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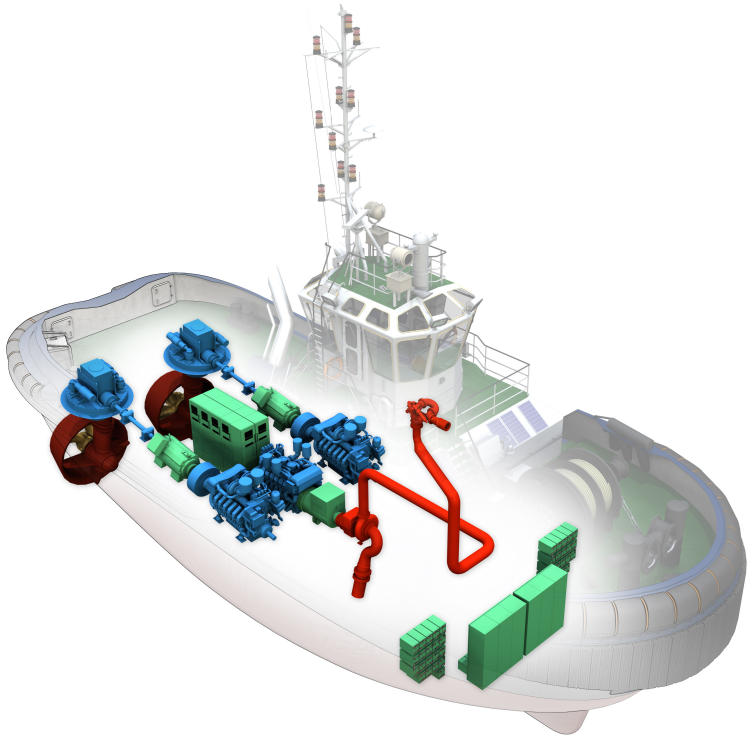

Development of a flexible hybrid control

Development of a flexible control for a simulation model of a hybrid tug propulsion system

Master's thesis in Naval Architecture and Ocean Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2016

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A report describing the work to develop a flexible hybrid control unit in Simulink

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Cover: The ASD HYBRID Tug 2810 from Damen that have been the reference ship in this report.
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Abstract

Development of a flexible hybrid control
Development of a flexible control for a simulation model of a hybrid tug propulsion system

This thesis is carried out at the request of Damen shipyards research department. As a step in the process of developing new fuel efficient hybrid tug-boats, simulation models of different hybrid system layouts is used to get a quick estimate of the performance of a complex system. In the process of building these models a time consuming part is to construct the control system. The question for this thesis is whether it is possible to find a flexible or modular control strategy that can be used for several different hybrid-system layouts. The question is limited to three specific system layouts and variants of these. By analysing a Simulink simulation model provided by Damen and concluding requirements on the control, a new, flexible control with a user interface to input specific system parameters have been developed. The simulation model has then been used to verify the functionality of the new control. The model has also been used to evaluate the performance of the different systems when using energy stored in the battery. A reduction of the fuel consumption of up to 42% from a reference case is obtained. The flexible control works within the given limits and can be used for quick setup of new simulations. It is a functioning platform with large potential to make further improvements and implementing more functionality.

Chalmers University of Technology
Department of Shipping and Marine Technology
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Keywords: Damen shipyards, hybrid propulsion, hybrid tug, simulation, Simulink, flexible control.

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Glossary and Abbreviations

ASD Azimuth Stern Drive. 1, 3

bollard pull Bollard pull is a conventional measure of the pulling (or towing) power of a watercraft. 9, 18, 19

C-rating The C rating is the maximum safe continuous discharge rate of a battery pack. A 1C rated battery can can fully discharge in 1 hour, which means that a 100kWh battery can deliver 100kW continuously. 36

diesel electric A power transmission where the mechanical power from the engine is converted to electrical power with a generator and back to mechanical power with electric motor. 28, 32

gen-set Diesel engine connected to a generator that generates electrical current. 3, 4, 16, 22, 27, 28, 32, 51

GUI Graphical user interface is a type of interface that allows users to interact with electronic devices through graphical icons and visual indicators. 18, 46

ICE Internal Combustion Engine. 7, 8

KPI Key Performance Indicator. 1

main engine The primary power producer on board the vessel, in this report used to describe a engine with direct mechanical connection to the propeller shaft. 19, 28–30, 32

Maximum Continuous Rating The engine manufacturers rated maximum at which the engine can operate continuous the peak performance of the engine is located at a higher point. 9

operational profile The operational profile is a set of data containing vessel speed in knots and required bollard pull in tonnes at every time instant that is used to input how the vessel is operated in the simulation model. 6

RPM Revolutions Per Minute. 9

sfc Specific Fuel Consumption. 9

simulink A MATLAB toolbox used for simulations. 2

SoC State of charge, energy level in the battery. 11, 13, 16, 29

1
Introduction

In this chapter, the background of the thesis project, aim, goals, limitations, a description of the hybrid tug propulsion system and operational profile, are described. In chapter 2, theory about hybridization etc. is provided. The methods used are described in chapter 3. Results of a simulation model verification are presented chapter 4 and the main results of the thesis are presented in chapter 5. Finally a discussion and conclusion of the project are presented is chapter 6 and 7.

1.1 Background

Hybridization of tugs have been shown to be beneficial in previous studies [1]. This master thesis will discuss the implementation of models in Simulink and how to adjust the hybrid control for different propulsion concepts of the hybrid tug.

A proper control strategy is crucial to get good performance of the system. Damen shipyards is in the front line of hybrid tugs and have already implemented the systems needed for hybrid drive in their ASD tug 2810 Hybrid. The control theory and strategy are constantly improved with the automotive industry as a main driver. The fuel consumption is usually chosen as an important Key Performance Indicator, KPI. For a tug used in large sea ports such as Hamburg with around 10,000 [2] calls a year the local emissions from tugs could potentially be a important KPI. An important note with the hybrid system for seafaring vessels is that they can not regenerate energy as for a car when driving downhill.

When developing a hybrid system many different parameters should be varied to see how it affects the total system. Sizing of the components are important, the system must be designed so that the component can interact in a good way. One important component is the battery, a large battery gives the control system more flexibility but is heavy and expensive to install. The electric motor sizing must be adapted to both battery power capacity and the main engine. The main engine together with the electric system needs to be powerful enough to fulfil the power requirements of the tug.

When considering a hybrid system the complexity of the system increases. To lower the developing time and costs Damen uses simulation models to get a first idea of how the system will be affected when changing the components and size. The simulations are done in Simulink and each component is modelled by Damen.

When modelling this kind of systems, the difficult part is to have a control that can change operating mode for different systems. This is the underlying interest to why this subject was given as a master thesis. To produce a flexible hybrid control unit in Simulink to easily change between different components and concepts.

Damen shipyards provided, together with Francesco Baldi, the subject for the master thesis. Damen has built a number of specialized tugs that have the capability to run as hybrids. When Damen is developing tugs in the simulation stage they construct Simulink models of each component. To connect each component is an easy job when all the different components are modelled properly. But to control them are more difficult due to the more complex way of operating a hybrid vessel. When changing between different hybrid system layouts the control needs to change in order to control each system properly. The company has not yet implemented this kind of Simulink control and therefore a new control for each concept was needed. To make development faster and easier the task for this master thesis is to make a flexible control, able to operate multiple different hybrid concepts in different modes.

1.2 Aim

The aim of the thesis is to simplify one part in the process of setting up a simulations model of a new system in Simulink. Can this be achieved by creating a flexible or modular control? Is it possible to find a control strategy and implement a control where the user can input necessary parameters to make the control adapt to the system that should be simulated? Another aim is to test the control with various systems and compare fuel consumption and engine running hours etc. of the systems. How much can the fuel consumption of this tug be reduced by using energy stored in a battery?

1.3 Goal

The goal of the thesis is to create a code that implement a flexible or modular control strategy for the hybrid tug. The control code should be able to adapt to a new system model and/or operational conditions. The system parameters and other necessary information should be input in a user interface that is prompted to the user. The goal is also to be able to verify the functionality of the control code by using the simulation model from Damen. Another goal is to be able to simulate and compare the performance of some different hybrid system layouts for the tug.

1.4 Limitations

To make the project manageable within the time frame, several limitations apply, the main limitations are listed below.

- The thesis is limited to hybrid tugs of a specific type and the scope is not widened to look at other kinds of vessels.
- The simulations and calculations is be done in MATLAB and Simulink.
- The models provided from Damen is used to simulate the different concepts, to create new Simulink models is not the focus of the thesis. Only minor changes, adaptions and scaling of components in the existing models is done in this thesis.
- The functionality of the control is limited to be able to handle simulations of the systems described in chapter 1.5.
- The time frame of the thesis work is 5 months.
- Only a rule based approach to control is used. The goal is not to find a strategy for optimal control of a specific system but to create a control that can be used for a variety of systems.

1.5 System description

In this thesis the ASD tug 2810 Hybrid is studied. The propulsion system layout of that tug is shown 1.1. A product data sheet of the tug can be seen in appendix A. Variants of the propulsion system shown in 1.2 and 1.3 are also studied.

The hybrid system consists of a battery, one or more gen-sets, two main engines, two electrical shaft motors/generators and a shore connection. The gen-set produces electricity that can either be stored in the battery for later use or be used to drive the propellers, using shaft motors. The shaft motors/generators can either apply a positive or negative torque on the propeller shaft depending on if they are used as motors or generators. The two main engines are diesel engines, preferably operated at high loads. The battery in the system can be operated differently depending heavily on the storage capacity of the battery and its characteristics.

In the figures 1.1, 1.2 and 1.3 the three concepts mainly in focus are shown. In figure 1.1, a quite conventional system is shown, the difference from a conventional system is that a battery is included. Apart from the battery, it contains two main engines, shaft generator/motors, a gen-set and a emergency gen-set. In the system in figure 1.2, the gen-set is replaced by a larger battery. In this system the battery provides all electricity when the main engine is not running. In figure 1.1 the battery is smaller and is complemented by two smaller gen-sets.

The main difference with these from a conventional system is the battery. The battery can store energy for later use. Therefore a time dimension is introduced. The question is then when to use the energy stored in the battery and when to charge the battery to get the lowest fuel consumption of the whole system during a typical operational cycle of the tug. The most preferable operation points of the gen-set are dependent on the type and size of the engine.

Table 1.1: System concepts

System	*ME (kW)*	*Gen.-set (kWe)*	*Shaft gen. (kWe)*	*Battery (kWh)*
Full hybrid ***A***	2x1865	650	2x250	240
Battery hybrid ***B***	2x1865	0	2x250	500
Diesel-electric hybrid ***C***	2x1865	2x350	2x250	100

The sign convention for the figures below are as following:

- M = Electrical motor/generator
- DE = Diesel engine
- G = Generator
- BAT = Battery

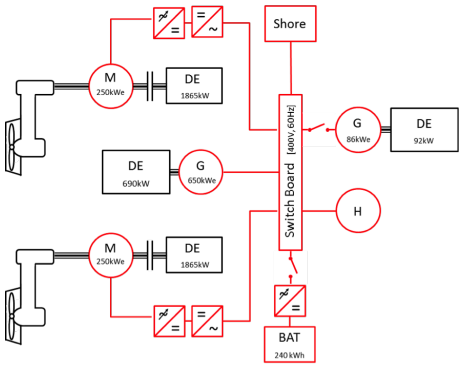

Figure 1.1: Full hybrid

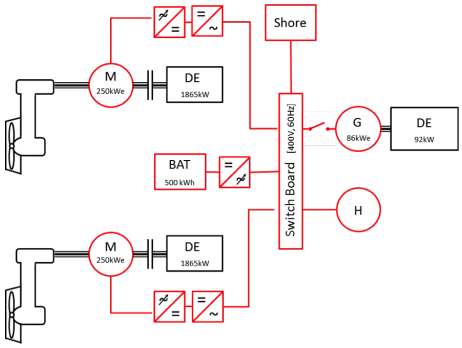

Figure 1.2: Battery hybrid

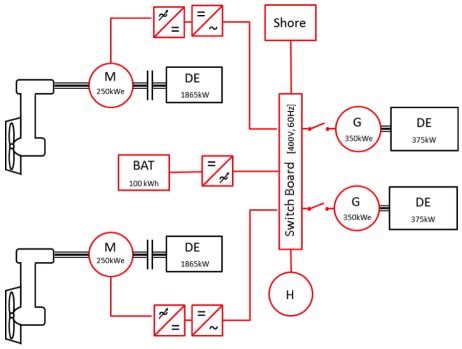

Figure 1.3: Diesel-electric hybrid

1.5.1 The operational profile

The operational profile used when simulating is provided together with the model, it is a profile measured by Damen from a real operational case. In figure 1.4 both the speed and bollard pull requirements are shown. The total time for the cycle is 4275 seconds. The maximum bollard pull reaches 55 tonnes for a short period of time. The maximum bollard pull is an important feature of tugs since this indicates how much force the tug is able to produce. The top speed for the tug is during transit. The tug needs to relatively fast meet up the approaching vessel in need of assist in to or out of port. In this operational cycle the top speed of the tug reaches 13 knots for a shorter period.

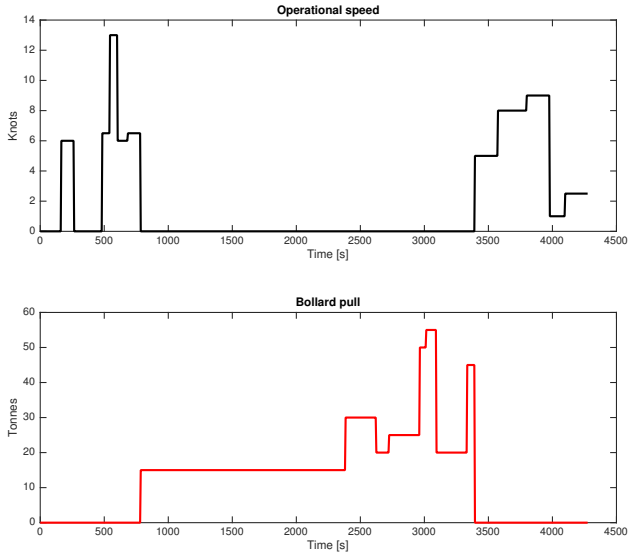

Figure 1.4: Operational profile

2
Theory

In section 2.1 the categorization of hybrid systems is explained. In section 2.2 the possible improvements of a hybrid system is discussed. In section 2.3 the efficiency of a internal combustion engine is described. In section 2.4 control strategies are explained with focus on rule based control.

2.1 Hybrid system categorization

A hybrid propulsion system is distinguished from a conventional propulsion system by the the use of two or more prime movers and power sources [3]. A hybrid system does not necessary include electrical components; it could just as well be a mechanical, hydraulic or pneumatic system. Though most commonly a hybrid propulsion system is referred to as a system with a ICE running on a liquid fuel and a electric motor with a electrochemical battery for energy storage [3].

Hybrid propulsion systems can look and operate very differently depending on the layout, components and operation. When talking about the system layouts they are usually categorized in three broad categories; Series hybrid (figure 2.2), Parallel hybrid (figure 2.1) and series-parallel (or combined hybrid) [3].

In a parallel hybrid layout, both the electric motor and the ICE are mechanically connected to the propeller shaft. In a series hybrid only the electric motor is connected to the shaft, and the power is delivered over a electrical link from the ICE. A series-parallel hybrid has is a combination of both and power can be delivered to the shaft via a mechanical and a electric link [3].

As can be realized from the systems description in section 1.5, the hybrid tug propulsion systems is most accurately categorized as a combined hybrid since there as both mechanical and electrical links from the power units to the shaft. The categorization depends on the layout of a specific system. In some cases the systems can be either a parallel or series hybrid, depending on how it is operated.

The system layout and configuration is not the only way to categorize a hybrid system. It can also be categorized further by the degree of hybridization and how it is operated [3]. According to Guzzella and Sciarretta[3], the degree of hybridization is categorized on a scale from a pure ICE propulsion, through every combination of both, to a pure electric propulsion system. A micro or mild hybrid only has a small

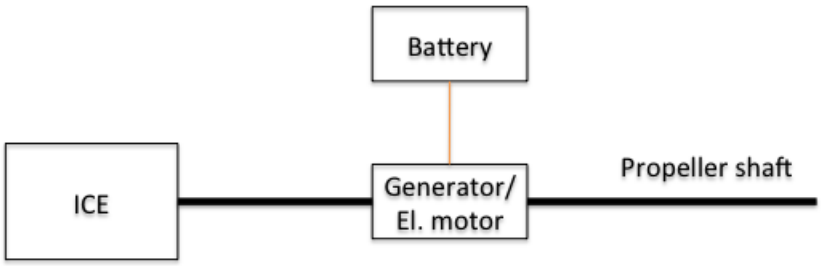

Figure 2.1: Parallel hybrid

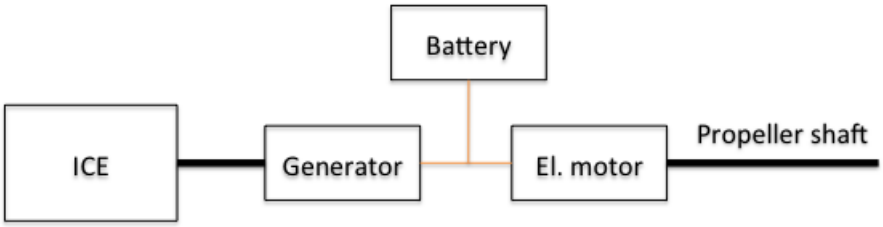

Figure 2.2: Series hybrid

electric motor. In a full hybrid system, the electric motor can be used for propulsion in combination with the ICE. A variant of a full hybrid is a plug-in hybrid where the battery is used to store electrical energy and deplete it during operation. The next step is a electric system, a variant of this is extended-range electric where the system mainly operates electrically but has a axillary power unit for range extension [3].

2.2 Hybrid system improvement possibilities

The hybridization of a propulsion system offers many opportunities in improving the system total efficiency [3]. Guzzella and Sciarretta[3] specifically states five possibilities with hybridization. First, the possibility to downsize the ICE, while maintaining the performance of the system. Second, the ability of a hybrid system to recuperate energy from braking. Third, the ability to optimize the power distribution, depending on which operational condition that is most efficient. The fourth reason is to eliminate idling losses by turning off the engines when no, or very low power is needed. Lastly Guzzella and Sciarretta[3] mentions the possibility to eliminate losses from clutches by matching the shaft speed to the engine speed before the engine is engaged. In addition, a plug-in hybrid system can be used to reduce the direct fuel consumption and local emissions since the battery can be recharged from the power grid and the system be operated as a pure electric system.

2.3 Efficiency of large internal combustion engine

Marine diesel engines operate most efficient at around 60-80% of their nominal load. For port-to-port operations in cases like container ships and tankers the tuning be-

tween propeller and engine can be done very precisely. These types of ships have a distinct service condition [1]. The design speed will be kept for a majority of the lifetime. For more complex service conditions such as for a tug (see figure 1.4) the tuning between engine and loads are more difficult. With a hybrid concept the complexity increases along with the options of how to tune the load.

This section will describe why an effective control of the main engine can increase their efficiency. In this thesis, in general, the fuel efficiency is calculated using equation 2.1. Where P is the power produced at each instance. Variable $\dot{m}$ is defined as the mass flow of fuel in kg/s.

$$sfc = \frac{\dot{m}}{P} \tag{2.1}$$

For all engines there is an optimum load point. The optimum load point is where the sfc has its minimum. The basic characteristics of the engine determine where this optimum point will be. For most types of engines the optimum point is located somewhere around 60-80 % of Maximum Continuous Rating [4]. Since the main engines are C-rated at 1865 kW to be able to produce the needed bollard pull seen in figure 1.4 they have a high load point for low sfc. One of the main purposes of hybridizing propulsion systems is to lower the specific fuel consumption, and thereby the total fuel consumption [3]. To make this possible a higher load on the main engines would be favourable. When using batteries this is possible by charging the battery in the areas where the engines are at low point to increase the load on them.

2.4 Rule based control

In many studies for mainly cars the rule based strategy has proven to be sufficient for lowering fuel consumption [5], [6]. The rule based control switches between a finite number of states in which the system can operate. The rules are designed based on heuristics, intuition, expertise and even mathematical models.
The rules are based on whether or not certain criterion are fulfilled, in a binary state 1 or 0. The criterion are based on output signal from the systems on board. A few examples of criteria that can be used are:

- Demanded engine power
- Battery state of charge
- Engine/propeller speed
- Bollard pull or vessel speed
- Location of the vessel
- Particulate matter in PPM

These criteria can be combined together to match specific goals of the control. In the original control from Damen the rules was based on the engine RPM and the required bollard pull as the two criterion. Based on how precise the model is, and how close to the "real" system it is more signals can be used for basing the rules on.

3
Methods

Chapter 3 presents the methodology used in this master thesis, the steps taken in order to understand and develop a flexible control is described. First the original Simulink model is described, then in detail the control parts that are modified in order to make it flexible. A verification of the original control was made to identify the behaviour of the model and to gather information of how it works. The different tests to obtain results are described.

3.1 Overview of the methodology

For understanding the model different tests cycles were used as input to the model and the simulation results were analysed in a separate MATLAB program. The analysing program plots graphs of different relevant variables such as fuel consumption, which components are active, SoC (State of charge) of the battery and more. All this data was used to verify that the model worked in a satisfactory manner. From the verification, requirements on the control system are concluded. These are then used as a base for building the flexible control. Finally the flexible control system and its interaction with different system models are investigated. These results are also used to compare and evaluate the different hybrid systems. To conclude the process, the method for creating and testing the control can be summarized as in the list below.

- Understanding the model, model description (section 3.2)
- Model verification and identification of problems (section 3.3)
- Conclusion of control requirements (section 3.4)
- Development of the flexible control(section 3.5)
- Verification of the flexible control and model interaction (section 3.6)
- Evaluation of different hybrid propulsion system layouts (section 3.7)

3.2 Introduction to the Simulink model

The model provided by Damen consists of a setup program and a Simulink model. The development of the complete Simulink model is described thoroughly in *Development of a hybrid propulsion simulation model* by HJ Boonen, MSc [7]. The setup program loads all the variables needed to be able to run the Simulink model. The loaded variables tell the model what operational profile is supposed to be run and how long the simulation time is. The operational profile contains information about the bollard pull the tug should deliver and the speed it should keep at every time of the simulation. The program also loads the parameters for each component such as the efficiency of the parts and fixed properties such as weight, length and beam of the tugboat. The Simulink model is divided into two main blocks (see figure 3.1); the command system and the operation system. In the following section these two systems are described.

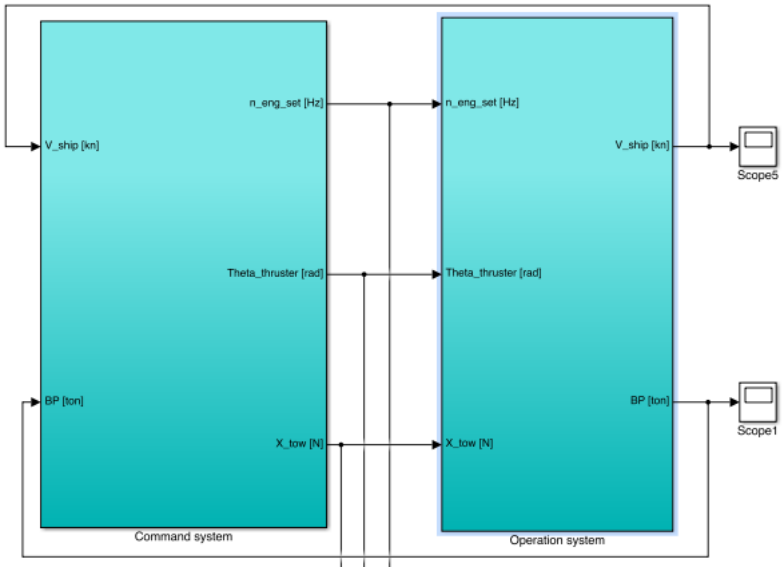

Figure 3.1: Simulink start view

3.2.1 Command system

In the command system the operational profile data is the input, with set speed and set bollard pull. The actual vessel speed and tow force are subtracted from the set speed and set tow force to get the deviation from desired speed and tow force, as can be seen in figure 3.2. With this data a set value rotational speed of the shaft is calculated and a tow force to correct the deviation. The command system also decides how the thrusters are angled with the help of a single lever command control.

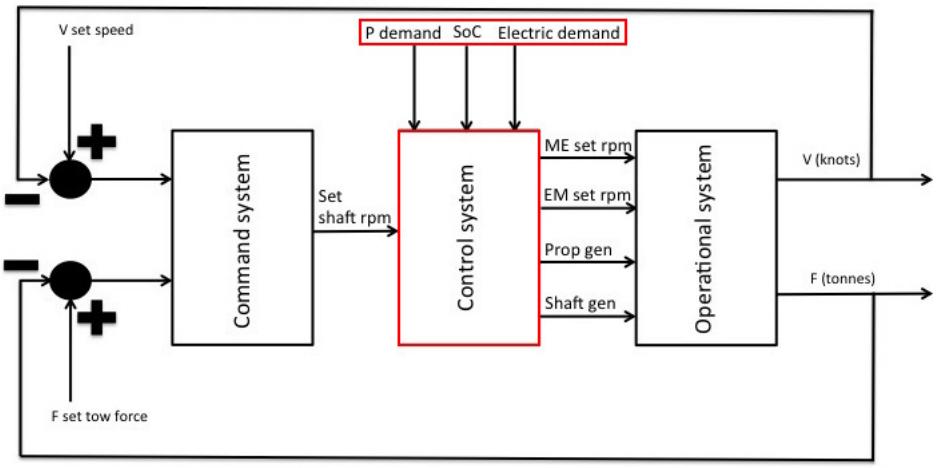

Figure 3.2: Simplified control view

3.2.2 Control system

The control system is inside the operational block in figure 3.1. The decisions of how to operate the system are made in this block. This has been the main focus of the thesis work. The changes that are made to the model mainly relate to this block of the model. In figure 3.2 the red marked boxes are the systems which have been modified in the model during the thesis work. Power demand, SoC and electrical demand are connected from the operational system. These three input signals are added to the control system. They are used by the newly developed control as signals to base control decisions on.

3.2.3 Operation system

The operation system is modelled based on the actual parts installed on the tugboat. The engines, generators, shaft motors, batteries and hybrid control. The inputs from the command system to the operation system are shaft speed set value, required bollard pull and thruster angle. With this data the hybrid control unit decides when which mode is supposed to be operational, the details of the controller are discussed more in section 3.2.4. The accuracy of the model response depends very much on which level of detail these systems are modelled.

3.2.4 Original hybrid control

The original control is a rule-based control that was already implemented in the model. The rules decide when the different systems should be enabled or not. There are two inputs in the control system, the set shaft speed [Hz] and the tow force [N]. These values are determined by the command system. The components/functions that are controlled by the original hybrid control unit are:

- Battery

- Electrical motors
- Propulsion generators
- Electrical generators
- Main engines
- Electrical boost

The control rules are based on the tow force mainly, if the tow force is larger than 0 N, the main engine are always used. Depending on the set rotation of the engine the main engine is also accompanied by the generator and electrical boost. In other words, when towing, the vessel will always engage the main engines. See the last two rows in table 3.1.

For tow forces equal to zero depending on the set engine rotation in the drive cycle the different modes are decided. For engine speeds lower than 450 rpm the electrical motor are enabled. For engine speeds between 450 and 850 rpm the propulsion generator is enabled, the electrical motor and the battery discharge. For engine speeds above 850 rpm and below 1400 rpm with no tow force the main engine is enabled and the shaft generator is enabled inducing a negative torque on the shaft line.

Table 3.1: Original rule based control

Rules	**Tow force [N]**	**cond.**	**N set [RPM]**
Electric motor and battery	<= 0	and	<= 450
Electric motor and genset	<= 0	and	450 <N set <850
Main engines and shaft generator	<= 0	and	>850
Main engines and shaft generator	>0	or	>850
Main engine, electric boost and battery	>0	and	>1400

3.2.5 The concepts modelled in Simulink

The three concepts that are in focus were suggested by Damen and described in section 1.5. The concepts are implemented in Simulink for testing and comparing. Damen provided the first model of the full hybrid concept, see figure 1.1. The other concepts are adapted easily from the existing model from Damen. The battery hybrid's only difference in the model is the larger battery. Going into the battery variables in the Matlab file there is a variable specifying the battery size. Changing this to the larger 500 kWh battery modifies the system according to the concept seen in figure 1.2. The last concept, the diesel-electric hybrid, has the difference of two generator sets and a smaller battery. In the Simulink model the propulsion generator is duplicated and the parameters are modified to suit the larger diesel

generators. The demanded current from the generator sets are divided in two. See figure 1.3 for the concept overview. Component sizes can be seen in detail in table 5.2. When analysing the operation cycle an additional concept was added to the three suggested from Damen, this is described further in section 3.7.1.

3.3 Model verification

This section describes some of the verification tests performed on the model. The results of the verification process are shown in chapter 4. To be able to rely on the results from the finished model the verification part is important. The model from Damen enabled us to make many tests and analyse them quickly with the help of analysing programs. The many different test simulations gave us a good overview of the model. The verification process includes creating a number of different tests, see list in section 3.3.1. To verify the output data basic thermodynamics has been most useful. Particularly the 1st law of thermodynamics stating: *Energy cannot be created nor destroyed*. This is done by checking that the produced power and the total consumed power add up. Other verification methods have been to check how engines are operated. The verification tests have pushed the model to the limits to see how robust it is. For many of the tests the model did not respond in a realistic way. The uncertain behaviour of the model for some of the test gave vital knowledge about the models restriction. Some of the behaviours noticed had to be dealt with and were put in to a list of requirements seen in section 3.4.

3.3.1 Simulation model testing

To test the function of the simulation model, several tests are set up to answer some questions about the model response in different situations. The main questions about the model that is answered by these test are listed below.

- What happens when a component is used over its maximum power capability? Will the model respond in any way or will this crash the model immediately?
- Does the model have a way to make sure that electrical power demanded from the grid is actually delivered by a power producer?
- Can several components be used for delivering electrical power at the same time to share the load?
- What is the control decision the control can make? Can the component load be controlled or can only the choice of active components be done?

To test how the model reacts in different situations several simulations are carried out with different operational cycles and activated components. One example of such a testing cycle is seen in figure 3.3. In this cycle the vessel speed is increased in steps from 0 to 11 knots and no additional bollard pull is added. From this test the reaction of the model to stepwise changes can be evaluated. Other model characteristics are tested with constant acceleration cycles, this will give a very clear view of how the system behaves.

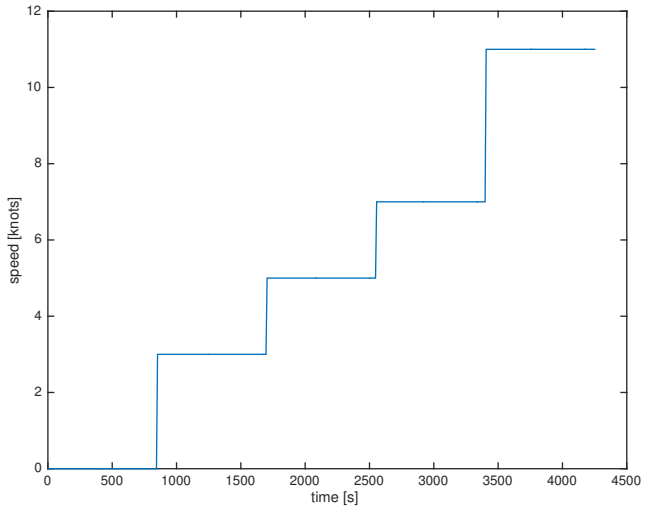

Figure 3.3: Test cycle, stepwise increasing speed

3.3.2 Analysing program

To analyse the large amount of data output from each simulation of the model a analysing program was created. The program consists of different sections dedicated to specific outputs. The Simulink model is large and there are many interesting outputs. The main focus of the program are the specific fuel consumption, power, running time of engines and SoC of the battery. It takes about 20 seconds to conduct a simulation, depending on how complex the model is built. When the simulation finishes the outputs appear in the workspace of MATLAB. When the output has been generated, the program can use it to draw graphs and calculate fuel consumption and engine run-time.

3.4 Control requirements

If the new flexible control is going to be able to control the simulation model is satisfactory way, it need to take the limitations of the existing model into account. To do this, a list of requirements on the new control is formulated. The requirements below are for the new control, these things have been found as results of the verification process it is described in chapter 4. The requirements mainly concern how the simulation model is built and how it should be operated to give correct result outputs. There are also some other requirements that are connected to the aim of the thesis, to simplify the simulations set-up process.

- Only one power producer can be used at once.
- The control signal is binary, the only decision for the control is whether or not to start a component, not how much power it should deliver.
- There is no feedback from the model if the power can not be provided. If for example the electrical motor is activated without activating the gen-set or the

battery the electric motor will run fine and demand the electrical power but it will not be produced, this will give a incorrect result output.
- There are no clear component limitations implemented. In some cases the component models will crash if the control attempts to use them at a too high power. The control must keep track of how much power is actually used and use the components accordingly.

Other requirements on the control, related to the aim of the thesis are stated below.

- The control must be able to handle at least the three systems described in chapter 1.5.
- Some kind of battery charging functionality should be included in the control.
- The control should be easy to use and all necessary settings of the control should be either automatically set or possible to edit from a user interface.

3.5 Development of the flexible control

Once all the requirements and functionalities of the control are determined, the process of creating the actual control block is mainly coding in the Simulink environment. The main problem in this stage is that the control must have functionality for controlling several components and functionalities in different combinations. To achieve this, the control is made up of several separate blocks, connected in series that is activated by the user in a user interface. The functionality of the flexible control is thoroughly described in chapter 5.1.

For making decisions of which components to use for producing the demanded power, a rule based control, described in chapter 2.4, is used. This is a simple but very effective way of controlling the system. The two main reasons for using this kind of control origins from the requirements on the control described in chapter 3.4. One of the requirements is that the control signal is a binary decision of which components use, rather than how much power the components should produce. The other is that no power split between power producers is possible in the model. This makes the control decision simple and enables the use of a simple control method.

To simplify the use of the control, the signal that the rule-based control uses is a sum of the power demand from the system at each time instant in the simulation. The usage of power as the control signal also ensures that the active components can produce the demanded power, given that the user input is correct values of component capacities. This is necessary since the model does not provide any feedback if the power demand can not be meet by the active components and the control must keep track of how much power is actually used.

Since this thesis focus is on the three systems, described in chapter 1.5, provided by Damen, only the functionality for these components included is implemented in the control. Functionality for charging is also included in a separate block that can be activated in combination with any other configuration of components.

3.6 Verification of the flexible control and model interaction

To verify the functionality of the newly developed flexible control several tests of the control together with simulation models of the different systems is conducted. This is done in similar manner to how the original model was verified.
To do this verification the simulation model had to be adapted to a approximate model of the three systems described in chapter 1.5. The same basic components in the simulation model are re-used in the models of the different systems but some parameters are changed.

When setting up the control for the different systems, only the parameters that are possible to change in the GUI of the control block is visible. This is necessary in order to verify that the control works the way it is supposed to with all the system layouts. When analysing the results of the simulations the same analysing scripts as described in chapter 3.3.2 is used.

3.7 Evaluation of different hybrid propulsion system layouts

The results of the simulations in terms of data of the fuel consumption etc. are analysed to compare the potential of the different system layouts. The three given layouts (see figure 1.5) are simulated and their output data is collected. The data is input to a Excel document and compared. In addition to collecting and comparing data another method is introduced. This method seeks to evaluate the given drive cycle to see if other systems layouts with different component sizing could be interesting to investigate further.

3.7.1 Operational cycle evaluation

The operational profile input used in the simulation is from a real case and is provided by Damen. When the operational cycle is run the model needs to provide a certain amount of power for each time step. When the bollard pull is at the maximum at 60 tonnes the highest power output is recorded from the simulations. To get a better overview of the energy demand of the drive cycle a MATLAB script that sorts the energy demand at each time instant is run. Where the largest energy demand is sorted first and then in descending order to lower energy demand. The overview also gives a first hint to if there is fuel saving potential of hybridization. In figure 3.4 below the unsorted energy demand can be seen. At 3000 seconds in to the simulation a large power can be seen which corresponds to a large bollard pull in the operational profile.

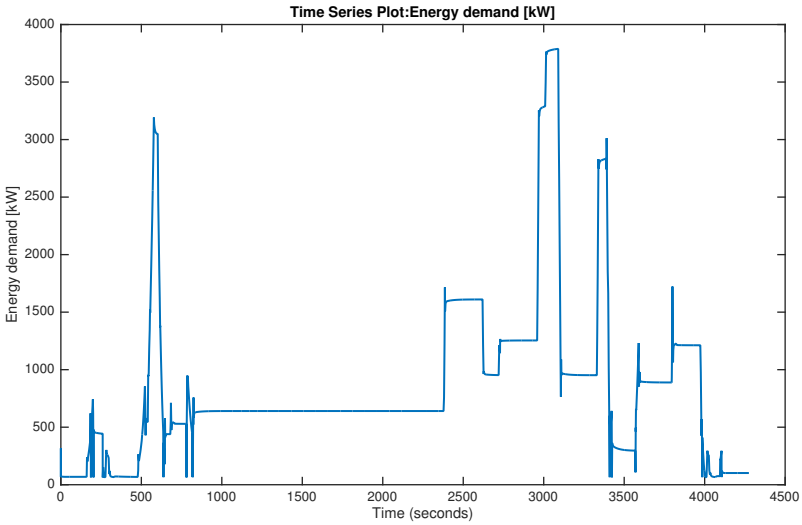

Figure 3.4: Energy demand for the operational cycle

In the next figure 3.5 the sorted energy demand can be seen. The peak at 3000 seconds from figure 3.4 at around 3500 kW is located in the beginning. A long period of a constant power is seen at 1500 seconds until 3000 seconds. This corresponds to approximately 35 % of the total cycle time. Where as the maximum power is only during 1.2 %. The specifications for the tug states that it should be able to give a bollard pull up to 60 tonnes. To reach this goal the main engines are dimensioned to meet this requirement.

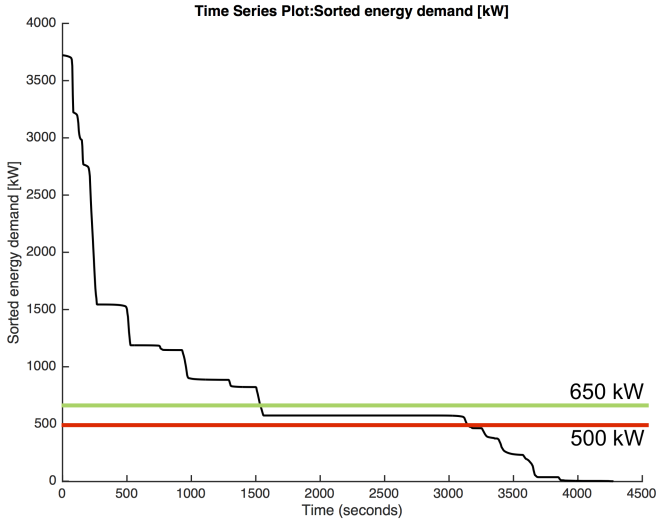

Figure 3.5: Sorted energy demand

The maximum power capacity of the electrical components (Battery pack and electric motors) in the system layouts provided by Damen is 500kW. This is, as can be seen in figure 3.5, just below a step in the power curve. This means that the

electrical propulsion system can only be used for pure-electric propulsion for a very limited amount of time. By increasing the size of the electrical components the hybrid system will be much more useful and will be able to operate in more parts of the operational profile. Because of this, a additional variant of the system in figure 1.2, called battery hybrid with large battery and electrical motor, is added as a system to evaluate in the thesis.

4

Model verification results

To answer the questions about the model described in section 3.3.1, different test were performed to see what the response of the model is in different situations. In this chapter the output data from model verification simulations is presented. These results is used to determine how the model should be operated and to establish requirements on the control. The verification results consist of plots of the results from the tests described in section 3.3.

4.1 Model response to stepwise speed increments

To get a good overview of the system performance simulations was performed with a test cycle. The purpose of the test cycle is to see how different components in the vessel are affected. The control unit in this case is the original hybrid control from Damen. The drive cycle is stepped up in steps in four steps from 0, 3, 5, 7, 11 knots over the time. The steps are seen in figure 4.1. On the left y-axis the power in kW is seen. The simulation time is 4275 seconds. For the different steps the hybrid unit control is changing how the system is supplying power depending on the power demand. The constant power requirement is the on board hotel load. The hotel load supplies the radios, air conditioning, lights and winches etc. The other loads depend on the operations of the ship speed and tow force. In the end of the cycle the electrical motor has a negative value, which indicates that it is instead generating electricity. As seen in the figure below, after each increment a overshoot in the power occurs. This is a numerical issue and not considered as a problem since it is only present for a few time steps in the simulation.

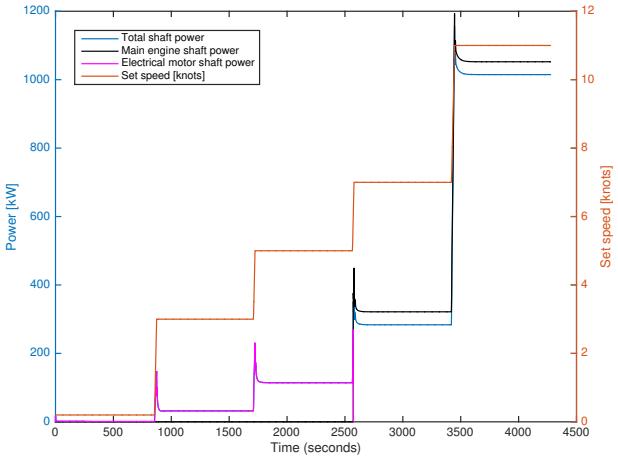

Figure 4.1: Total shaft power, electric motor, engine power and vessel set speed. Power on the left y-axis, vessel speed on the right y-axis and time on the x-axis

4.2 Component power limitation

To answer the questions described in section 3.3.1, What happens when a component is used over its maximum power capability? A test where the gen-set is used outside its maximum power limit were performed. From this test, it is concluded that in the model, there is no clear component power limitation implemented. If a component is used over its maximum limitation the simulation will continue, but the results will not be valid. In some cases the simulation is not able to complete and the model crashes.

One example of this is the gen-set model, when more power than its maximum limit is demanded, the mechanical part of model, where the inertia of the component is accounted for, crashes. The simulation will complete and at a first look at the electrical power is everything will seem good. One have to take a closer look at the mechanical power to notice the problem. This is very important since the mechanical model will determine the fuel consumption of the gen-set.

In figure 4.2 this behaviour is shown. For this test a simple operational cycle with constant acceleration and no bollard pull is used. The most important conclusion from this test is that the model has no way of dealing with the power limits of the components. Therefor it is important that the control system can handle this and make sure that the components are used properly.

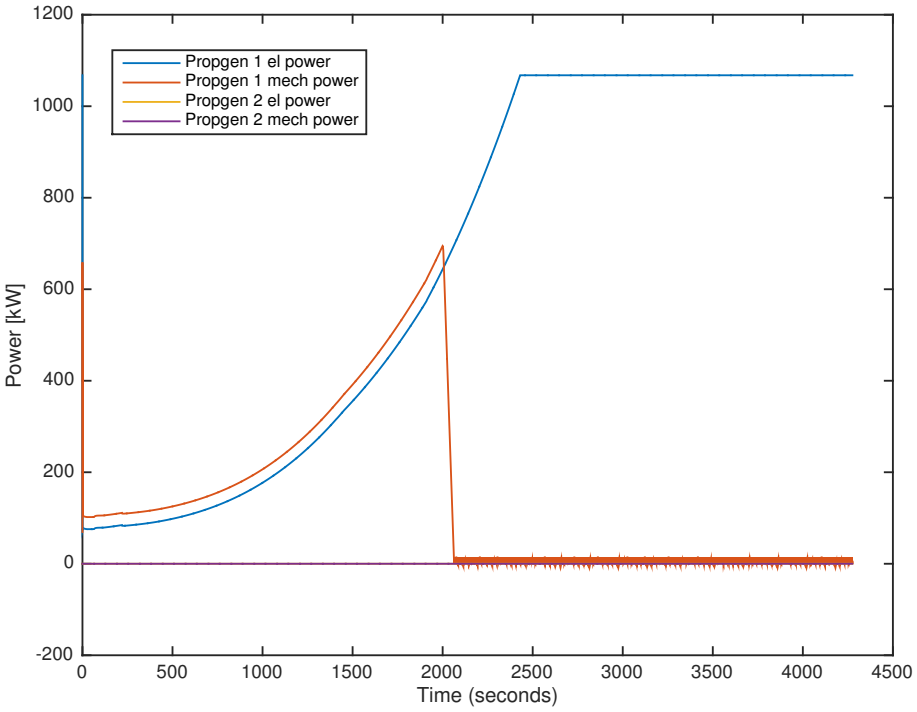

Figure 4.2: Gen-set mechanical model crash

4.3 Combination of power producers and power consumers

Is this section, the results of verification tests is presented, the test is set up to answer the questions in 3.3.1, about how the electricity demand and electrical power distribution is managed in the model.

When the electrical motors are used, they constantly demand electrical power from the grid. If no component that delivers electrical power is activated, either the battery pack or gen-set, the simulation will not give a accurate result. It will appear as if the fuel-consumption and battery depletion is much lower than it should be. Therefor the control must always make sure to combine a power consumer with a matching power producer or accumulator. In figure 4.3 this behaviour is shown. The electric motor is running and consuming power but the power form both the gen-sets and the battery pack is zero. For this test a simple short operational profile with constant acceleration and no bollard pull is used.

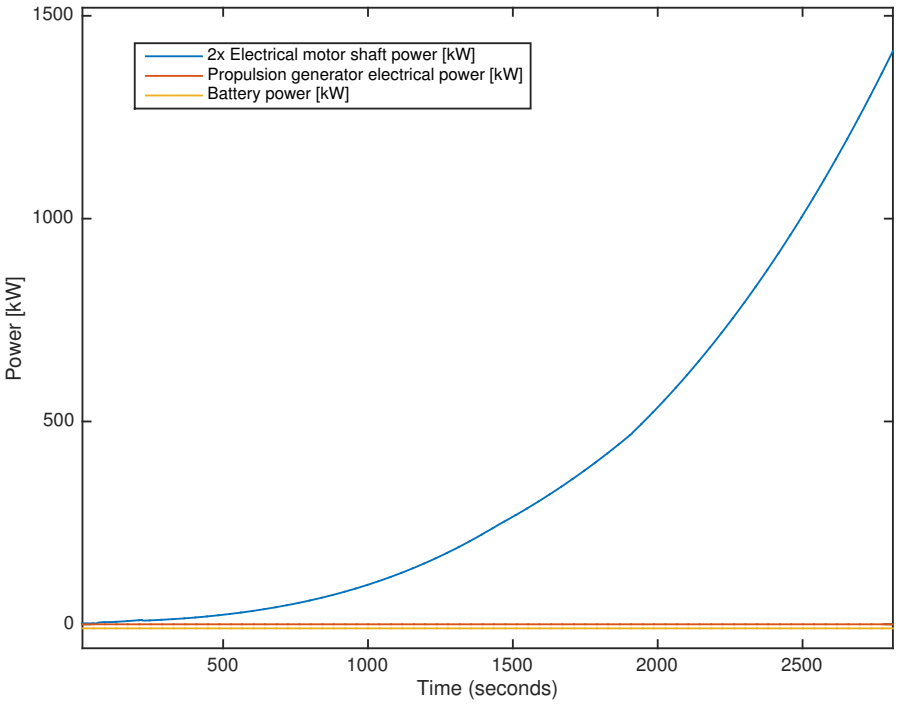

Figure 4.3: The electric motor is running, but no component is delivering the necessary electrical power

Another issue related to these characteristics of the model is that when an electrical power consumer is activated and more than one "producer" (gen-set, shaft generator, battery pack) is active, the consumer demands the same current from all the activated power producers. This leads to that the required power is produced twice in the simulation.

This can be seen in figure 4.4, where the electrical motor is propelling the vessel with constant acceleration. The electric motor demands power from the grid and both the battery pack and the gen-set is activated at the same time. The way the model is set up, these components cannot be used to share the load and they will instead both deliver the demanded power to the grid. It is therefor necessary that the control accounts for this and never tries to use several components to share the load.

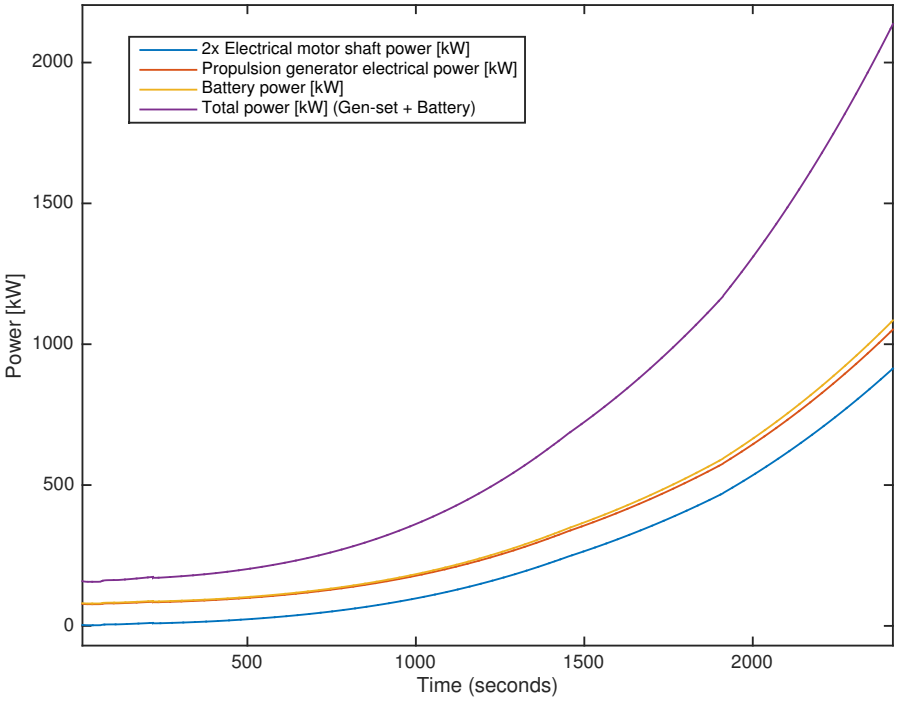

Figure 4.4: The electric motor is running and two components is both delivering the necessary electrical power

5
Results

In the following chapter the results are presented. The major result of the thesis is the flexible control. A detailed description of how the control works, and how to operate it is seen in section 5.1. Other results are from running a number of models with the control. The different models tested are the same as Damen requested in the introduction to the master thesis. The results are seen in section 5.2.

5.1 The flexible control

In this section the Simulink control-block, that is able to control simulations of multiple concepts, is described. The control block is built in Simulink and has a integrated graphical user interface, which in Simulink is called the mask of a block. In the mask, the user of the control can input necessary data about the system and the wanted behaviour of the control.

When a new model of a hybrid system layout is to be simulated, the control block can easily be copied into the new model. The block is then connected to the system with the predefined input and output ports of the block. The appearance of the control block when connected to a simulation model is seen in figure 5.1. The outputs of the block in the right hand side are Boolean values, either 1 or 0 depending on if a subsystem is enabled or not. In the figure the outputs ports are connected to "Goto" sinks that pass the signals forward to the system block. The display seen next to the Goto blocks indicates the value at each specific moment of the simulation. If a signal output port can not be connected to the system, for example in a system with no gen-sets, the gen-set ports (PropGen and PropGen2) can simply be terminated since it is not in use.

To set the control for running simulations the user interface is opened by double-clicking the outside of the control block. In the dialog box that appears several settings can then be manipulated. The first choice the user does is what kind of control that should be used. This dialog box can be seen in figure 5.2, the "Original control" is the old control that was in the model from start and has been kept for testing purpose. Another option is "manual control" were each component will be activated constantly with out any further control, this can be used for simple component tests in the model but is not intended for actual simulations. Selecting the first choice, "Hybrid control", accesses the new hybrid control. When this is selected more options and settings appear.

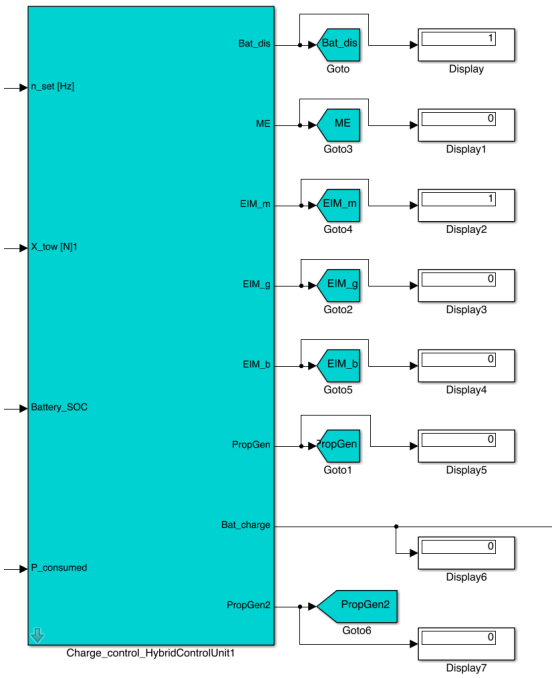

Figure 5.1: Appearance to the control block

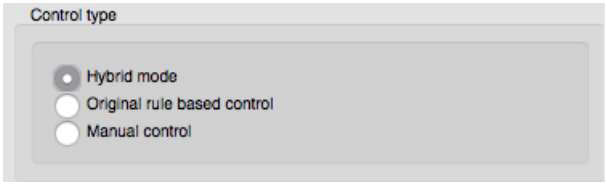

Figure 5.2: Choice of control

In the hybrid control, the first setting is what components, or what operational modes that is to be used. The modes that can be selected is shown in figure 5.3, here the system layout is chosen. The user can include main engines (Main engine enable), electric motor in combination with battery packs (Pure electric enable) and electrical motor in combination with gen-sets (Diesel electric enable). On board charging and electric boosting can also be turned on or off. For example, if a system that contains a main engine, electric shaft-motor, battery pack and no gen-sets is to be simulated. Then only "Main engine enable, "Pure electric enable" should be ticked. On board battery charging and electric motor boosting can also be selected depending on what behaviour of the system you want to simulate.

A table to denote the terms used in the figure above is seen below.

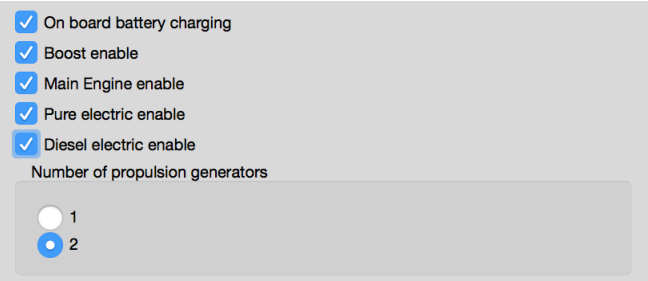

Figure 5.3: Choice of components

Table 5.1: Notation

On board battery charging	The electric power is generated on board while operating
Boost enable	Battery can deliver power alongside the ME
Pure electric	The electric motor with the battery is activated
Diesel electric	Electrical motors in combination with gen-sets

Another option, which only is valid if the "on board charging" box is selected, is the battery SoC limits. The model will start with 100% charged battery but the charging control will keep the battery within the limits selected by the sliders shown in figure 5.4. These limits are important for because the capacity of the battery, depends how much it is discharged and how many times.

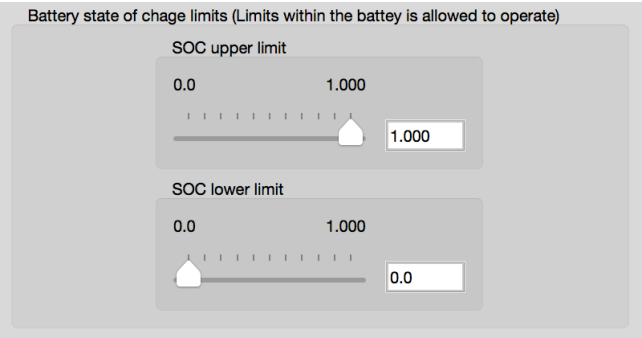

Figure 5.4: SOC limits

Some of the most important settings for the control is the power capabilities of the components included in the model and the switching load of each component. The dialog box for this settings is shown in figure 5.5. When setting up the model the user should input the maximum power of each of the components used in the system and the maximum load at which the control should switch to the next power-mode. For example the battery maximum power at which the control should switch to either diesel-electric or main engine, depending on the system.

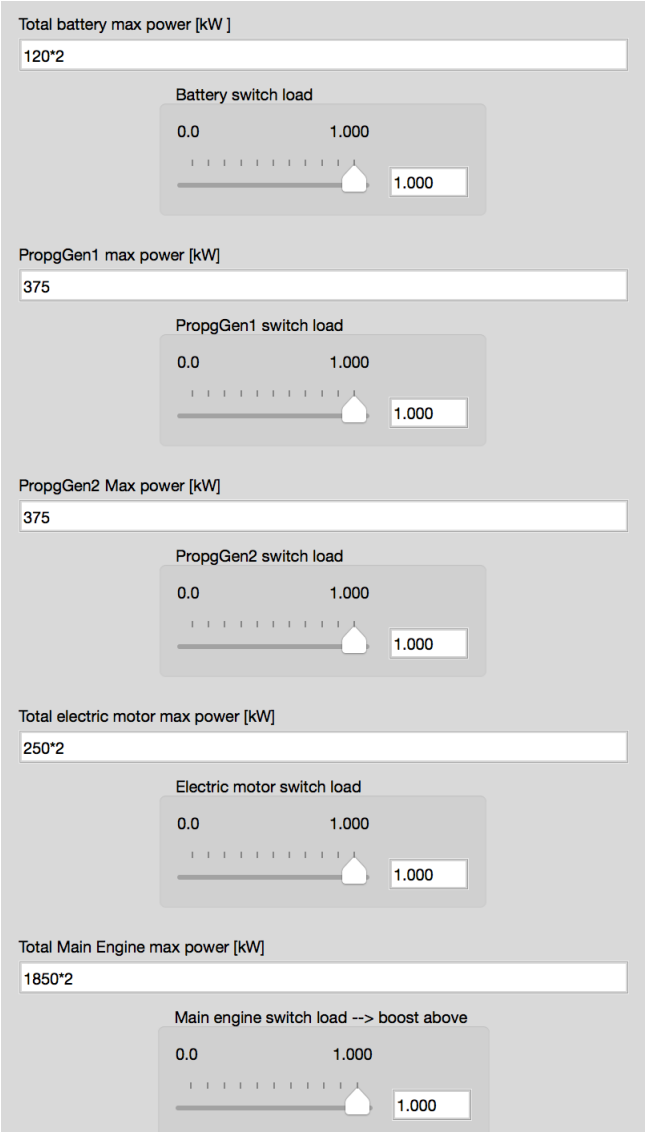

Figure 5.5: Component power settings

The actual functionality of the control block can be seen when opening the block by right clicking it and select "look under mask". Then the actual Simulink code with logical blocks etc. is shown, a overview of this is seen in figure 5.6.

The control is built of sub-blocks connected in series from left to right. The control signals of each component are first set in the sub-block to the left. This block represent the "pure electric"-mode and in this block only the electric motor and battery discharge control signals is activated by setting the value of these signals to 1. The rest of the control signals is set to 0, which deactivates the rest of the components in the model. When in the "pure electric"-mode, the rest of the blocks is disabled and the control signals is transmitted through the blocks without being manipulated. An example of how this is modelled can bee seen in figure 5.7, which shows the inside of the main engine sub-block. If the block is not activated, the switches pass the signal trough.

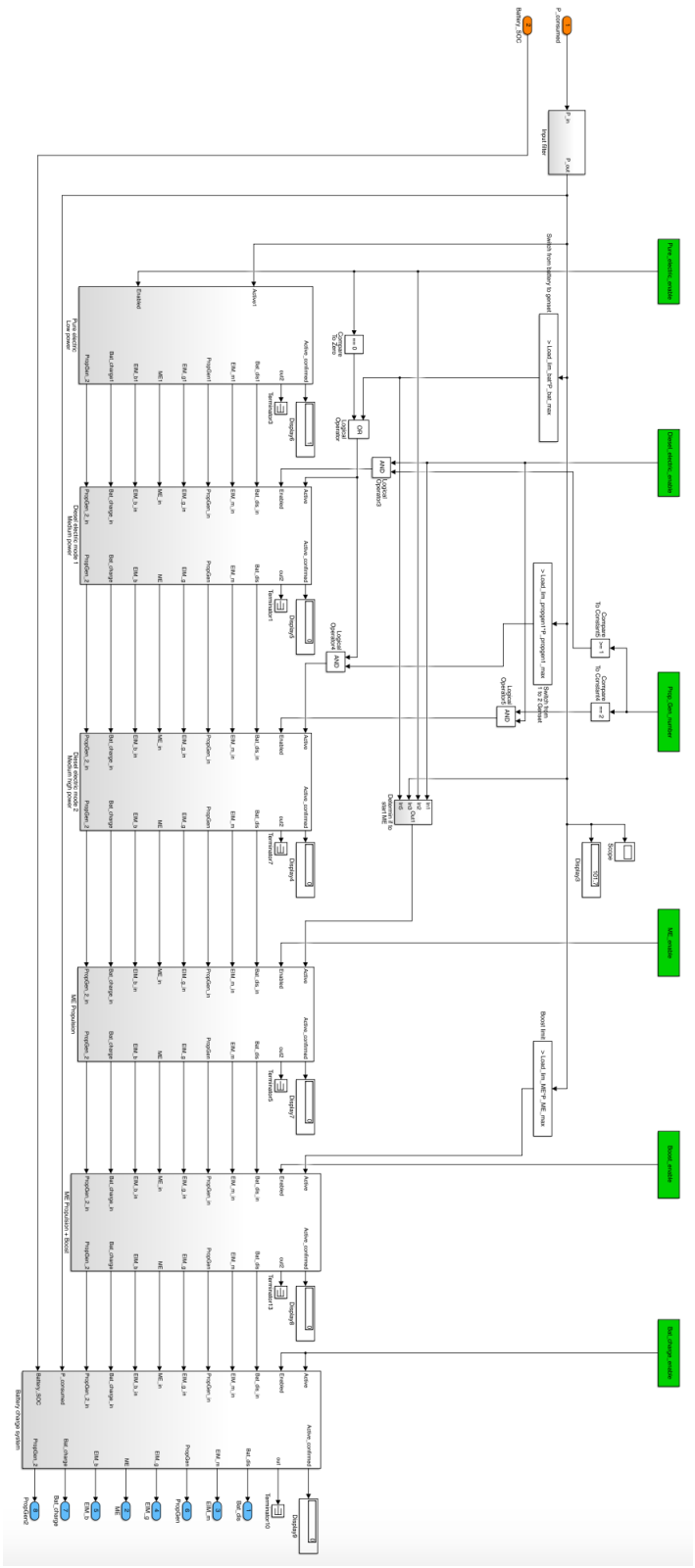

Figure 5.6: Inside the control block

There is both an enable signal and a power condition connected to each sub-block, which both have to be active to enable the block. The enable signal is set in the

user interface when selecting which components or operational modes that is to be included in the control. The power condition is the maximum power of a component multiplied with its maximum switch load factor. When the power demand from the system increases above the next power-condition in line, the next sub-block in the series will be activated. The second block represents the diesel-electric mode. In this block the first gen-set is activated and battery discharge function is deactivated. If there is no diesel electric functionality in the system, and the "Diesel electric enable" option has not been selected. There is a separate condition skip this block and switch over to the next mode, which most likely would be to start the main engine.

The switching between the sub-blocks goes on as the power increases. There are six sub-blocks that represent, from left to right, battery electric, diesel electric with one gen-set, diesel electric with two gen-set, main engine propulsion and main engine propulsion with boosting. Finally the last block in the sequence represent the battery charging functionality. In this block the charging of the battery is controlled, this block need to be the last is the sequence because it need to know what components that is currently active to be able to use the most beneficial power-source for charging. It also needs to be able to override the other blocks. If for example, the battery electric mode is currently in use, the charge control will start a gen-set to charge the battery and power the electric motors while charging.
figure 5.7

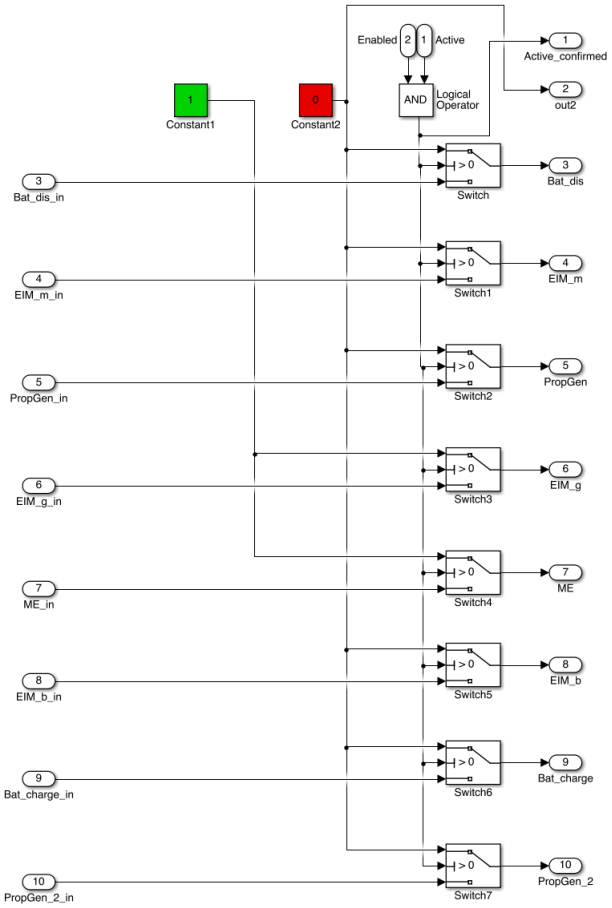

Figure 5.7: Inside the main engine mode sub-block

5.2 Hybrid system simulation results

In this section the results of simulations using the control described in chapter 5.1 is presented. The purpose of these simulations is both to investigate the performance of different systems and to verify the function of the new simulation control in various conditions. The simulation control box proved to be flexible and it was easy to change between two systems. This can be done in a short period of time. Results of this are difficult to measure with graphs but from the experience during the work a significantly easier control has been made. This is noticed while setting up the all the systems in the table below.

The models are configured as the concepts in section 1.5. One extra system **D** is introduced, as described in section 3.7.1. Each system and its components sizes are shown in table 5.2. Furthermore the result of each test will be categorized by **A-D** to make it more easy to follow the results. To compare the results to a system without hybrid functionality a reference system is added. The reference system consists of the same components as the hybrid systems but the battery model is disabled.

All the simulations presented in this section is carried out with the same control box

but with different settings in the user interface to adapt the control to the system. The different models are created with components from the original model, which is a model of the "Full hybrid" system. The battery model is scaled to fit the battery size of each system but the rest of the components are not scaled or modified. The same operational profile is used for all simulations and is the one described in section 3.7.1. In the table below each system is describe and their component sizing.

Table 5.2: System concepts

System	*ME (kW)*	*Gen.-set (kWe)*	*Shaft gen. (kWe)*	*Battery (kWh)*
Reference system ***REF***	2x1865	2x250	2x250	N/A
Full hybrid ***A***	2x1865	650	2x250	240
Battery hybrid ***B***	2x1865	0	2x250	500
Diesel-electric hybrid ***C***	2x1865	2x350	2x250	100
Larger battery hybrid ***D***	2x1865	0	2x325	650

5.2.1 Reference system

To be able to make a comparison, results of a simulation with a reference system are included. The reference system is in this case containing the same components as the other systems but the battery is not included. The vessel operates diesel-electric below 500kW shaft power and main engine direct above that. Either the gen-set or the shaft generator produces all the electrical demand. The obtained simulation data for the reference system is shown in 5.3. In figure 5.8 the active power source is shown, the battery power signal is included but it is zero because the system does not contain a battery pack. This graph is included for all results. A different colour line indicates that a different system is active.

The table below is included in the results for all test results. When stated "N/A" it means that in that simulation the component was not included. The total run time is the same in all cases since the same operational profile is used. The main engine, gen-set and battery electric denotes what system is used for propelling the vessel. In table 5.7 these values adds up to more than 100% which indicates that the systems are overlapping each other.

Table 5.3: Results reference system

Reference system	
Total fuel consumption	116.6 kg
Battery depletion	N/A
Battery depletion	N/A
Run time total:	4275 sec
Main engine:	76.5%
Gen-set:	23.5%
Battery electric:	N/A

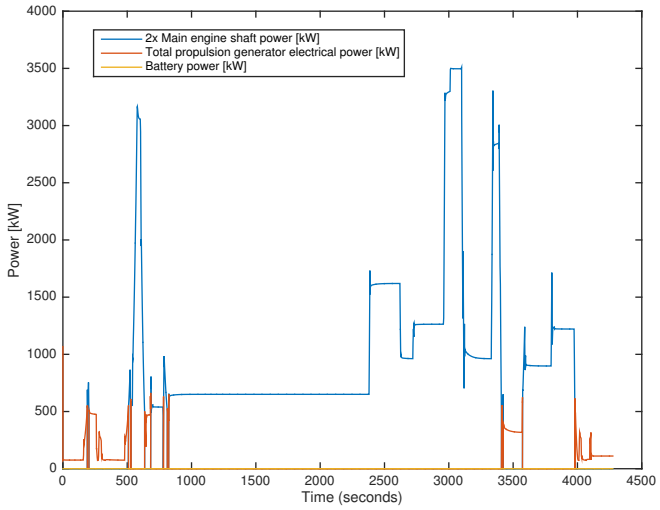

Figure 5.8: Power source active during the simulation for the reference system

5.2.2 Full hybrid

Simulation results for the full hybrid are seen in table 5.4. The total installed battery capacity is 240 kWh as seen in table 5.2. In the user interface of the control, the pure electric, diesel-electric and main engine enable options are selected. No battery charging is activated since it is assumed that the battery is only charged on shore in this simulation case. The switching loads for each component is set to 100%, which means that each component is used to its maximum capacity before switching to the next power level. No boost functionality is enabled for this simulation case.

Table 5.4: Results full hybrid

Full hybrid	
Total fuel consumption	110.4 kg
Battery depletion	7.29%
Battery depletion	17.5 kWh
Run time total:	4275 sec
Main engine:	76.5%
Gen-set:	8.30%
Battery electric:	15.20%

In figure 5.9 the power produced by the different components at each time of the simulation is shown. In low power the battery is delivering the power (yellow), at medium power the gen-set is producing power (red), and at high power the main engines is producing the propulsion power (blue).

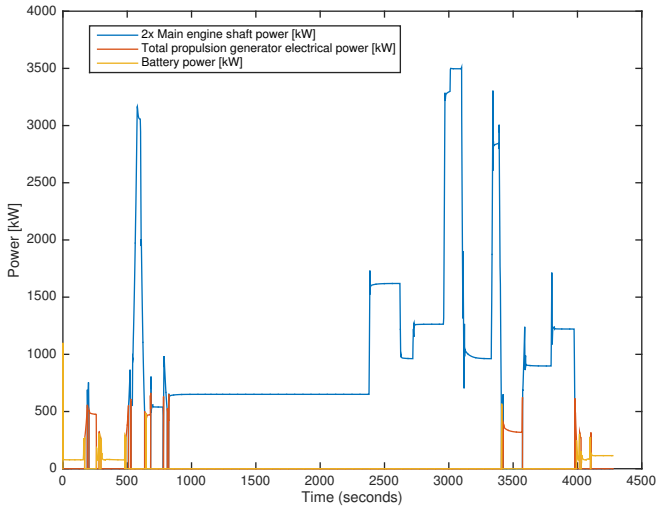

Figure 5.9: Power source active during the simulation

5.2.3 Battery hybrid

The battery hybrid test is done with the same components as previous simulation. The main difference is the battery. The change is done by configuring the battery file *Var_Battery.m* in the components folder. In the MATLAB file the variable *Battery.C_pack* is changed to 500 kWh, see table 5.2 for the other components. In the user interface the pure electric, and main engine enable options are selected. The reason why the battery is used much more in this case is due to the C-rating of the battery. The C-rating indicates the maximum safe continuous discharge rate of battery pack. In all test results the C-rating is set to 1 for the batteries. This means that the batteries can be discharged at 1 times the installed battery capacity. Now when introducing a larger battery the capacity is increased and therefore the discharge time. The system can discharge more often and for higher powers.

For the battery hybrid two simulation setup cases is tested. In the first case the on-board charging and boost is disabled. The switch loads are set to 100% for all components. When the main engine is running the shaft generator is used to provide electrical power for the hotel load.

In the second case, the battery is used as much as possible. This is done by running the vessel battery-electric at low speed and then when the main engine is turned on, using the battery to provide power for the hotel load and boosting with the shaft motors at high engine power.

In figure 5.10, below, the power produced during the simulation is shown. The blue line shows where the power is produced by the two main engines. The yellow line indicates where the battery is delivering the power. Since there are no gen-sets in this system the red line, which is gen-set power is always zero.

Table 5.5: Results battery hybrid - Case 1

Battery hybrid - Case 1	
Total fuel consumption	101.6 kg
Battery depletion	11.10%
Battery depletion	55.5 kWh
Run time total:	4275 sec
Main engine:	76.5%
Gen-set:	0.0%
Battery electric:	23.50%

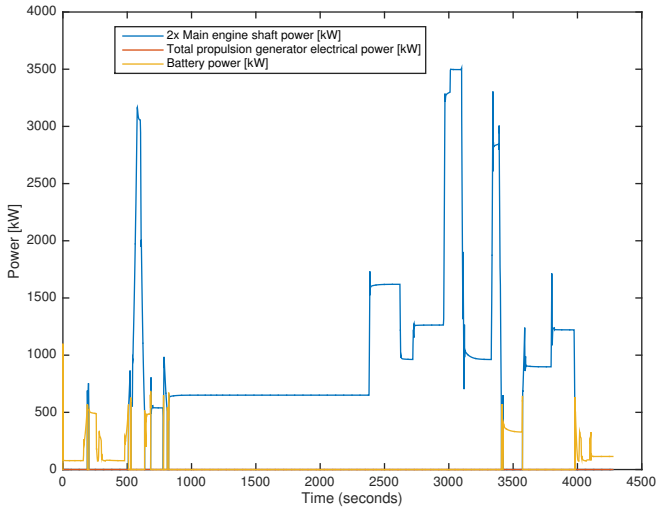

Figure 5.10: Power source active during the simulation - Case 1

In the second case, which is the same system but operated differently, the battery is depleted more and the fuel consumption is lower the data is seen in table 5.6. In figure 5.11 the power from the different components is shown. The interesting part in this figure, which differs from the first simulation case, is the battery power which is constantly delivering power for the hotel load and also for boosting when the main engine power is high.

Table 5.6: Results battery hybrid - Case 2

Battery hybrid - Case 2	
Total fuel consumption	93.4 kg
Battery depletion	26.3%
Battery depletion	131.6 kWh
Run time total:	4275 sec
Main engine:	76.5%
Gen-set:	0.0%
Battery electric:	23.50%

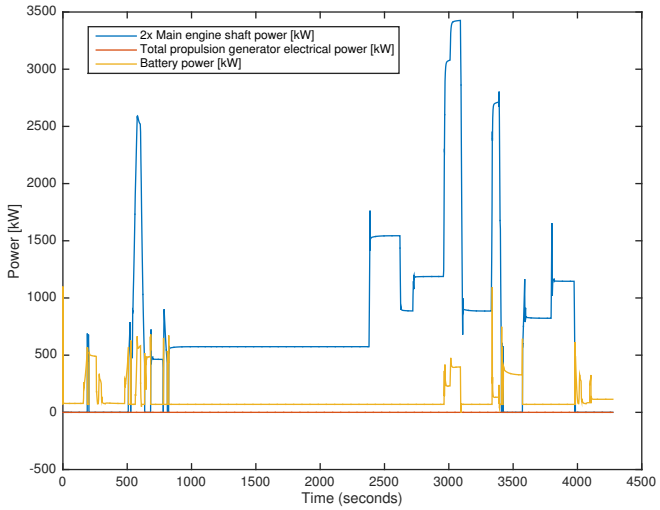

Figure 5.11: Power source active during the simulation - Case 2

5.2.4 Diesel-electric hybrid

Simulation results for the diesel electric hybrid are seen in table 5.7. The total installed battery capacity is 100 kWh as seen in table 5.2. In the user interface of the control, the pure electric, diesel-electric and main engine enable options are selected. In this system the option for two gen-sets is selected to make the control use both gen-sets. No battery charging is activated since it is assumed that the battery is only charged on shore in this simulation case. The switching loads for each component is set to 100%, which means that each component is used to its maximum capacity before switching to the next power level. No boost functionality is enabled for this simulation case.
In figure 5.12 the power produced by the different components at each time of the simulation is shown. In low power the battery is delivering the power (yellow), at medium power the both gen-set is producing power (red), and at high power the main engines is producing the propulsion power (blue).

Table 5.7: Diesel electric hybrid

Diesel electric hybrid	
Total fuel consumption	113.4 kg
Battery depletion	9.24%
Battery depletion	9.2 kWh
Run time total:	4275 sec
Main engine:	76.5%
Gen-set:	16.70%
Battery electric:	9.90%

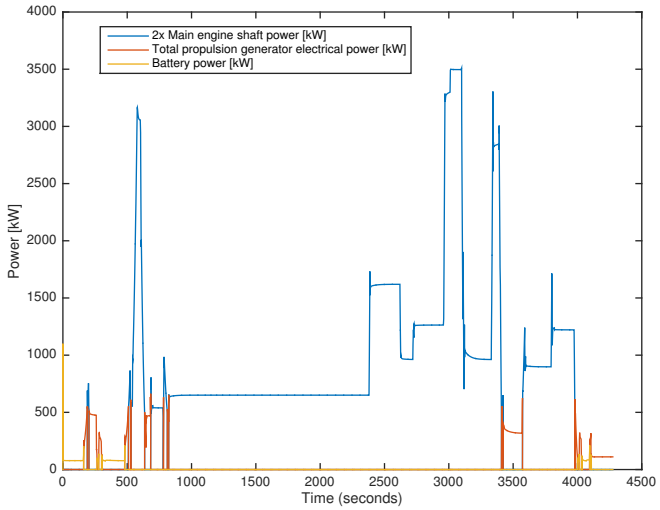

Figure 5.12: Power source active during the simulation, (Total gen-set power includes both gen-set 1 and gen-set 2)

5.2.5 Battery hybrid with large battery and electrical motor

In this simulation case the setup is similar to the battery hybrid system in section 5.2.3, but the battery capacity is increased to 650kWh which gives a battery maximum power of 650kW. The electric motors are also assumed to be larger and have a total power capacity of 650kW.
In figure 5.13, below, the power produced during the simulation is shown. The blue line shows where the power is produced by the two main engines. The yellow line indicates where the battery is delivering the power. Since there are no gen-sets in this system the red line, which is gen-set power is always zero.

Table 5.8: Battery hybrid large battery

Large battery hybrid	
Total fuel consumption	67.6 kg
Battery depletion	59.95%
Battery depletion	389.7 kWh
Run time total:	4275 sec
Main engine:	36.4%
Gen-set:	0.0%
Battery electric:	63.60%

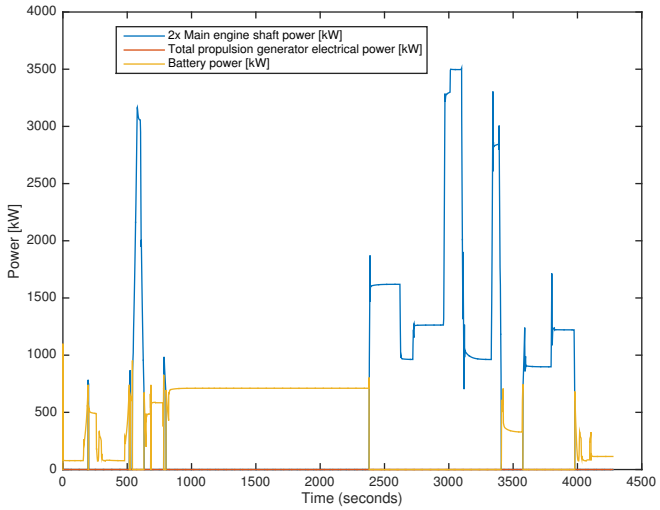

Figure 5.13: Power source active during the simulation

5.3 Result summary for systems

In this section the results are summarised for all the systems. The summarised data is divided in two tables. In table 5.9 the fuel consumption for each system is shown. The table states the consumption in the order the results are presented above.

Table 5.9: Summary energy consumption

Reference system	
Total fuel consumption	116.6 kg
Battery depletion	N/A
Battery depletion	N/A
Fuel cons. reduction to ref.	N/A
Full hybrid	
Total fuel consumption	110.4 kg
Battery depletion	7.29%
Battery depletion	17.5 kWh
Fuel cons. reduction to ref.	5%
Battery hybrid Case 1	
Total fuel consumption	101.6 kg
Battery depletion	11.10%
Battery depletion	55.5 kWh
Fuel cons. reduction to ref.	13%
Battery hybrid Case 2	
Total fuel consumption	93.4 kg
Battery depletion	26.3%
Battery depletion	131.6 kWh
Fuel cons. reduction to ref.	20%
Diesel electric hybrid	
Total fuel consumption	113.4 kg
Battery depletion	9.24%
Battery depletion	9.2 kWh
Fuel cons. reduction to ref.	3%
Large battery hybrid	
Total fuel consumption	67.6 kg
Battery depletion	59.95%
Battery depletion	389.7 kWh
Fuel cons. reduction to ref.	42%

In table 5.10 the run times are shown in the same manner.

Table 5.10: Summary run time

Run time total:	4275 sec
Full hybrid	
Main engine:	76.5%
Gen-set:	8.30%
Battery electric:	15.20%
Battery hybrid Case 1	
Main engine:	76.5%
Gen-set:	0.0%
Battery electric:	23.50%
Battery hybrid Case 2	
Main engine:	76.5%
Gen-set:	0.0%
Battery electric:	23.50%
Diesel electric hybrid	
Main engine:	76.5%
Gen-set:	16.70%
Battery electric:	9.90%
Large battery hybrid	
Main engine:	36.4%
Gen-set:	0.0%
Battery electric:	63.60%

In figure 5.14 the fuel consumption in kilograms is visualized with a bar diagram. Each bar represents the consumption for each system.

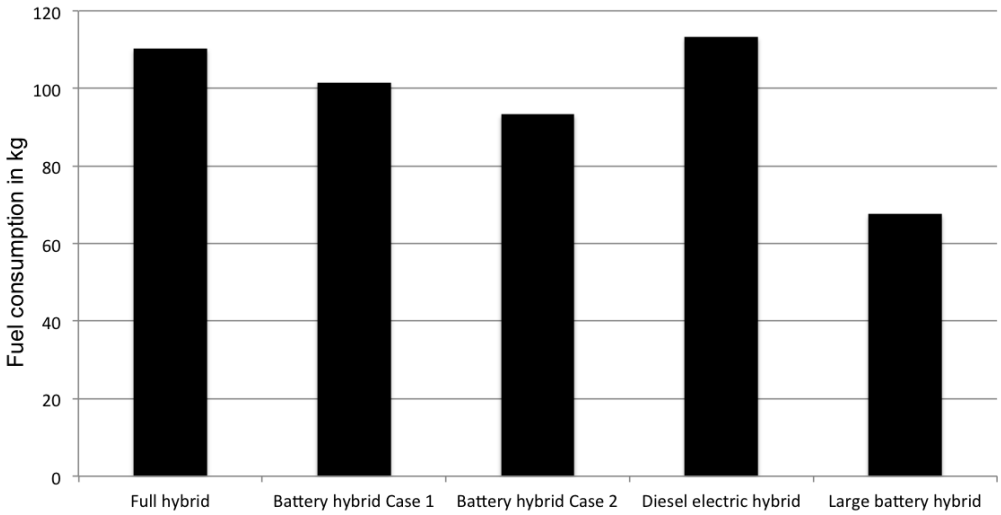

Figure 5.14: Fuel consumption

To be noted is that the batteries state of charge is not back at 100% where it started. Which means energy has been depleted from the battery and this is not corrected for in the fuel consumption. To visualize the energy consumption from the battery see figure 5.15.

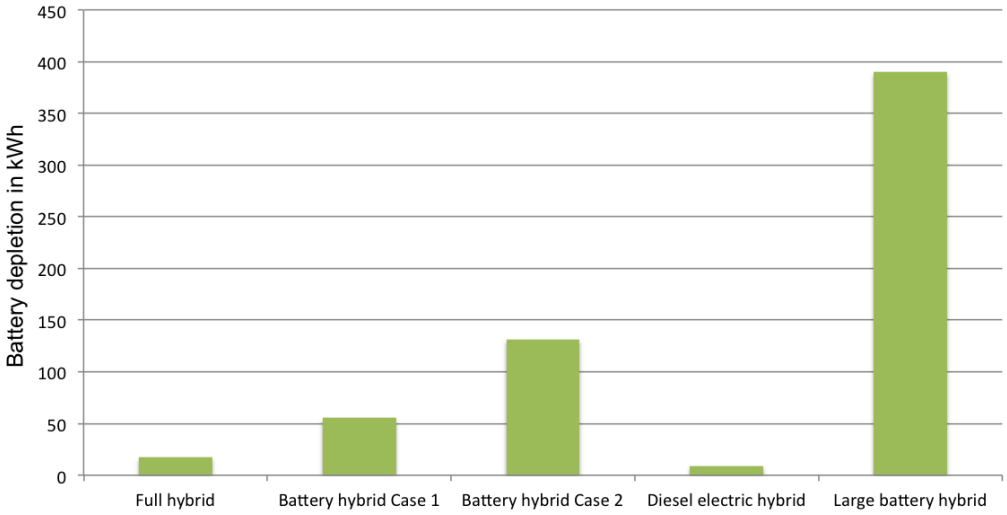

Figure 5.15: Battery consumption

6
Discussion

In this chapter the results of the work and method is discussed. Did the result impose any improvements, or was the existing model good enough. In what aspects is the new model better, in what areas is the old model already good enough? Where can further work be done and why is this important. These questions will be discussed with the results from the thesis as base.

6.1 Method discussion

The method used to obtain the results was quite time consuming in the beginning of the work. On the other hand it gave a deep knowledge about the model and the parts affecting the control performance. The method to get the desired results was quite straightforward when the control was finished. We configured the control to match each system intended to evaluate, and ran the simulation while extracting the data we set out to analyse like fuel consumption and run time. Furthermore the results of this thesis will be discussed in a broader perspective. How can the result potentially increase the use of hybrid tugs in the future if the modelling part of the development is made easier?

6.2 Flexible control performance

This section focuses on the improvements of the flexible control and its limits. The intended use of the flexible control is as a tool for development of new hybrid propulsion systems. By being able to simulate the performance of a complex system, a propulsion system tailored to the application can be developed quickly. Since the systems can be operated in several different ways, these models can also be used to find a good way to operate the system quickly. To evaluate a new system, the flexible control in combination with a library of component models, such as different main engines, gen-sets, battery packs and vessel models etc. can be used to quickly set-up a model and run various simulations.

6.2.1 The control interface

If the control should be of any use for the engineers at Damen it has to be easy to use. This was one of the control requirements stated in section 3.4, control requirements. The original control received from Damen had a control without any

GUI. In the case that the engineer is unfamiliar with Simulink, the environment can be somewhat difficult to work with. To make changes was even more complicated. In the original control the changes had to be made "by hand". By dragging and dropping the different connections to each component, the correct input and output needed to be satisfied with the right type of data and structure. All this would make the work very time consuming, even for someone familiar with Simulink and the model.

With the new control the engineer still needs to know some basics in Simulink. But to make the changes between a battery hybrid to a full hybrid for example can be done easily with a button click in the graphical user interface. From the perspective of someone working on modelling hybrid tugs of many different set ups the new control interface makes it more easy and understandable, even with less knowledge about Simulink. Although the control is now easy to use to be able to understand the outputs from the model MATLAB knowledge is imperative. Moreover the new control can be copied. This results in that a user can copy the whole control box and past it into another model. For this to work properly the control should be pasted in to a model with similar characteristics. The characteristics needed for the control to work are: a binary signal system and similar components. If the new system needs fewer outputs the excessive outputs can be left unused.

6.2.2 Flexibility and robustness

As seen in the method chapter 3 issues with the original control was found. The biggest issues was removed with the new control. The issue were that it could only control a specific model, it was not flexible enough. In other cases the issues was found to be insignificant, such as the short spikes most likely due to numerical problems with the model, and not the control, as seen in figure 4.1. Since the effect of these was considered small we left them unchanged. The robustness of the model is judged by how much the operation cycles can be changed without the model crashing. When running tests on the model many different operational cycles was input to the model. The model has the expected limits for speed and bollard pull but the model cannot work for a operational cycle starting from a value other than 0. Most of the limits are in the model itself and not in the control. In cases when the control makes the whole model unstable is when the consumed power is crossing over a limit in the control multiple times. When the limit is crossed another component is engaged, lets say the main engines, and the previous components are shut off. The uneven power output makes the power consumed bounce up and down around this limit making the model less stable. To prevent this to occur different approaches was tested. The implemented one and most successful one was to have a filter in the control making it less prone to giving a uneven signal as output. Although a solution is implemented there is surely improvements to be made.

The choice of using the current power as control signal is one of the reasons the unstable behaviour appears. It is also not very likely that the current power usage cannot be used as control input in a real vessel, but for the modelling purpose it

works well. One of the reasons for using power output as the control signal is that it combines the power needed to drive the vessel and to produce the amount of bollard pull needed in a single signal. To refine the control system even more, additional signals could be used, such as also incorporating the torque and bollard pull in the control. These ideas have been raised during the later stages of the work and not tested in practice but it could be a good approach for future work. We believe that when the control system get even more input signals into it the choices of how to control the model can be made more stable and better. The solution derived in this work is sufficient for the three cases focused on and for the give operational cycle. To make the model even more robust the addition of more input signal would achieve this.

The control is flexible but have a finite number of components that it can control as max. In the final case shown in this thesis the control can manage up to 2 gen-sets, one battery, two shaft generators and two main engines. If for example one wants a system with 4 gen-sets installed the control box needs to be modified. If these additional gen-sets are to be controlled individually the control needs to have two additional outputs.

6.2.3 Application of the flexible control in automated simulations

Since the use of the flexible control gives possibility to use the same control with several system layouts with different parameters, a possible application is to use it to automate simulations of many different system setups. Ranking of different systems and optimization of system parameters could then be made much more easily then if the control had to be manually adapted to all systems. The main challenge when doing this is to find a systematic way to evaluate the performance of the system since the model can produce very much output data and the system characteristics can vary a lot. A clear question about exactly how the system should behave in a certain operational profile and a system for evaluation of the system performance must be constructed to be able to draw conclusions of which system is most suitable for a certain application.

As the flexible control system is built, there is no problem to convert it from using the graphical user interface to setting the parameters automatically in a separate script. The only condition that has to be met is that the control should have the necessary parameters in the MATLAB workspace at the beginning of a new simulation. During the work we discussed using a generic algorithm in MATLAB to find a minimum for a function. This function could be of the fuel consumption for example. We did not have enough time or knowledge to follow up on this so in the end we opted for the more systematic method of having a set number of systems and analysing them and draw conclusions from the results.

6.2.4 Battery charging functionality

The needs for on board battery-charging functionality in the control is very much dependent on the need of the user and what behaviour of the system that is desired. There is charging functionality implemented, both for charging the battery when the SOC-level reaches a certain lower limit and a charging the battery when the main engine is running at low load.

It has shown that the need for charging is very much dependent of the operational profile. In the tested cases, where the tug has a quite short operational time and the components is sized so that they can only be used for a limited amount of time, the battery pack will not be depleted to a level where it needs to be recharged. In this cases the most economical way to operate the system is to recharge the battery on shore after the operation.

6.3 Hybrid propulsion system performance

In this section the potential of using a hybrid propulsion system for this tugboat application is discussed. How the hybrid system can be used to reduce the fuel consumption for this kind of vessel, but also how it could be operated and how the battery pack influences the weight of the vessel.

6.3.1 Reduction of the fuel consumption of a tug with a hybrid propulsion system

In this section a summary of all the research papers with similar topics as ours will be discussed. The differences and similarities and what conclusion their research have made. A major similarity in the marine based research papers are that the papers are basing their motivation on the fact that regulators in the marine sector (IMO, ECA, etc.) has introduced or will introduce more stringent limits for emissions in the near future. This forces ship owners and designers of new vessels to search for alternative solution for ship propulsion systems. Our results show potential for a reduction of fuel consumption for tugs. In previous research [8] a reduction of fuel consumption by 5 - 7 % is seen, specially for harbour tugs as in our case. The difference with our thesis is that the research paper is more focused on power train architecture and the incorporation of gas turbines.

In other papers [9] results points to a 20% decrease of CO_2 emissions, this has not been investigate in our thesis but with less run time of the engines the reduction of emission is inevitable. In a more general research paper [10] the same potential is found, to be noted is that this covers more conventional ships. Citing the paper "This study has shown that installing hybrid power technology on-board dry bulk ships can save fuel up to 1.27 million USD (at the price of 520\$/$tonne$) per vessel and per year, assuming that the 60% of the time ship sails in laden and 40% in ballast condition.". The difference with our thesis and this paper is the scope; they

have focused on conventional ships. The savings are from using more efficient way of operating the large engines, on more preferable loads. This the main focus in this paper. We discussed this part briefly in section 2.3.

A very important factor is the difference in power between the electric and main engine system, since the electric motors is very small in comparison to the main engines they can not be used to change the load point of the main engine in a significant way. On the other hand there is some operational cases where the vessel need very low energy and the main engines can than be shut of completely, this combined with charging of the battery on shore can significantly reduce the fuel consumption. When sizing the designer should be aware of the operational cycle of the tug to accurately size components. After sizing and configuring the control for the designed tug results can be analysed and presented for the customer. For the future owner of a hybrid tug it has to be economical to chose this tug before a conventional tug. Since the hybrid tug impose a higher initial cost on the tug owner, it has to recoup its cost over the lifetime of the tug. In our studies we first mainly focused on reducing the fuel consumption, but by sizing batteries and electrical motors in a sufficient manner a lower run time of the main engines can be achieved. This will in general, for the owner of the tug, reduce the periodical cost of owning a tug, by increasing the period between planned maintenance. But if the tug is used in a very broad way, meaning it has a variety of operational cycles this process can be a unnecessary. And in that case the owner might try to change the tugs operations to more be in line with the systems installed on board.

6.3.2 Increased electrical power consumption and on shore battery charging

When the fuel consumption of the vessel is decreased, the electricity consumption on shore is increased. This power has to be charged into the battery when the vessel is berthed. The simulations have shown that the battery can be depleted with up to almost 390kWh of electrical power. When charging, some more losses will occur, this is not taken into account in the simulations. In the simulations the battery is always assumed to be 100% charged at the beginning of the simulation.

To be able to make a comparison and properly evaluate the impact of the hybrid system, more circumstances considering the operation of the vessel must be known. To assess the difference in environmental impact when a part of the energy used by the vessel is shifted from using diesel fuel to using electricity from the grid, the source of the electricity must be taken into account. The environmental impact of the electric power differs depending on in which country the vessel is operating in and what power company that supplies the electric power. In some, favourable cases, the power may be supplied by wind or waterpower, under worse conditions the power on shore may be produced by a diesel generator. The actual environmental benefits of using a hybrid system is therefor very much depending on the local conditions where the tug is operated.

6.3.3 Application of the hybrid system

The simulations in this thesis are done for a very specific case and is not valid for all kind of smaller vessels in a variety of operational cases. The different systems are good for different applications and operational profiles. In this case the recharging of the battery is mainly done on shore. The systems with a battery with large power capacity show the highest reduction in the direct fuel consumption. For another application that may be different since the battery has another main purpose, for example to act as a quick power source for filling gaps in the power supply when switching between generators etc.

6.3.4 Interaction between the propulsion system and the operation of the vessel

The analysis of the provided operational profile and the simulations of the system has shown that there is a very limited amount of time during the operation that the demanded power is low enough to be able to operate electrically with the three original proposals of hybrid system layouts.

To increase the use of electric propulsion the components has to be sized accordingly, as in system **D**, Larger battery hybrid, described is chapter 5. An alternative to doing this could be to change the operation of the vessel, by steaming slower or using less tow force. If requirements on transit speed and tow force are reduced, this could possibly be a good way to better utilize the hybrid system without investing a lot of money on expensive components. The transit speed will only affect the time the mission takes and is a question of planning the missions. The tow force may be more problematic to reduce since it is the main task of the vessel. But using slightly longer time in tow-mode can reduce the required tow force and may enable electric operation in some cases; this makes the efficiency of the system very much a decision of the captain of the vessel in daily operation. Proper communication from the technical system to operators, for example of when a increase throttle will cause a main engine start-up, is essential.

It is also very important that the mission of the tug is included in the development process since sizing of the components without considering the specific operation may cause the system performance to be much lower than necessary. The simulation model and the flexible control offer a great potential in tailoring the system to a specific mission in a early stage in the development process.

6.3.5 Weight and volume comparison battery versus gen-set

In the last result subsection 5.2.5 an additional layout is introduced in addition to the ones stated in our goals and given by Damen. The idea for this layout/sizing of components is first seen in section 3.7.1. When analysing the given operational cycle and energy demand of the vessel, a potential saving was found by increasing the battery capacity. During the set up of the tests a decision to test our "own" set up was made. Since the control is very flexible and easy to use this took no time at

all and gave interesting results as seen in the summary of results.

To evaluate this layout properly some attention was given to the fact that using a large battery instead of the two gen-sets will change both weight and volume. In a brief study see table 6.1 with public information from Corvus Energy [11] a manufacturer of marine batteries an estimation of weight and volume properties for the battery was done. For the estimation of the gen-set properties the manufacturer MTU's [12] product sheet was used. Note that the weight is dry weight of the gen-set.

Table 6.1: Comparison weight and volume properties

	Two gen-sets	**Battery system**
Weight	5200 kg	6820 kg
Volume	9.7 m^3	7.25 m^3

As seen in the table the battery system will have a negative impact on the lightweight of the vessel compared to the two gen-sets. On the other hand it will require less space in the machinery department due to the reduced volume. With the gen-sets assumed to run on the same fuel as the main engines additional fuel tanks are not needed. In stability concerns the batteries can be placed more flexible and in that way increase stability and manoeuvrability of the tug. Gen-sets are assumed to need a larger amount of spare parts in store than the batteries.

6.4 Implications in a broader perspective

In a broader perspective the result of the work could indirectly drive the hybridization of tugs a step forward. One consequence of a flexible control is a easier and faster research and development phase of a new built tug. Simulating the operation of a tug before investing in a new build gives valuable information for the company investing. This enables to test many different models/systems without having to put in a large amount of hours in changing the control for each simulation. The information would be surrounding what kind of consumption and wear of the different components could expect. In our case Damen already have invested in hybrid tugs, but other shipyards that are looking into the possibility would probably be interested in simulating the systems before production. Another perspective in the more general manner is that hopefully urban ports and in specifically the port operators in a few years start using these kind of hybrid solutions for their tugs. And in that way people living in the vicinity of the port area would experience a lower amount of noise and particle emission. While the tugs maintain high operability.

6.5 Future work

The work done has fulfilled our requirements but still improvements and additions can be done. Some of the things that we want to point out is summarised here.

There is much room for improving and adapting the charge-control part of the control to better suit the needs of the user. This is hard to do in a general way without knowing more about the specific system components, the operational profile and the desired system behaviour. The flexible control offers a good base platform for doing this since the charge control is implemented as a separate block that can be modified without interfering with the rest of the control-structure.

It would be interesting to see work surrounding a optimization routine. The control itself would work fine with the correct inputs. It would be interesting to see if a optimum battery size for a certain operation profile could be found. The model might need to be modified a bit to be more robust to ensure that it will not crash.

Other things that could be interested to investigate are the local emission reduction when implementing this on shore charging function of the tugs. And see how much impact it does, and where it make sense to use this kind of tugs. If the energy is produced in a "green" way or if its produced with a generator somewhere else then the original solution could be sufficient.

More detailed work on cost of the different parts in the system would also be interesting to have a estimation of the total cost to install all the battery power for example.

7
Conclusion

7.1 Conclusion of the performance of the flexible control

The flexible control has proven to work as intended in the test simulations presented in this thesis. Controls for the provided three systems can quick easy be set up in Simulink. The user interface that is included is simple but effective in configuring the system and setting necessary parameters. Even though the flexible control and user interface is working, it is not perfect and it is more of a prototype with potential to develop further. For further development additional functionality can be added, some functions improved and more control signals used. The battery recharging control may also be needed to work on further since there is no actual need for recharging in the reference case that has been used in the development process. The flexible control is designed as the needs of the thought user are interpreted but some changes will most probably be needed as it is being used in a real case.

7.2 Conclusion of the performance of the hybrid propulsion system

In the evaluated test case, with a harbour tug operating at short missions with possibility to recharge the batteries between the missions, the best way to operate the system is to discharge the batteries as much as possible during the operational cycle. This is done in the parts of the cycle when the load is low and the diesel engines can be shut of. All electricity demand, hotel load, can also be delivered from the batteries which eliminates the need of using the generators on board.

When the fuel consumption of the vessel is decreased, the electricity consumption on shore is increased. To be able to compare the total environmental impact one must look into the area where the vessel is operated and how the used electricity is produced there. As a mean of reducing the fuel consumption of the vessel and thus the local emissions where the vessel is operated, this type of hybridization has shown to have great potential, with a reduction of the fuel consumption of up to 42% compared with a reference case. All the evaluated systems is good for this application but the systems with larger battery packs (higher power capacity) show the best potential since the electrical component sizes is limiting the electric operation.

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A

Appendix I

DAMEN ASD TUG® 2810 HYBRID

"BERNARDUS"

GENERAL

YARD NUMBERS	512319
DELIVERY DATE	May 2014
BASIC FUNCTIONS	Towing, mooring and fire-fighting operations
CLASSIFICATION	Lloyd's Register ✠ 100 A1 Escort Tug [✠] LMC UMS IWS
FLAG	Dutch
OWNER	Sleepdienst B. Iskes & ZN B.V.

DIMENSIONS

LENGTH O.A.	28.67 m
BEAM O.A.	10.43 m
DEPTH AT SIDES	4.38 m
DRAUGHT AFT	5.15 m
DISPLACEMENT(APPROX.)	604 ton

TANK CAPACITIES

FUEL OIL	72.3 m^3
FRESH WATER	14.9 m^3
FOAM	6.5 m^3
LUBRICATION OIL	9.0 m^3
DIRTY OIL	3.1 m^3
SEWAGE	2.2 m^3
SLUDGE	3.1 m^3
BILGEWATER	5.1 m^3
UREA	6.4 m^3

PERFORMANCES

BOLLARD PULL AHEAD	60.2 ton
BOLLARD PULL ASTERN	55.3 ton
SPEED AHEAD MAIN ENGINES	13.4 knots
SPEED AHEAD GENERATOR	8.5 knots
SPEED AHEAD BATTERIES	4.0 knots (1 hour max.)
SPEED ASTERN MAIN ENGINES	13.0 knots

PROPULSION SYSTEM

MAIN DIESEL ENGINES	2x MTU 16V4000M63R
TOTAL DIESEL POWER	3680 bkW (4935 bhp) at 1600 rpm
PROPULSION GEN SET	1x MTU 12V 2000 M41B, 800 kVA, 440V-60Hz
EXHAUST GAS TREATMENT	DOC+DPF+SCR system, IMO Tier III compliant
BATTERY PACKS	2x 120 kWh
MAIN ELECTRIC ENGINES	2x ABB M3LP450 / 2x 230 bkW
AZIMUTH THRUSTERS	2x Rolls Royce US 205
PROPELLER DIAMETER	2400 mm
FORCED VENTILATION	55.000 m^3/hr

AUXILIARY EQUIPMENT

GENERAL GENERATOR SETS	1x Caterpillar C4.4, 107 kVA, 230/400 V – 50 Hz
BILGE PUMPS	2x Sterling AKHA 5101 each 20 m^3/hr
FUEL PUMPS	Sterling AKHA 4101 and AOHA 3101
COOLING SYSTEM	Box cooling + anti-growth system
PRESSURE SET	Freshwater Sterling HBK 111 / AOHA 1202
HYDRAULIC SYSTEM	One electrically driven auxiliary pump
FIFI PUMP	Jason 250 x 350 OGF, 1200 m^3/hr
FIFI MONITOR	2x 600 m^3/hr water, 2x 300 m^3/hr foam

DECK LAY-OUT

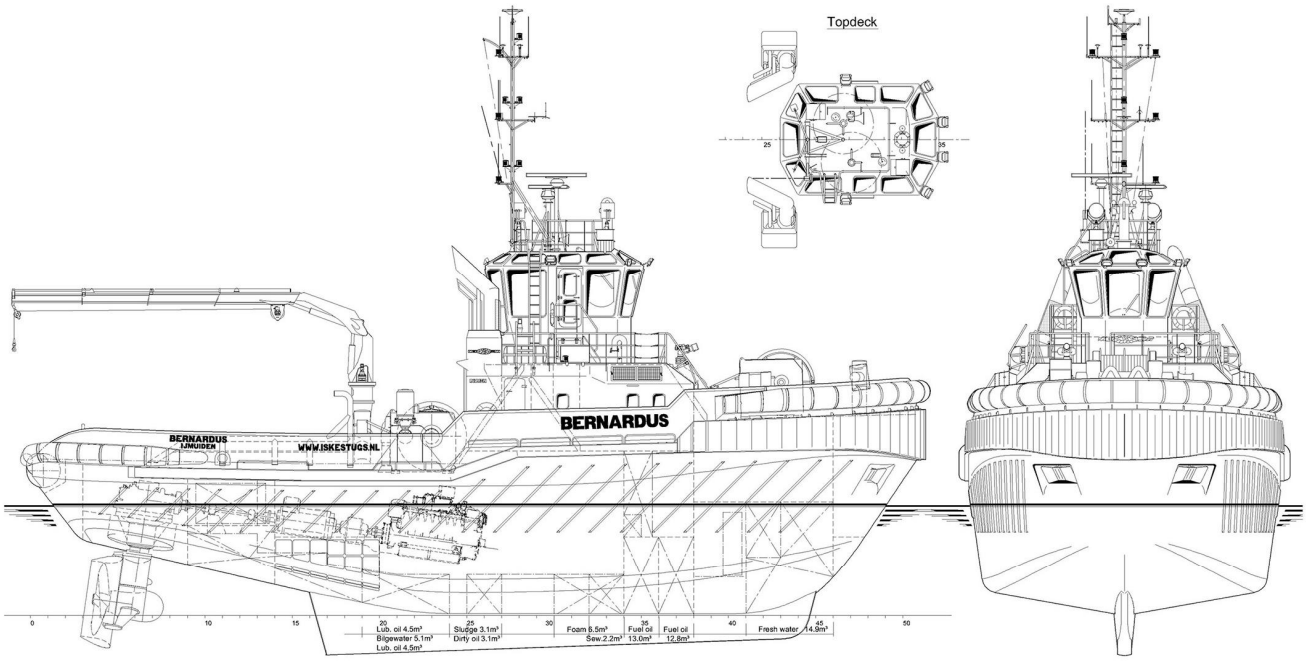
ANCHORS	2x 360 kg Pool (High Holding Power)
ANCHOR/TOWING WINCH	Electrically driven two speed winch with double drum and warping head, pull 35 ton at 9.1 m/min, slack rope speed up to 28 m/min, 150 ton brake
CAPSTAN	5 ton at 15 m/min. electrically driven
TOWING WINCH AFT	Electrically driven, two speed winch with double drum and spooling device, pull 35 ton at 9.0 m/min and 33 ton at 9.5 m/min, slack rope speed up to 27.0 m/min, 150 ton brake
TOWING PINS	MKB SWL 86 ton
FENDERING	D-fender at sides, cylinder fender at transom corners, cylinder and W-block bow fender with water spray

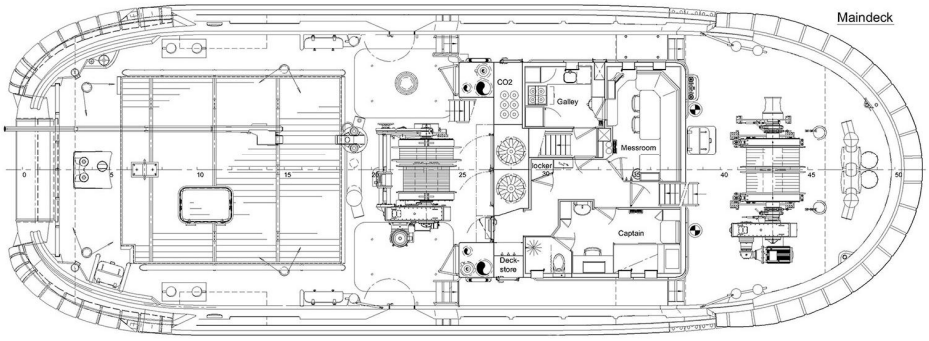
ACCOMMODATION

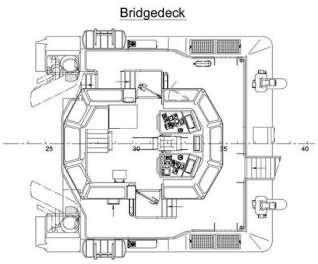
For 7 persons, insulated and finished with durable modern linings, acoustical ceiling in the wheelhouse, floating floors and air-conditioned. Captain's cabin, chief engineer's cabin, 2 double crew cabins, 1 single crew cabin, galley, mess/dayroom, dry store and sanitary facilities.

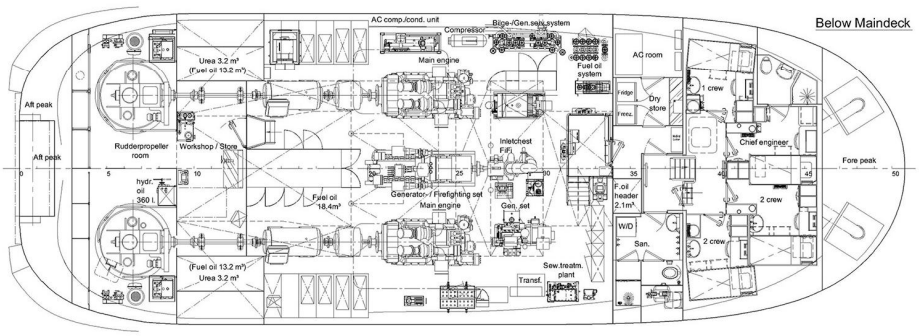
NAUTICAL AND COMMUNICATION EQUIPMENT

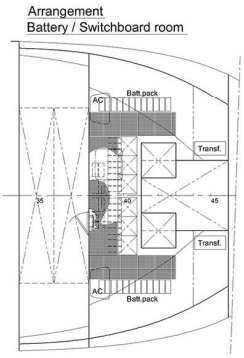
SEARCHLIGHT	2x Pesch 1000 W
RADAR SYSTEM	2x Furuno FAR-2117 with 19 inch screen
COMPASS	Magnetic Kotter
SATELLITE COMPASS	Furuno SC-50
AUTOPILOT	Simrad AP-50
GPS	Furuno GP-150
ECHOSOUNDER	Furuno FE-700
VHF RADIO TELEPHONE	2x Sailor 6222 (one with DSC)
VHF HANDHELD	2x Jotron TRON TR-20
NAVTEX	Furuno NX-700
AIS	Furuno FA-150
EPIRB	Jotron Tron 40S
SART	Jotron Tron Sart
SSB	Furuno FS-1575











DAMEN ASD TUG® 2810 HYBRID

"BERNARDUS"

DAMEN SHIPYARDS GORINCHEM

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