xiros [11]. Also the book *"Introduction to Modeling and Control of Internal Combustion Engine Systems"* by Lino Guzzella was used in order to get a better understanding of the model [6].

Modifications to the diesel generator model

A PID-controller is added to regulate the RPM of the modelled diesel generator by controlling the fuel rack position, and there is also added a function that limits the rate of change of the position of the fuel rack. The MATLAB script for this function can be seen in appendix A. In the script one can see that the rate of change for fuel rack position of the diesel generator can be changed in order to tune this to be as close to the real generator as possible.

6.1.1 Dynamics of the diesel electric generator model

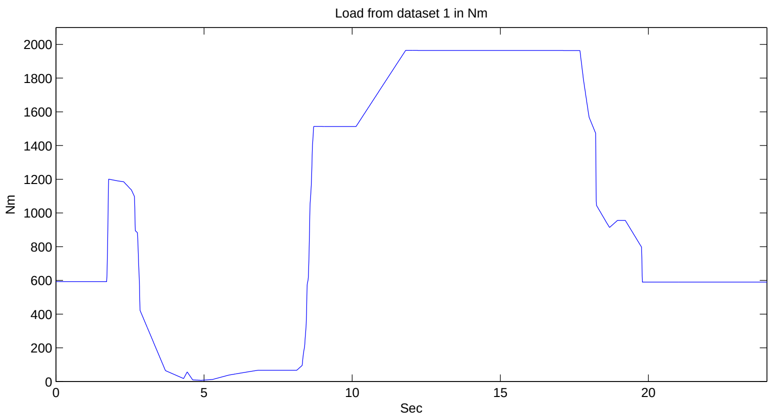
The modelled diesel generator has two parameters that can be used to tune its response. These are the parameters of the PID-controller that regulates the RPM, and the function that limits how fast the Fuel Rack Position can change.

The dynamics of the modelled diesel generator is shown by using the load sequences from datasets that were received from National Oilwell. The response of the modelled diesel generator is shown below.

Note that the RPM that is shown in the datasets are the responses of a real diesel generator with an unknown regulation structure included, so it is natural that the response of the modelled diesel generator does not match this, as it is obvious from the two different plots of the datasets that there are other things than the load that influences the RPM of the diesel generator.

Therefore these datasets could not be used to validate the model, but it was chosen to use the load sequences transformed from kW to Nm from the datasets to show the dynamics of the modelled diesel generator.

RPM when using dataset 1 as load



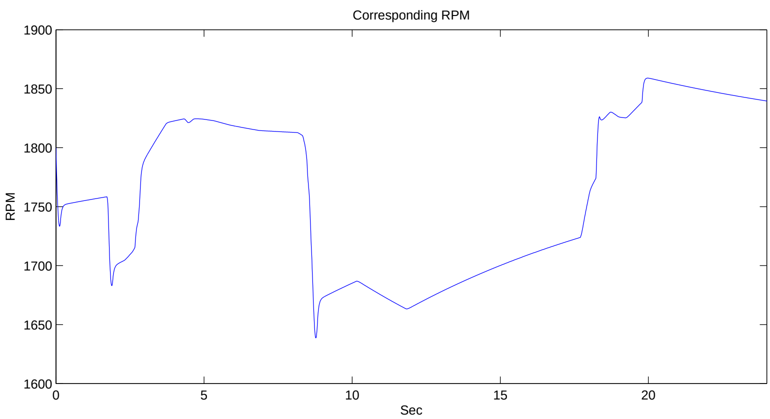


Figure 6.2: Load sequence from dataset 1 and corresponding RPM of the modelled diesel generator

RPM when using dataset 2 as load

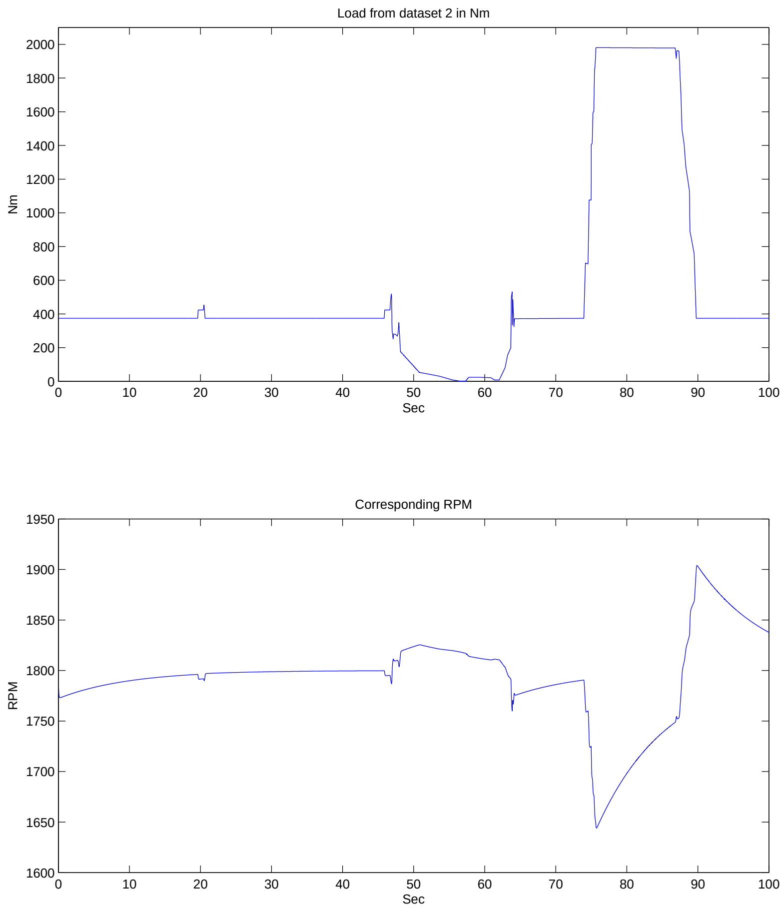


Figure 6.3: Load sequence from dataset 2 and corresponding RPM of the modelled diesel generator

One can see that the modelled diesel generator behaves as expected since there are no other factors that influences it than the load sequences from the two datasets. When the load increases or decreases, the RPM changes in the opposite direction before the regulator manages to get it back to its set-point at 1800 RPM.

Nevertheless, the modelled diesel generator has a relatively slow response. There are several factors that can be the cause of this.

It can be due to the regulator of the RPM of the diesel generator, which now is tuned to be not to aggressive in order to avoid overshoot an oscillations. Because when the feed forward functionality is included later in the project, it will take care of the big variations in the RPM because of a increase or decrease in load and the regulator of the RPM only has to manage the small remaining deviations.

Another cause can be that the model of a diesel generator that is used is actually meant for bigger generators than 400kW. As earlier mentioned, some of the parameters used in the model are found in a datasheet for a 440kW Caterpillar diesel generator while some are found in the book *"Robust control of diesel ship propulsion"* by Nicolaos Xiros [11]. The values found in the book are "typical values" for diesel generators and these values are then probably typical for bigger diesel generators since there usually are generators of bigger sizes than 400kW in marine vessels.

6.2 Model of hoisting system

When making the model of the hoisting system it was chosen to make a model of the whip hoisting system, since both systems are powered by the same electric motor it is not necessary to include both the main and the whip hoisting systems in this particular project. The only difference between the two systems are number of falls, which also influences the lifting capacity and hoisting speed.

The whip hoisting system is operated by the joystick in the operators cabin on the pedestal of the crane. The joystick is connected to the PLC which is further connected to the electric motor that powers the main hoisting system. The electric motor is connected to the winch drum through a gear and the wire is winded on the drum, and in the end of the wire the block and hook is connected.

The different parameters that are used in this model is from one of NOVs cranes, and they are all collected in a MATLAB script so that it is possible to convert the model to a different crane.

In reality there is a small non-linearity in the winch drum as the rope is winded on in several layers. This is ignored when making this model because the variations of the radius are only 0.032m pr layer. The radius used for the winch drum is the first layer, which has a radius of 0.432m. Also the load will change as the wire unwinds, because of the weight of the wire. [8]

It was given in the assignment text from NOV that the slewing system consumes 0-200kW which equals approximately 0-1000Nm.

The moment balance for the hoisting system is as follows [5]:

$$J_h\ddot{\theta}_h = \sum T$$

$$J_h\ddot{\theta}_h = T_M N - T_L - F\dot{\theta}_h$$

$$\ddot{\theta}_h = \frac{T_M N - T_L - F\dot{\theta}_h}{J_h} \tag{6.8}$$

$$\textit{Where} \;\; T_L = r * (-ma + mg)$$

T_M	-	*Motor torque*
T_L	-	*Load torque*
J_h	-	*Total moment of inertia of the hoisting system*
N	-	*Gear ratio*
F	-	*Speed dependent friction coefficient*
θ_h	-	*Winch drum angular position*

6.2.1 Dynamics of the hoisting system

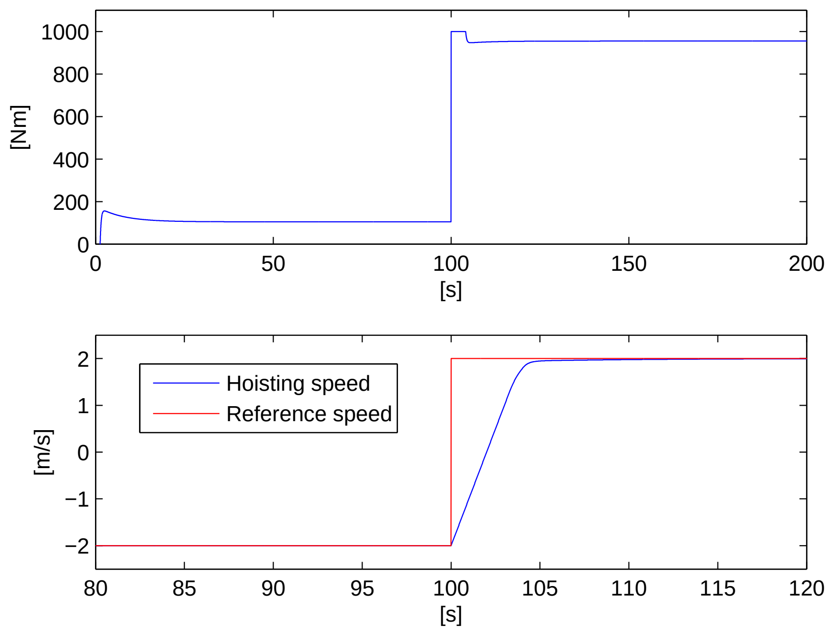


Figure 6.4: Hoisting system step response

As you can see in figure 6.4, the modelled hoisting system is tuned so that it uses approximately 4 seconds from -2m/s to 2m/s which corresponds well with the specifications for the real crane.

6.3 Model of luffing system

The luffing system is operated by the joystick in the operators cabin on the pedestal of the crane. The joystick is connected to the PLC which is further connected to the electric motor that powers the luffing system. The electric motor is connected to the winch drum through a gear and the wire is winded on the drum, and connected to the tip of the boom.

The different parameters that are used in this model is from one of NOVs cranes, and they are all collected in a MATLAB script so that it is easy to convert the model to a different crane.

It was given in the assignment text from NOV that the slewing system consumes 0-200kW which equals approximately 0-1000Nm.

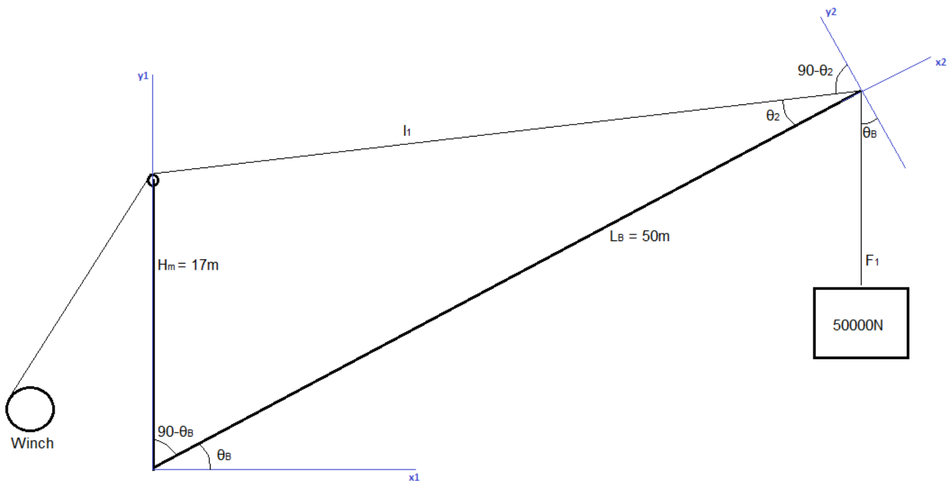


Figure 6.5: Luffing system sketch

6.3.1 Trigonometric calculations

In order to calculate the force that is applied to the luffing wire from the load hanging by the hoisting wire, some trigonometric calculations had to be made. The cosine sentence was used in order to find the length of the luffing wire from the mast of the crane to the tip of the boom, which resulted in the following expression:

$$l_1^2 = l_m^2 + l_b^2 - 2l_m l_b * \cos(90 - \theta_B)$$

$$l_1 = \sqrt{l_m^2 + l_b^2 - 2l_m l_b * \cos(90 - \theta_B)} \tag{6.9}$$

By using this expression for l_1, the angle θ_2 can be found by using the sine sentence:

$$\frac{\sin(90-\theta_B)}{l_1} = \frac{\sin(\theta_2)}{l_m}$$

$$\sin(\theta_2) = \frac{l_m * \sin(90-\theta_B)}{l_1}$$

$$\theta_2 = \sin^{-1}\left(\frac{l_m * \sin(90-\theta_B)}{l_1}\right) \tag{6.10}$$

l_1	-	*Length of wire from top of mast to the boom tip*
l_m	-	*Height of mast*
l_m	-	*Length of boom*
l_m	-	*Height of mast*
θ_B	-	*Angular position of luffing boom*
θ_2	-	*Angle between luffing boom and luffing wire at boom tip*

The force applied to the luffing wire from the load hanging by the hoisting wire can then be calculated:

$$F_L = \frac{F_{1,y_2}}{\sin(\theta_2)} = \frac{F_1 * \cos(\theta_B)}{\sin(\theta_2)} \tag{6.11}$$

F_1	-	*Load in hoisting wire*
F_L	-	*Force applied to the luffing wire from the load hanging by the hoisting wire*

These values can then be used to set up the moment balance for the winch and for the boom in the luffing system [5]:

Moment balance luffing winch

In reality there is a small non-linearity in the winch drum as the rope is winded on in several layers. This is ignored when making this model because the variations of the radius are only 0.032m pr layer. The radius used for the winch drum is the first layer, which has a radius of 0.432m.

$$J_W \ddot{\theta}_W = T_W - T_L = F_W * r - F_L * r$$

$$Where \;\; F_L = F_1 \frac{\cos(\theta_B)}{\sin(\theta_2)}$$

$$\ddot{\theta}_W = \frac{F_W * r - F_L * r}{J_W} \tag{6.12}$$

θ_W	-	*Angular position of winch drum*
θ_B	-	*Angular position of luffing boom*
θ_2	-	*Angle between luffing boom and luffing wire at boom tip*
J_W	-	*Moment of inertia winch drum*
T_W	-	*Winch torque*
T_L	-	*Load torque*
r	-	*Radius of winch drum*
F_W	-	*Force from luffing wire applied to luffing boom*
F_L	-	*Force from luffing boom and load in hoisting wire applied to luffing wire*

Moment balance boom

In order to get a moment balance for the boom, a second coordinate system is fixed at the tip of the boom where the x-axis is parallel to the boom as shown in figure 6.5.

$$J_B \ddot{\theta}_B = F_w * l_B * \cos(90 - \theta_2) - F_1 * l_B * \cos(\theta_B)$$

$$\ddot{\theta}_B = \frac{l_B(F_w * \cos(90 - \theta_2) - F_1 * \cos(\theta_B))}{J_B} \tag{6.13}$$

θ_B	-	*Angle of luffing boom*
θ_2	-	*Angle between luffing boom and luffing wire at boom tip*
l_B	-	*Length of boom*
F_w	-	*Force from luffing wire applied to luffing boom*
J_B	-	*Moment of inertia boom*
F_1	-	*Vertical force applied to boom by load in hoisting wire*

6.3.2 Dynamics of the luffing system

As expected, this model is very non-linear and it proved very hard to manage the speed of the luffing boom by controlling the luffing winch using a PID-controller with a given speed reference. No matter what, the boom moved either towards a 90° position or −90° position. As shown in these plots [7]:

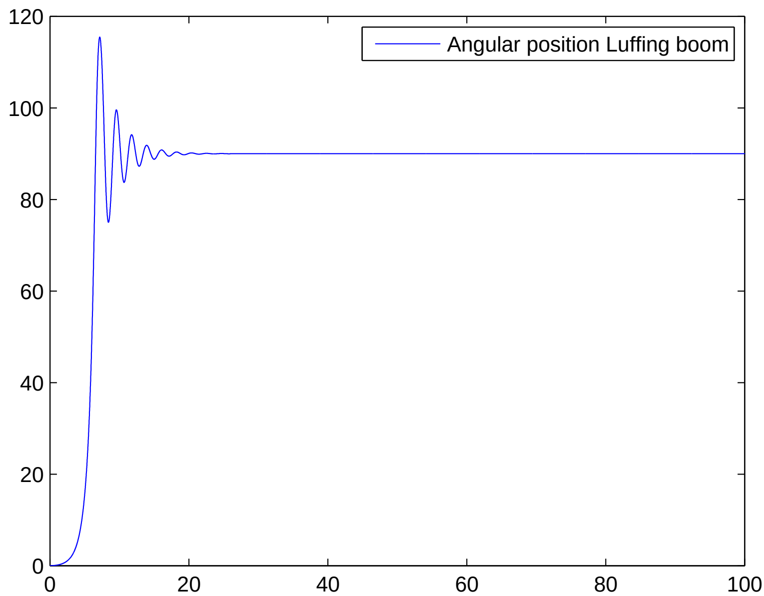


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Figure 6.6: Luffing boom position

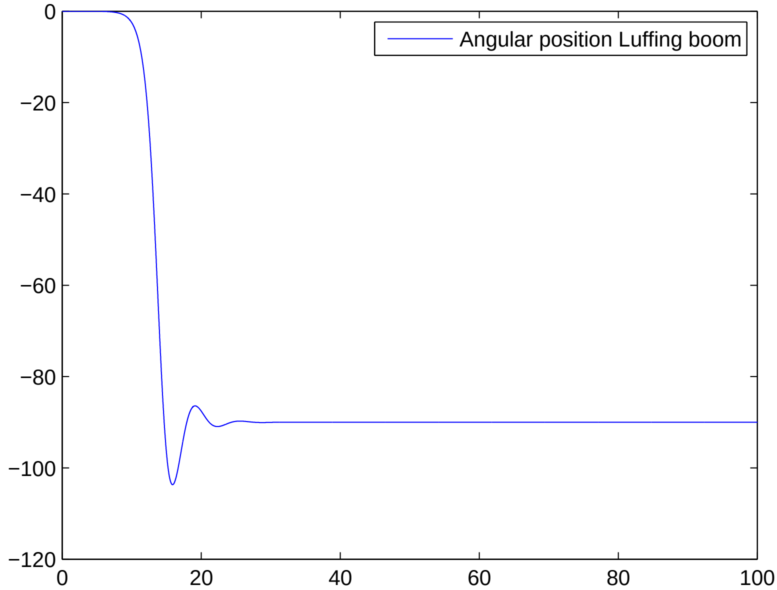


Figure 6.7: Luffing boom position

As the main objective in this project is to control the power consumption it was decided to simplify this model in order to simulate the power usage. With limited time available it was not prioritized to implement a non-linear controller in order to use this non-linear model.

6.3.3 Simplified luffing system

For further work in this project it was made a simplified model of the luffing system, this model is simplified by that it is linearised around 45° luffing angle [3]. This results in that the forces applied to the boom by the luffing winch and by the load that is hanging by the hoisting wire does not vary when the boom is hoisted or lowered and the PID-controller manages to control the luffing boom to its given speed reference.

6.3.4 Dynamics of the simplified luffing system

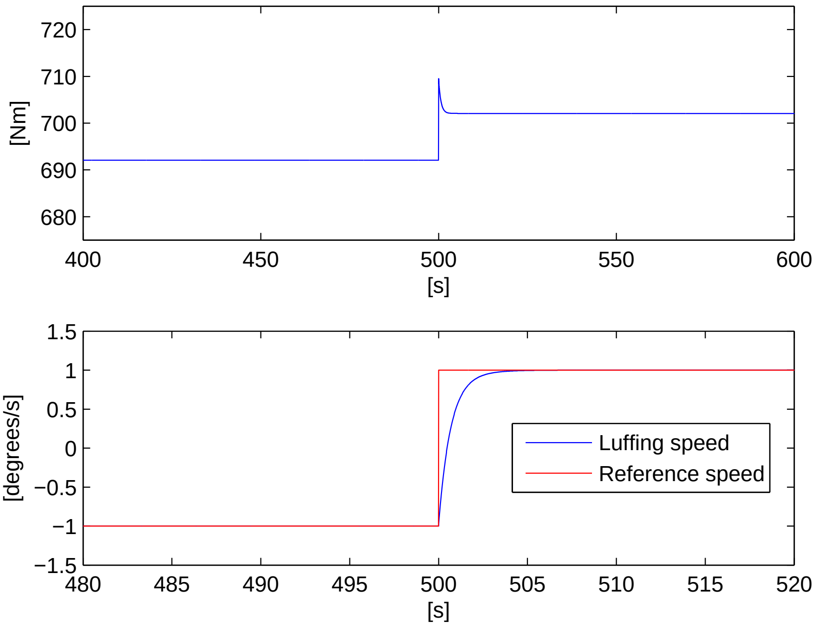


Figure 6.8: Simplified luffing system step response

As you can see in figure 6.8, the modelled simplified luffing system is tuned so that it uses approximately 4 seconds from $-1°/s$ to $1°/s$ which corresponds well with the specifications for the real crane.

6.4 Model of slewing system

The slewing system is operated by the joystick in the operators cabin on the pedestal of the crane. The joystick is connected to the PLC which is further connected to the electric motor that powers the luffing system. The electric motors are physically connected to the crane through sprockets.

The different parameters that are used in this model are from one of NOVs cranes, and they are all collected in a MATLAB script so that it is easy to convert the model to a different crane.

It was given in the assignment text from NOV that the slewing system consumes 0-100kW which equals approximately 0-500Nm.

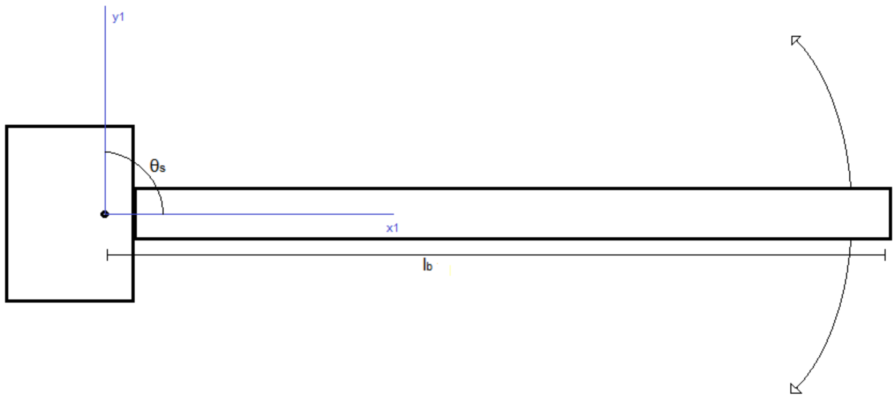


Figure 6.9: Slewing system sketch

Moments of inertia

There are three moments of inertia that effects the slewing system, these are the moment of inertia for the operators cabin and all other things that are fixed to the crane, the moment of inertia of the boom and the moment of inertia that follows from the load that is hanging in the hoisting wire. The moment of the inertia for the boom and for the load changes as the boom is raised or lowered, and therefore has to be calculated continuously. The moment of inertia for the rest of the crane is found in the data specifications for the crane.

The moment of inertia for the boom is calculated as follows [5]:

$$J = \frac{1}{3} m L^2$$

$$J_b = \frac{1}{3} m_b (l_b \cos(\theta_b))^2 \tag{6.14}$$

J_b	-	*Moment of inertia of the boom*
m_b	-	*Weight of boom*
l_b	-	*Length of boom*
θ_b	-	*Angular position of boom*

The moment of inertia that effects the slewing machinery of the load in the crane is calculated as follows [5]:

$$J = m L^2$$

$$J_l = m_l (l_b \cos(\theta_b))^2 \tag{6.15}$$

J_l	-	*Moment of inertia that affects the slewing machinery from load*
m_l	-	*Weight of load*
l_b	-	*Length of boom*
θ_b	-	*Angular position of boom*

The moment balance for the slewing system is as follows [5]:

$$J_s \ddot{\theta}_S = T_M - F\dot{\theta}_s$$

$$\textit{Where} \;\; J_s = J_b + J_l + J_f$$

$$\ddot{\theta}_s = \frac{T_M - F\dot{\theta}_s}{J_s} \tag{6.16}$$

J_l	-	*Moment of inertia that affects the slewing machinery from load*
J_b	-	*Moment of inertia of the boom*
J_F	-	*Moment of inertia for the fixed parts of the crane*
J_s	-	*Total moment of inertia that affects the slewing system*
T_M	-	*Motor torque*
F_s	-	*Friction coefficient slewing system*
θ_b	-	*Angular position of boom*

6.4.1 Dynamics of the slewing system

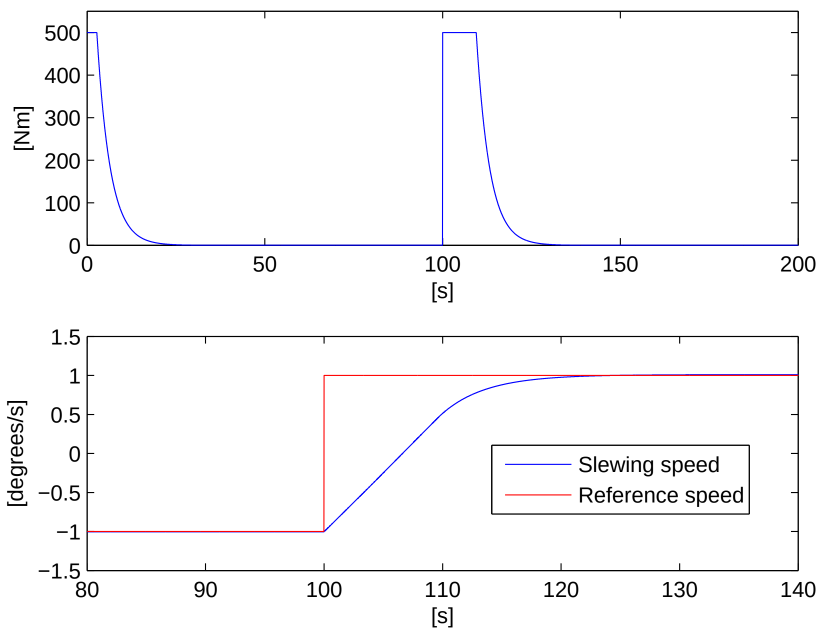


Figure 6.10: Slewing system step response

As you can see in figure 6.10, the modelled slewing system is tuned so that it uses approximately 10 seconds from $-1°/s$ to $1°/s$ which is a little bit slower than the actual crane, but close enough.

6.5 Model of auxiliary system

It was given in the assignment text from NOV that the auxiliary system consumes 0-50kW which equals approximately 0-250Nm. The auxiliary system is simply simulated by a function that returns a random value between 0-250Nm for each 100 second, as shown in figure 6.11.

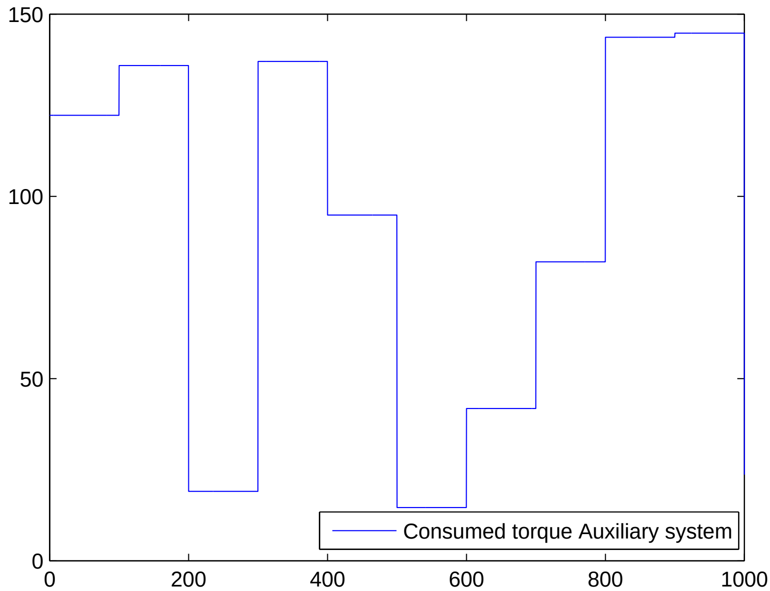


Figure 6.11: Consumed torque Auxiliary system

This is not a completely realistic or accurate simulation of the Auxiliary system, but it provides the load variations that is wanted for this project.

6.6 Remarks on the crane model

The crane model that is made in this project is only an approximation of the actual crane and is made for the purpose of testing and developing the PMS. Because of this, and the limitation of time to work on this project, there are certain aspects of the crane that are not included in the model.

For example the elasticity of the wires in the luffing an hoisting systems are not included, the movement of the rig or the vessel that the crane is mounted on is not included, and the different frictions for the different parts of the crane are represented by one friction coefficient in the moment balances for the different systems on the crane. These are things that can be implemented in order to make the crane model even more realistic and accurate.

Also, a non-linear speed controller could be implemented in order to use the non-linear model of the luffing system, this task was not prioritised during this project.

Chapter 7

Controlling the power consumption

This chapter addresses the difficulties regarding the constraints on the rate of change of the generators produced power and the constraints on the generators maximum produced power.

As earlier mentioned, if the crane drives all system at full speed with enough load attached, the generator is not able to generate enough electrical power. Therefore the requested power from the speed controllers have to be limited to overloading the generator. Also, this should have as little influence on the operating of the crane as possible.

Both when handling the rate of change and the power available, the hoisting system has a 100% priority, while the luffing and the slewing system shares the remaining power with respect to how much power they consumes at maximum, and how much power the speed controllers for the two different system requests.

The solutions to these problems are tested on simulations on the implemented model of a diesel generator.

7.1 Feed forward in order to reduce frequency variations

This section explores the advantages of feeding the requested power from the speed controllers for the three different systems forward to the regulator that controls the RPM of the generator.

This will presumably help reduce the variations of the frequency in the power delivered by the generator. Because the regulator of the RPM for the generator will then instantly increase the fuel rack position when the speed controllers for the different systems of the crane gives signal to increase the speed of the crane, instead of waiting until it measures the RPMs deviation from set point because of the increased load.

In order to explore the advantages of this functionality there are set up three simulation Scenarios, where the first one is based on simplified model of the power consumption from chapter 6, and the two next Scenarios are based on load sequences from the datasets from an actual crane delivered by NOV.

7.1.1 Simulation scenario 1

For the first simulation scenario, the simplified crane model is used in order to simulate the load. With the following sequence of reference speeds for the different systems speed controllers:

Speed references

- Hoisting System: Initial speed reference at -2m/s, set to 2m/s at 150 seconds and is set to 0m/s at 300 seconds.
- Luffing system: Initial speed reference at 0°/s and set to 1°/s at 450 seconds.
- Luffing system: Initial speed reference at 0°/s and set to 1°/s at 650 seconds.
- Auxiliary system: Random sequence of load torques between 0 and 250 Nm.

This results in the following load sequence presented along with the RPM of the generator with, and without the feed forward included:

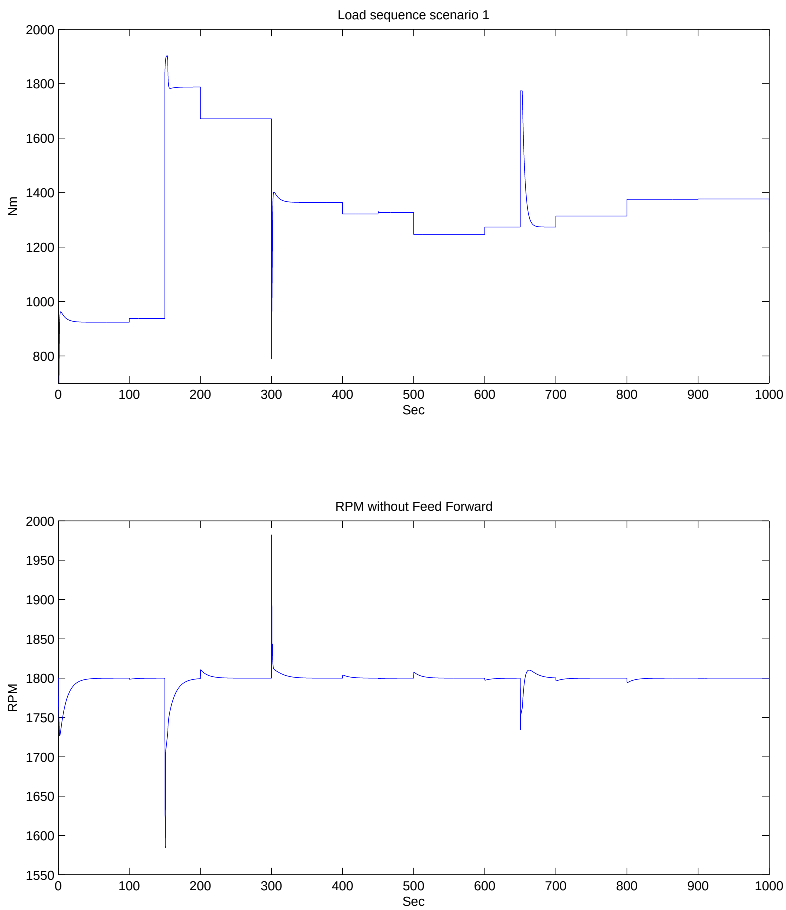
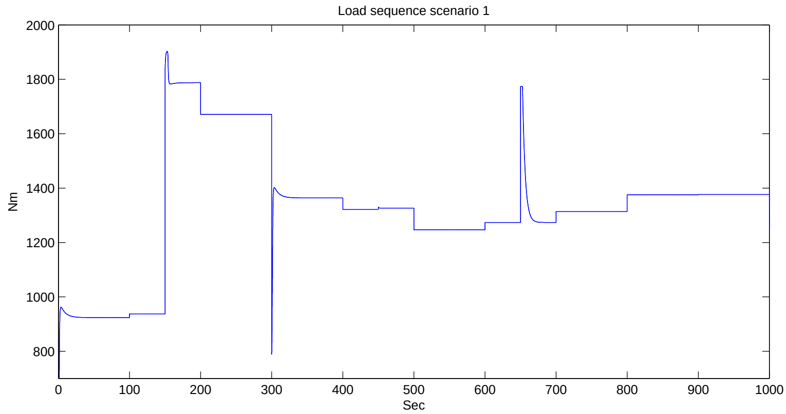


Figure 7.1: Load sequence from simulation scenario 1 and the corresponding RPM for the diesel generator without feed forward



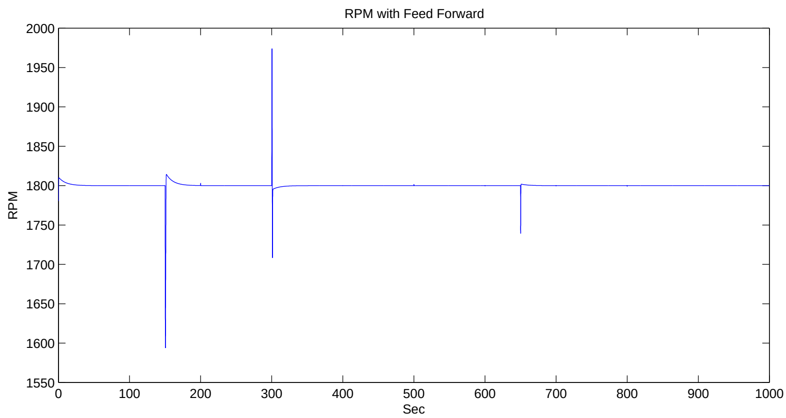


Figure 7.2: Load sequence from simulation scenario 1 and the corresponding RPM for the diesel generator with feed forward

7.1.2 Simulation scenario 2

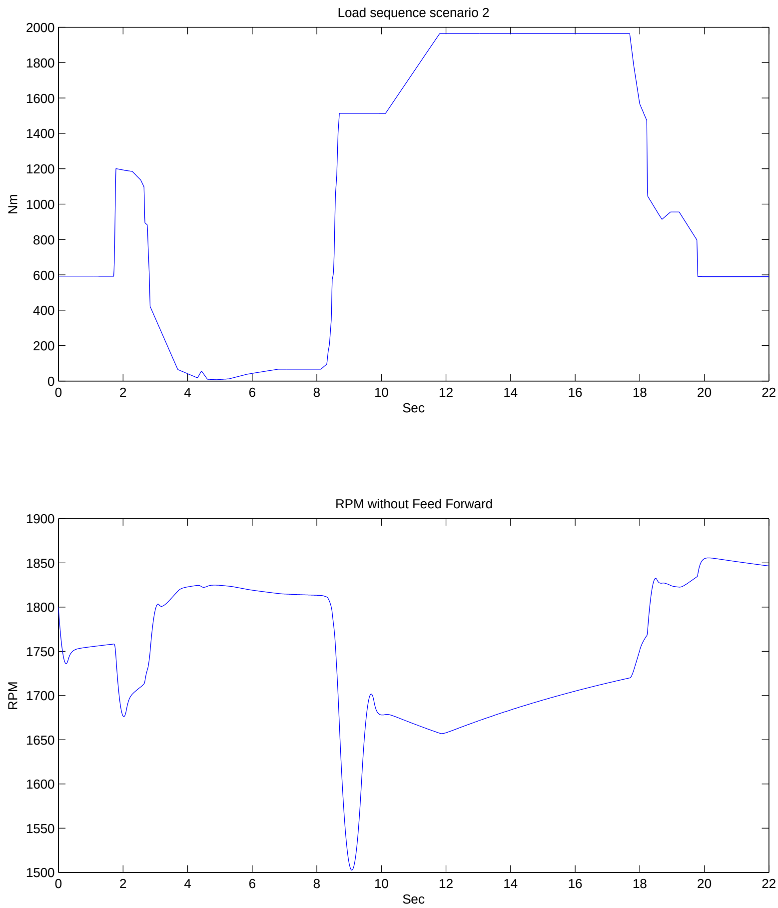


Figure 7.3: Load sequence from dataset 1 and the corresponding RPM for the diesel generator without feed forward

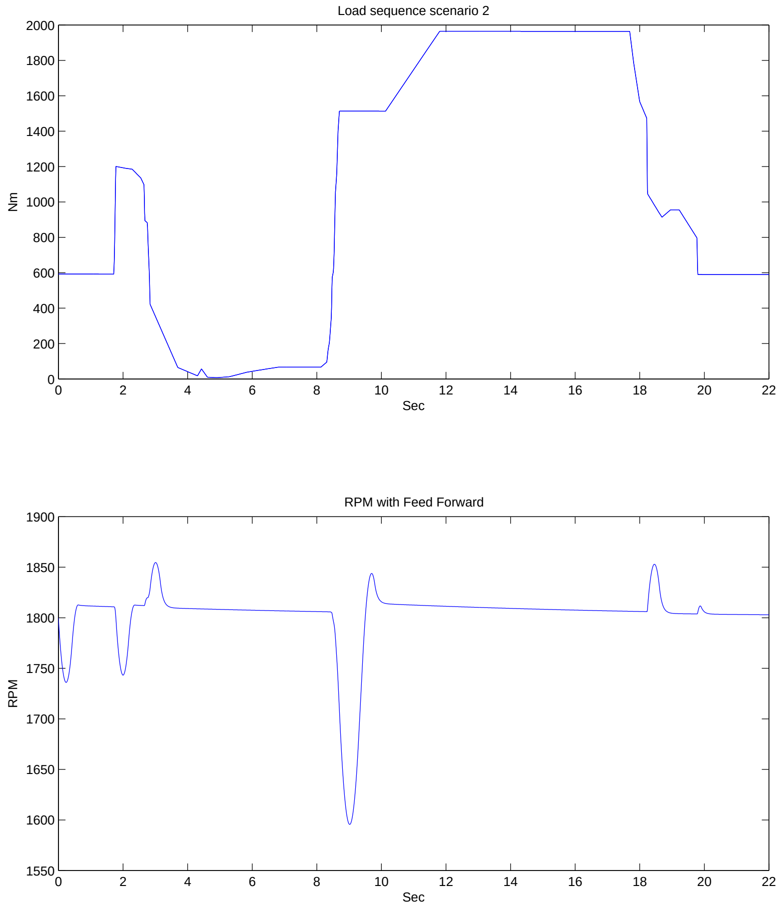


Figure 7.4: Load sequence from dataset 1 and the corresponding RPM for the diesel generator with feed forward

7.1.3 Simulation scenario 3

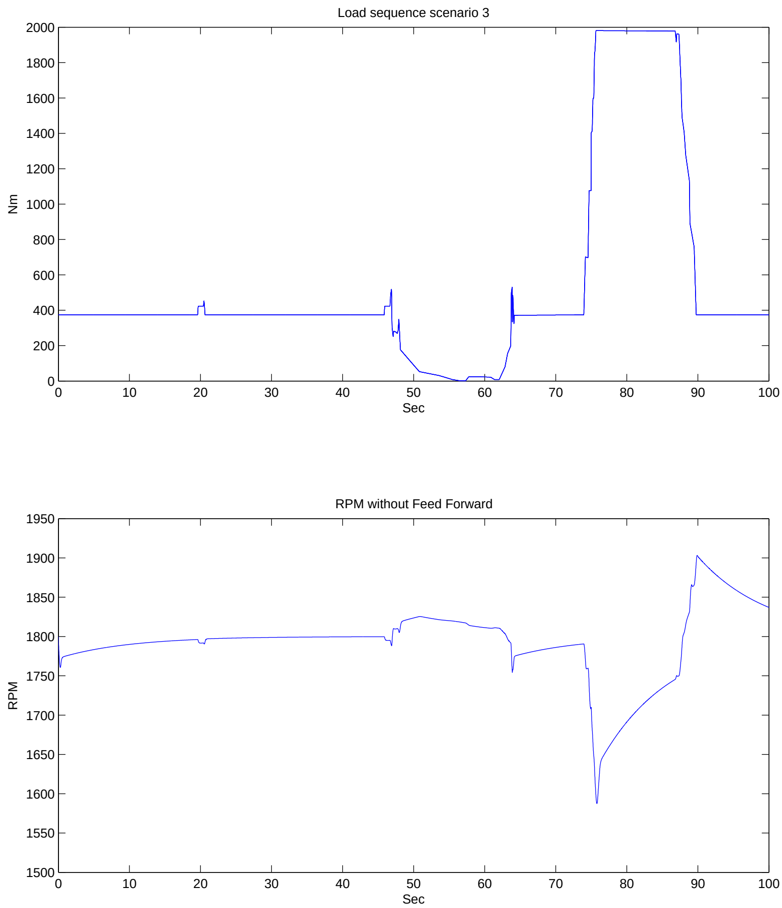


Figure 7.5: Load sequence from dataset 2 and the corresponding RPM for the diesel generator without feed forward

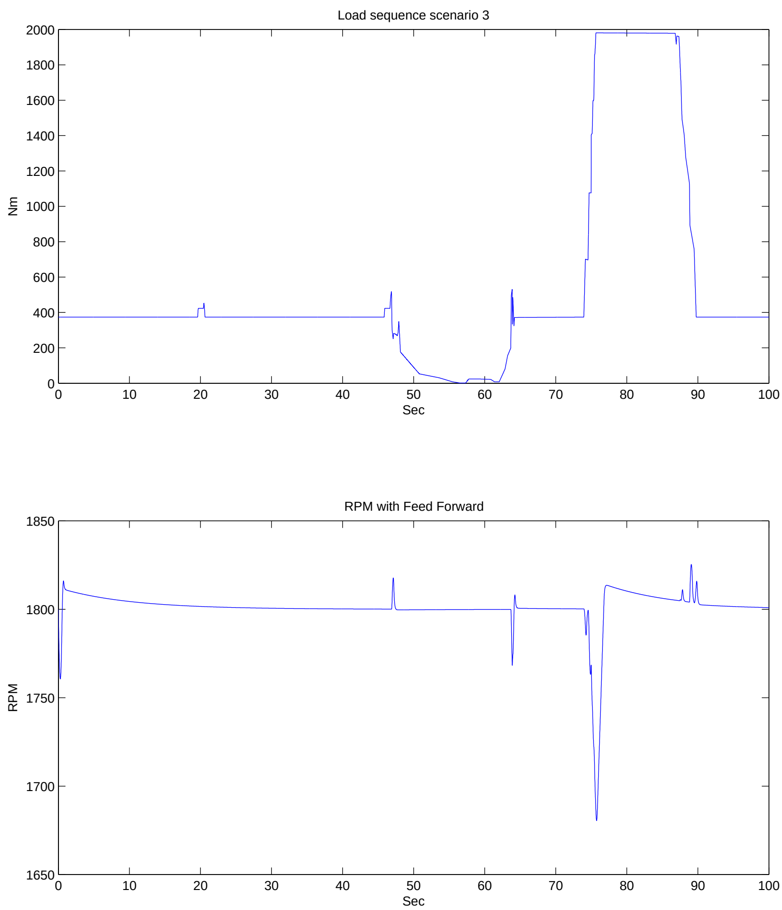


Figure 7.6: Load sequence from dataset 2 and the corresponding RPM for the diesel generator with feed forward

7.1.4 Advantages of including feed forward

As you can see in the three different scenarios that are presented in this section, the feed forward reduces the variations in the RPM of the diesel generator. This is because when the speed controllers for the different systems on the crane increases the power for one or more of the electric motors, this increase is also fed to the controller of the RPM of the Diesel Engine, so the fuel rack position is increased instantly. Without the feed forward, the increase in the fuel rack position does not happen until the controller on the diesel generator measures a deviation in the RPM from its set-point, which will result in that the RPM controller always will be "a small step behind" and struggle to keep the RPM at its set-point as long as there are variations in the load.

As you can see, the feed forward has a better effect in scenario 2 and 3, than in the first scenario when looking at the large peaks. In the first scenario, the peaks are almost not reduced at all, while in the second scenario the largest drop in RPM is reduced from approximately 1500 to 1600 and in the third scenario the largest drop in RPM is reduced from approximately 1575 to 1675.

The reason for this difference is most likely that the load from the dataset increases slightly gradual, as you can see in the plots. While the load sequence that is generated from the crane model has instant steps in the load. The load from the datasets increases gradually either because of a limitation of the rate of change in the unknown regulation structure or simply because of that the joystick is moved gradually towards full speed when making the plots.

It is also worth noting that the response of the modelled diesel generator with feed forward included is very much like the response from the real diesel generator, especially in scenario 3(load sequence from dataset 2). This suggests that there might be a feed forward included in the unknown regulations structure for the diesel generator in the datasets.

As mentioned, it is particularly the small variations that are removed when including the feed forward, while the large peaks still remains. This is because even though the fuel rack position reacts instantly it has to be increased gradually. This problem has to be handled by limiting the rate of change of the requested power from the speed controllers for the different systems on the crane, which will be examined in section 7.2.2.

7.2 Limiting the load in order to prevent blackout

This section addresses the difficulties regarding the constraints on the rate of change of the generator's produced power, and the constraints on the generator's maximum produced power. If the crane drives all system at full speed with enough load attached, the generator is not able to generate enough electrical power.

In this example the different systems of the crane and the diesel generator has the following specifications:

Specifications

- The hoisting systems electrical motor produces a maximum 1000Nm at 200kW.
- The luffing systems electrical motor produces a maximum of 1000Nm at 200kW.
- The slewing system electrical motor produces a maximum of 500Nm at 100kW.
- The generator produces a maximum of 2100Nm.
- The generators rate of change is maximum 500Nm pr. second.

This problem is solved by creating a MATLAB function that limits the total amount, and the rate of change of power that the speed controllers for the different systems requests from its electrical motors.

7.2.1 Limiting the total load

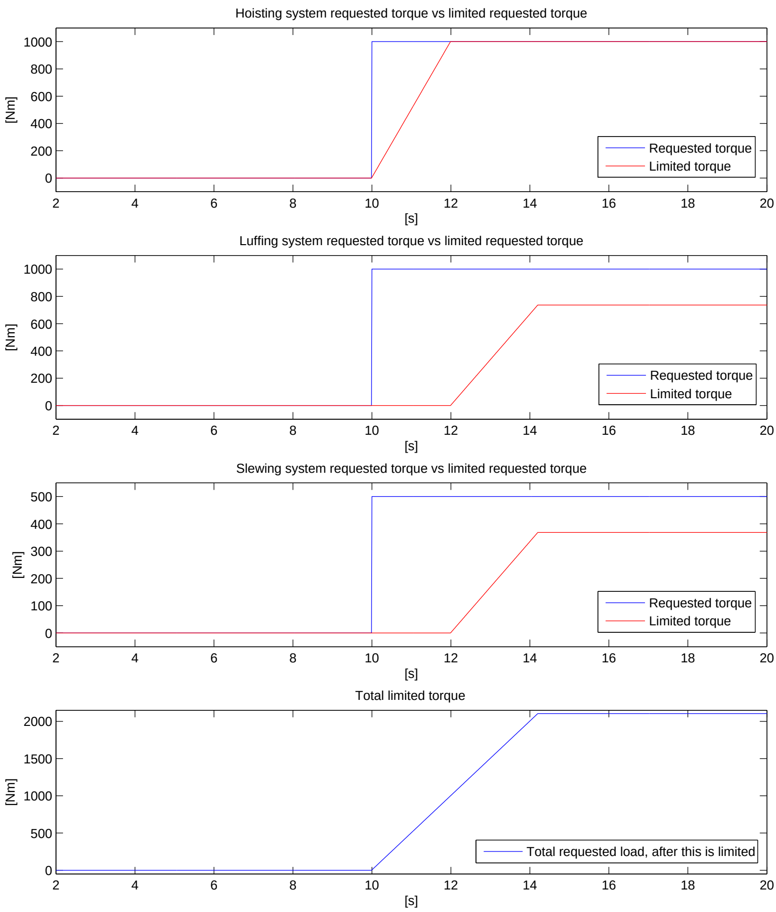


Figure 7.7: Plot 1-3: 100 % Requested load vs limited load for the three different systems. Plot 4: Total load after limitation

As mentioned earlier, the total power of all systems of the crane combined is bigger than the maximum power that the diesel generator is able to produce. Therefore this has to be handled in the PMS, to avoid overloading the diesel generator.

Figure 7.7 shows a scenario where the speed controllers for each system requests full power from its electrical motors at the same time. As you can see in the plots, the hoisting system is the only one to reach its requested power. This is because it has 100% priority. The luffing and the slewing system then has to share the remaining available power. This sharing is based on the size of the motors (maximum power) and how many percent of the maximum power for each of the system their respective speed controllers requests.

The following Figure 7.8 shows how the MATLAB function shares the available power when all functions requests full power, and the hoisting system goes back to requesting no power after a given time.

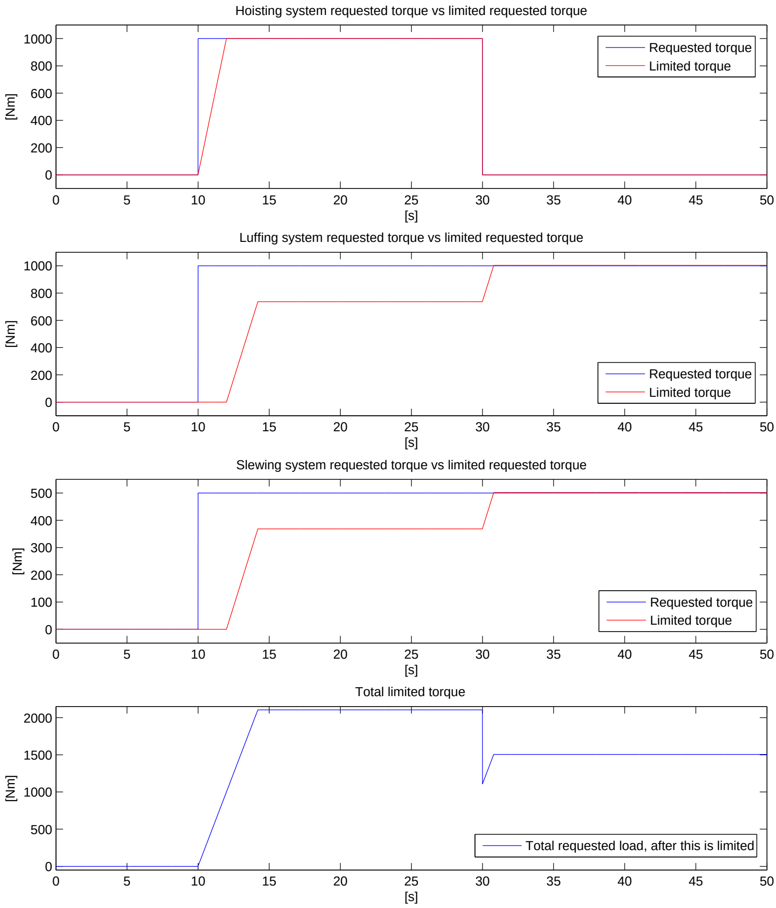


Figure 7.8: Plot 1-3: Requested load vs limited load for the three different systems. Plot 4: Total load after limitation

7.2.2 Limiting the rate of change in load

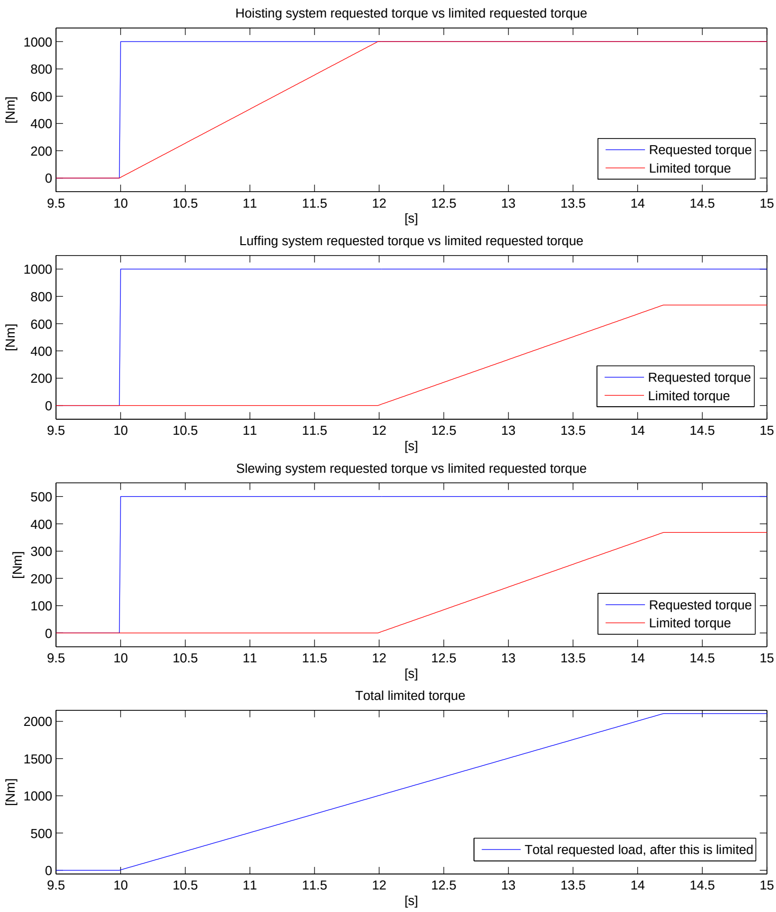


Figure 7.9: Plot 1-3: Requested load vs limited load for the three different systems. Plot 4: Total load after limitation

Figure 7.9 shows how the rate of change of the requested loads are limited. In this case all systems requests full power and one can see that at first, the hoisting system is the only system that increases its requested load. This is because the hoisting system requests a rate of change that is bigger than the maximum rate of change of the power produced by the diesel generator, and since the hoisting system has a 100% priority, the other system has to wait for the hoisting system to reach its requested power.

It is also worth noting that as you can see in the fourth subplot in figure 7.9, the total change in the limited load remains constant. This value, the maximum allowed rate of change is set in the MATLAB function, and has to be the same or smaller than the maximum rate of change of the produced power by the diesel generator.

The two remaining systems, the luffing and the slewing system shares the ”available” rate of change after the hoisting system has gotten its share. How much of the available rate of change they each get, depends on how much power they consumes at maximum, and how many percent of the maximum power that is requested for the two different systems. This is calculated by the following formulas:

$$C = \frac{Y3_{requested}}{Y2_{requested}}$$

$$Y2_{limited} = Y2_{previous} + \frac{Y_{tot,available}}{1+C} \tag{7.1}$$

$$Y3_{limited} = Y3_{previous} + \frac{Y_{tot,available}}{1+C} * C \tag{7.2}$$

$Y3_{requested}$	-	*Requested torque Slewing system*
$Y2_{requested}$	-	*Requested torque Luffing system*
$Y3_{previous}$	-	*Actual Y3 in previous time step*
$Y2_{previous}$	-	*Actual Y2 in previous time step*
$Y_{tot,available}$	-	*The available rate of change pr. time step*
$Y3_{limited}$	-	*The new calculated Y3 after rate of change limitation*
$Y2_{limited}$	-	*The new calculated Y2 after rate of change limitation*

It is illustrated in the following figure, where the hoisting system requests no power, the luffing requests 1000Nm(100%) and the slewing requests 200Nm(40%). Where you can se that the two reaches its desired value at the same time, even though they requests a different percentage of their maximum power.

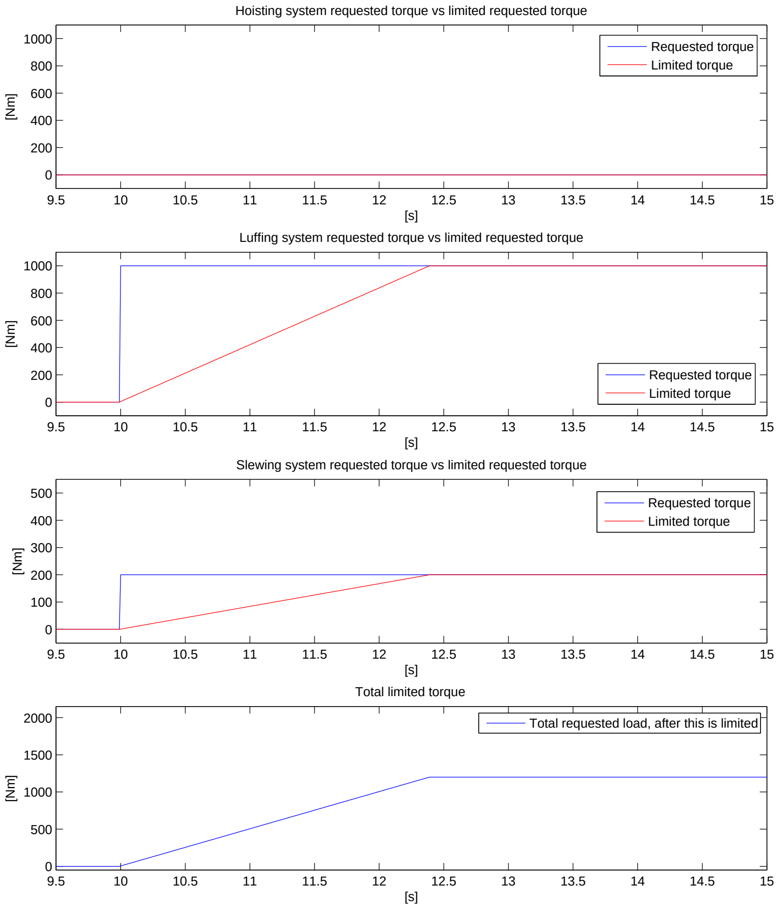


Figure 7.10: Plot 1-3: Requested load vs limited load for all systems. Plot 4: Total load after limitation

7.3 Scenario 1 with feed forward, load limitation and rate of change limitation

In this section, the result of simulation scenario 1 is shown, both with and without the load and rate of change limitation included. The reason for choosing scenario 1 for this simulation is that it is the only load sequence where the loads for the three different systems on the crane are available separately. The two datasets received from NOV only contains the total load of all three systems combined.

The following plots shows the biggest step in the load sequence from simulation scenario 1, with- and without the total load and rate of change limitation included.

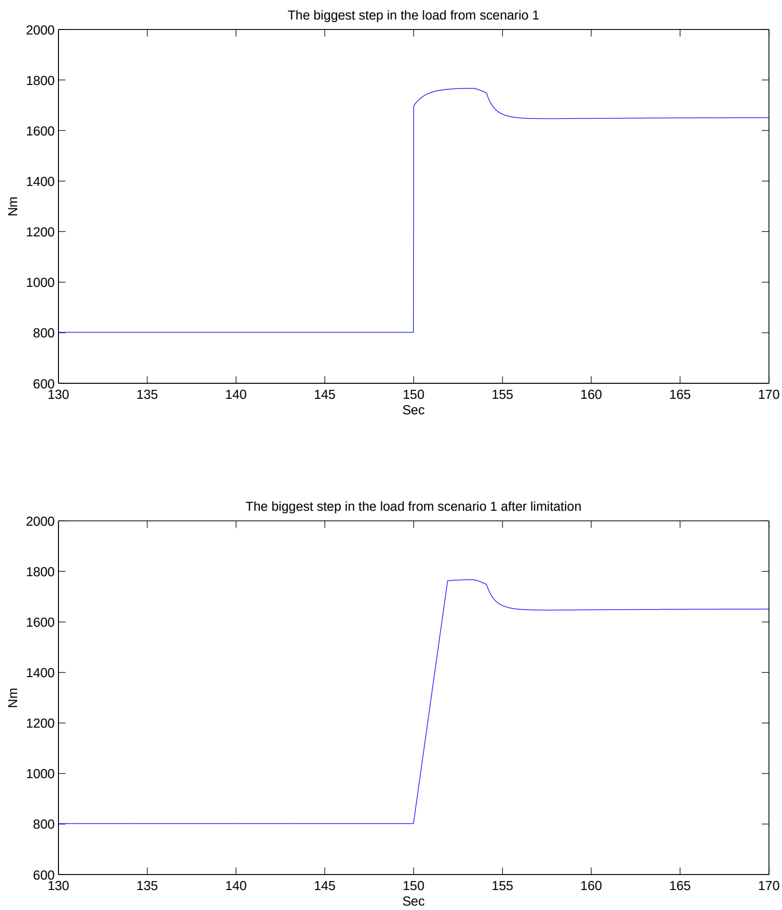


Figure 7.11: Plot 1: Shows a section of the load sequence from simulation scenario 1 where the biggest step is, Plot 2: Shows the same step after limitation

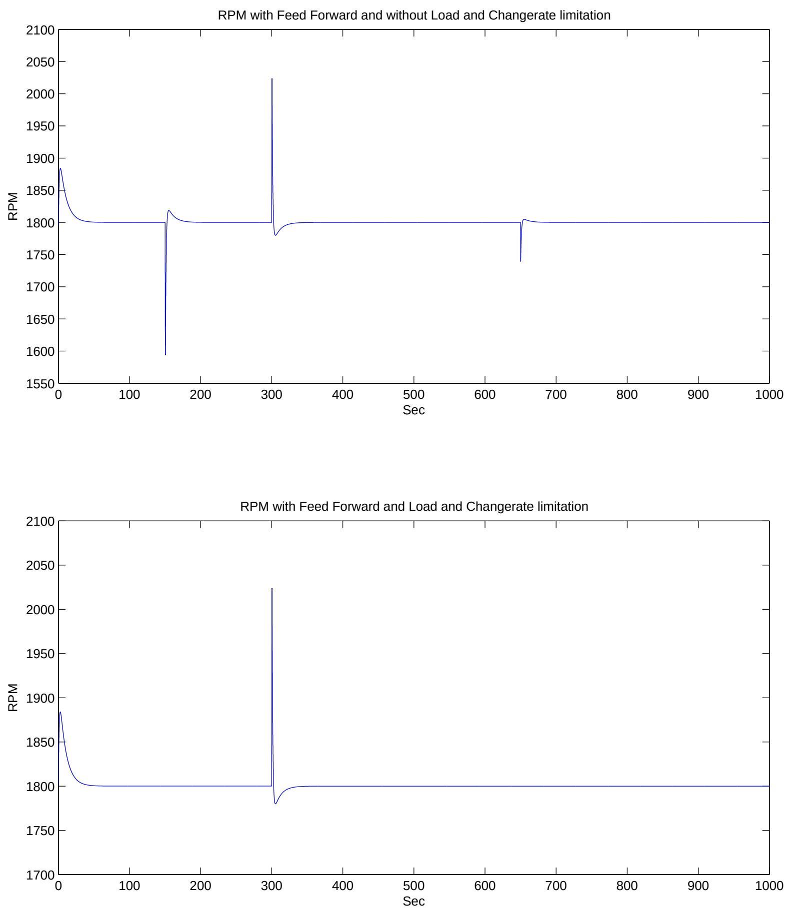


Figure 7.12: Plot 1: RPM without Load and Rate of change limitation, Plot 2: RPM with Load and rate of change limitation

As you can see in figure 7.12, the limited Load and rate of change of the load results in that the RPM is steady at its set-point for every increasing step in the load. Both peaks where the RPM drops significantly are removed. This is because the rate at which the load increases is smaller than the rate of which the diesel generator manages to increase its power produced.

7.4 Remarks on the results

Feed forward requested load from speed controllers or reference signals from Joystick

In this solution the requested load from the speed controllers is the signal that is fed forward to the regulator of the RPM of the diesel generator. One could argue that feeding the reference signal from the joysticks forward to the diesel generator would make it react even faster.

Feeding the joystick reference signals forward resulted in that the fuel rack position increased to soon and this resulted in positive peaks in the RPM above the set-point.

Therefore it was decided to feed forward the requested load from the speed controllers for the three systems on the crane instead.

No rate of change limitation for decreasing steps in load

There is no limiting of the rate of change of the decrease in load. This is not included in the solution because of safety reasons.

If a dangerous situation occurs and the operator of the crane has to stop the movement instantly in order to avoid damage to people or equipment, the crane can not keep on moving for a second or two in order to ramp the power usage down to avoid frequency variations.

Heave compensation and Constant tension functionality

The feed forward and the limitation of the rate of change and the total load will not effect the functionality of the heave compensation or the constant tension in a huge manner. Both these functionalities uses the hoisting system of the crane, and since this system always has 100% power available, the only limitation will be if the rig or vessel that the crane is mounted on or the load is lifted from, is moving to fast vertically.

This vertical movement must then not exceed the acceleration of the hoisting winch which then again can not increase its power usage faster than the diesel generator is able to increase its produced power.

Chapter 8

Conclusion

Model of the power consumption of the crane

The crane model that is made in this project is only an approximation of the actual crane and is made for the purpose of testing and developing the PMS. Even though improvements can be made to the crane model, it is good enough for what it is meant for. Which is to generate load sequences for the different systems on the crane in order to use for testing the PMS on the modelled diesel generator.

Further work on the model of the crane must be to, as earlier mentioned, include the movement of the rig, the elasticity of the wires and include the different frictions for the different parts of the crane instead of collecting all these in a friction coefficient for each system of the crane. A non-linear speed controller can also be implemented in order to use the non-linear model of the luffing system instead of the simplified one.

Model of the diesel generator

The model of the diesel generator that is used in this project is a fairly simple one. There are no disturbances or frictions included in the model, so that the only external influence of the RPM is the load. Nevertheless, the response of the diesel generator to the different load sequences seems reasonable. Therefore it is safe to say that measures that are made in order to reduce the frequency variations and to prevent blackout on this model also will have the same effect on a real diesel generator to some extent.

Further work on the diesel generator must be to either develop or find a model that is more suited for a generator this small. Alternatively, datasets that shows the load and corresponding RPM of the real diesel generator with no unknown regulation structures included can be used to adjust the model or to make a new one. If there are enough different load sequences and data available, System Identification theory can be used to make a new model. Also, the model from this project can be used as a base along with datasets to be tuned by for example decreasing the moment of the inertia and introducing a suitable friction coefficient in order to get a model with a faster response.

Feed forward, Limitation of total load and Limitation of the rate of change in the load

The measures that were made in this project reduces the variations in the RPM significantly, and thereby also reduces the frequency variations.

These measures are feeding the requested load from the different speed controllers for the different systems on the crane forward to the PID-controller that regulates the RPM of the diesel generator and limiting the rate of change of the requested load from the speed controllers.

One could argue that the limitation of the rate of change alone, would keep the RPM of the diesel generator within tolerated areas, but the feed forward helps reduce these variations and thereby the limitation does not have to be as severe as it would have been without the feed forward. Thereby the operation of the crane is lesser influenced by the limitation when the feed forward is included.

The total load is also limited so that this does not exceed the total power that the diesel generator is able to produce, in order to avoid overload.

The way that the limiting of the total load and the rate of change in the load is shared between the different systems also meets the requirements, which is 100% power priority to the hoisting system. The way that the remaining power is shared between the luffing and the slewing system of the crane, makes the operation as smooth as possible for the driver of the crane.

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Appendices

Appendix A

MATLAB script

Limiting the rate of change of the fuel rack position in the diesel generator

```
% This function limits how fast the fule rack position
    can change. The fuel
% rack position is scaled to a range 0-2100.

function y = SomeFuncSimplified(x)
u=x(1);
t=x(2);

% Loads previous values from base in workspace. If no
    values assigned,
% values are set in "catch".
try
    uprev = evalin('base','uStore');
    tprev = evalin('base','tStore');
catch me
    uprev = 0.0476*2100;
    tprev = 0;
    assignin('base','uStore',uprev);
    assignin('base','tStore',tprev);
end
```

```
fcr     = 100; % Defines how many % of maximum value the
    fuel rack position
             % can maximum change per second.

deltat = t - tprev;
deltau = 100*21*deltat; % Total allowed change in fuelr
    rack position
                          % pr timestep


% The following if-sentence makes sure that the change in
     the fuel rack
% position does not exceed the maximum allowed change. If
     the requested
% change is to big, it is set to maximum allowed change.
if u - uprev > deltau
    u=uprev+deltau;
elseif u - uprev < -deltau
    u=uprev-deltau;
end

% This if-sentence defines the lower bound for the fuel
    rack position.
if u<0
    u=0;
end


% This if-sentence defines the upper bound for the fuel
    rack position.
if u>2100
    u=2100;
end

assignin('base','uStore',u);
assignin('base','tStore',t);

y = u;
```

Appendix B

MATLAB script

Limiting the load and the rate of change in the requested load

```
function y = Function(x)
y1_req=x(1); %First input is the requested power for the
    hoisting system
y2_req=x(2); %Second input is the requested power for the
     luffing system
y3_req=x(3); %First input is the requested power for the
    hoisting system
t=x(4);

G_max  =  2100; %Maximum produced power by generator
y1max  =  1000; %Maximum power electric motor hoisting
    system
y2max  =  1000; %Maximum power electric motor luffing
    system
y3max  =   500; %Maximum power electric motor slewing
    system

% This part controls the requested power, so that this
    does not exceed the
% maximum power for each system (Hoisting, Luffing and
    Slewing) and
% that the requested power in total does not exceed the
```

```
    power the
% generator is able to produce.

y1_req=min(y1_req,y1max); %Saturates requested power
    hoisting system
y2_req=min(y2_req,y2max); %Saturates requested power
    luffing system
y3_req=min(y3_req,y3max); %Saturates requested power
    slewing system
y_reqTot = y1_req + y2_req + y3_req; %Total requested
    power

% This if-sentence makes sure that the total requested
    power does not
% exceed the power that the generator is able to produce.
% If the requested power is to big, the hoisting system (
    y1) gets
% it share since it has 100% priority, while the luffing
    system
% and the slewing system divides the rest of the
    available power
% in relation to how much they are requesting.

if y_reqTot > G_max
     G_avail = G_max - y1_req;
     C1 = (y3_req/y2_req);
     y2_req = min(G_avail/(1+C1),y2max);
     y3_req = min((G_avail/(1+C1))*C1,y3max);
else
end

y1_req=min(y1_req,y1max); %Saturates requested power
    hoisting system
y2_req=min(y2_req,y2max); %Saturates requested power
    luffing system
y3_req=min(y3_req,y3max); %Saturates requested power
    slewing system

% Loads previous values from base in workspace. If no
```

```
    values assigned,
% values are set to 0.
try
    y1prev = evalin('base','y1store');
    y2prev = evalin('base','y2store');
    y3prev = evalin('base','y3store');
    tprev = evalin('base','t2store');
catch me
    y1prev = 0;
    y2prev = 0;
    y3prev = 0;
    tprev = 0;
    assignin('base','y1store',y1prev);
    assignin('base','y2store',y2prev);
    assignin('base','y3store',y3prev);
    assignin('base','t2store',tprev);
end



%This part controls the change in the requested power
    from the controller
%to the electrical motors. This code makes sure that the
    power of the
%electrical motors is ramped up so that the diesel
    generator manages to
%follow it, and thereby avoiding a drop in the frequency.

deltaG = 500; %Maximum change pr.second in produced power
     by generator
deltat = t - tprev;
deltaTot = deltaG*deltat; %Total allowed change in load
    pr timestep

% This if-sentence makes sure that the total changerate
    of power usage
% for all the systems of the crane does not exceed the
    rate that the
% generator is able to increase its power produced. This
```

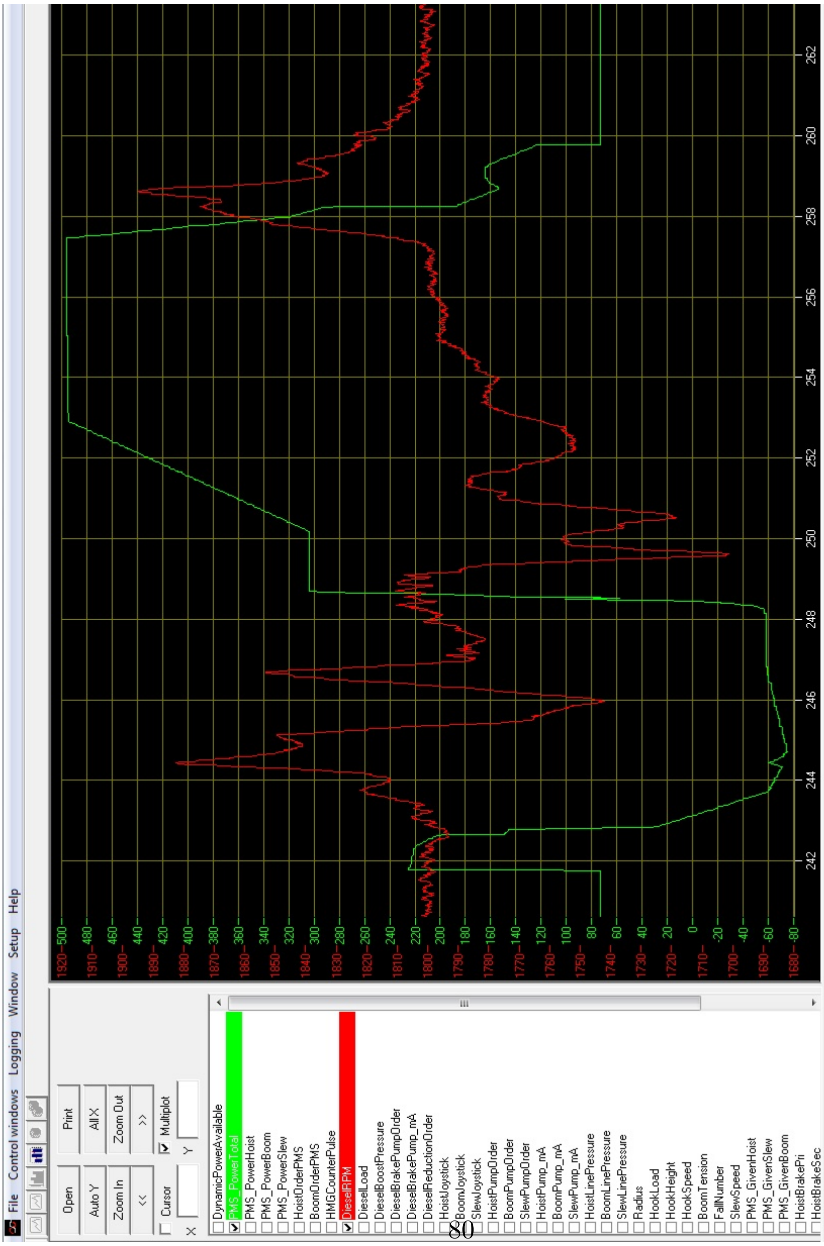
```
    if-sentence is
% also written so that the hoisting system has 100%
    priority.

if (y1_req - y1prev) >= deltaTot
     y1 = y1prev + deltaTot;
     y2 = min(y2prev,y2_req);
     y3 = min(y3prev,y3_req);

% The following if-sentence handles when only the slewing
     system requests
% power and not the luffing system.
elseif ((y2_req - y2prev) == 0) && ((y3_req - y3prev) >
    0)
     y1 = y1_req;
     deltaTot2 = deltaTot - (y1_req - y1prev);
     y2 = y2prev;

          if (y3_req - y3prev) >= deltaTot2
              y3 = y3prev + deltaTot2;
          else
              y3 = y3_req;
          end


% The following if-sentence handles when only the luffing
     system requests
% power and not the slewing system.
elseif ((y3_req - y3prev) == 0 && (y2_req - y2prev) > 0)
     y1 = y1_req;
     deltaTot2 = deltaTot - (y1_req - y1prev);
     y3 = y3prev;

          if (y2_req - y2prev) >= deltaTot2
              y2 = y2prev + deltaTot2;
          else
              y2 = y2_req;
          end
```

```
% The following if-sentence handles when both the luffing
    and the slewing
% system requests power
elseif (((y2_req - y2prev) > 0) && (y3_req - y3prev)) > 0
    y1 = y1_req;
    deltaTot2 = deltaTot - max(y1_req - y1prev,0);

    C2 = (y3_req/y2_req);
    y2 = y2prev + deltaTot2/(1+C2);
    y3 = y3prev + (deltaTot2/(1+C2))*C2;

else
    y1 = y1_req;
    y2 = y2_req;
    y3 = y3_req;
end

% Calculating the total power
ytot=y1+y2+y3;

assignin('base','y1store',y1);
assignin('base','y2store',y2);
assignin('base','y3store',y3);
assignin('base','t2store',t);

y = [y1,y2,y3,ytot];
```

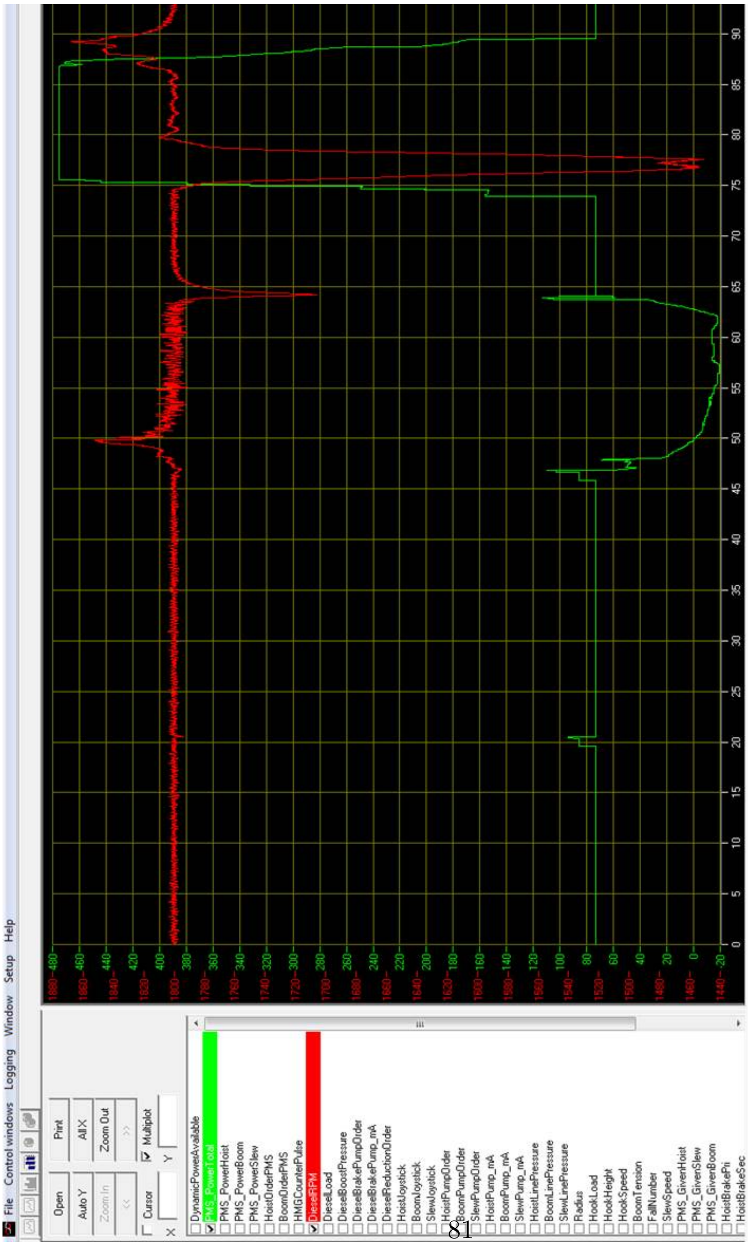
Appendix C

Datasets

Dataset 1 shows total load and the corresponding RPM for an actual diesel generator



Dataset 2 shows total load and the corresponding RPM for an actual diesel generator



Appendix D

Problem description (from NOV)

Power Management System for crane

- INTRODUCTION:
- Offshore cranes have often limited available power and the sum of power requirement to the main functions will be limited by this.
- Simple PMS systems will affect the crane operation by reducing speed and make the crane uncomfortable to drive.
- An more intelligent way to control the power will give improved speed to each function and more smooth operation. This will also give improved safety and increased lifting capacity when lifting from ship in wave height above 1 meter.
- Optimizing the power will reduce cost of crane and give customer improved functionality.

THESIS:

- Investigate the power consumption for an offshore crane
- Set up a mathematical model of power system in the crane
- Set up a control philosophy for the PMS on a offshore crane to share the power according to minimum requirements and to avoid as far as possible influence of the crane operation
    - Compare more than one control philosophy
- Make simulations and detect system characteristics
- Suggest system improvements and further work

INFO:

- Lifting capacity – 15 ton
- Maximum outreach – 50 meter
- Hoisting speed 15 ton – 1 m/s
- Hoisting speed 5 ton – 2 m/s
- Luffing speed – 60 sec (15-85°)
- Max available power – 400 kW
- Max hoisting power – 200 kW
- Max luffing power – 200 kW
- Max slewing power – 100 kW
- Aux system – 50 kW