LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT

School of Energy Systems

Degree Programme in Electrical Engineering

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VERSATILE SIMULATION MODEL FOR DC DISTRIBUTED HYBRID VESSEL PARAMETER OPTIMIZATION

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ABSTRACT

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Versatile simulation model for DC distributed hybrid vessel parameter optimization

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M.Sc. Hanna Huppunen

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Electrification and digital tools are both on the rise. Digital tools can save time and resources, while for example hybrid and full electric marine vessels decrease operating costs and emissions in transport. These vessels require their power electronic devices to work perfectly in synchronization as a complete system, which requires careful parameterization of the equipment and control logic. The objective of this thesis is to create a simplified simulation model of a generic marine hybrid powertrain to be used in parameter testing. The minimum required parameters needed to parameterize the model to match a real-life vessel and a verification of the model's function are also needed.

The simulation model was made with Matlab and Simulink from MathWorks. The modelled system's layout is based on multiple existing Danfoss Editron projects, as the model would need to be usable for different set-ups. Existing simulation models and their components were used for guidance and as building blocks. The model's logic and rules are based on Danfoss Editron's internal instructions, manuals, and knowledge.

The final product is presented in sections. The simulation model contains genset models, an energy storage model, a load model, a power balance model, and a DC-link model. Input and output signals as well as relevant equations are given for each of these sections. Continuous testing was done throughout the development of the model, and the performance of the final version was verified by parameterizing it to match an existing vessel and comparing the model's output data to measured data. A list of minimum required parameters for setting up the model was constructed during the verification tests and these parameter lists are presented. Based on the relatively small errors between simulated and measured data, the model could be used in parameter and control logic testing in pre-commissioning. Further development could be done to include for example a PLC model, more precise diesel and battery models, more options for different control types, and more user interface functions.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto LUT
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Sähkötekniikan koulutusohjelma

Venla Holttinen

Muokattava simulaatiomalli DC-hybridilaivojen parametrien optimointiin

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Hakusanat: laivakäytöt, hybridi, DC-järjestelmä, simulaatiomalli, parametrit.

Maailma sähköistyy ja digitaaliset työkalut yleistyvät. Digitaalisilla työkaluilla voidaan säästää aikaa ja resursseja, kun taas esimerkiksi hybridi- ja täyssähkölaivat vähentävät käyttökustannuksia ja päästöjä liikenteessä. Tällaisissa laivoissa käytetyn tehoelektroniikan on muodostettava yhtenäisesti toimiva järjestelmä, mikä vaatii tarkkaa laitteiden ja ohjauslogiikan parametrisointia. Tämän työn tarkoituksena on tehdä yksinkertainen ja yleispätevä simulaatiomalli hybridilaivan sähköisestä voimansiirtojärjestelmästä parametritestaamista varten. Vähimmäisvaatimuksena olevat parametrit, joilla mallin saa parametrisoitua vastaamaan oikeaa laivaa, sekä mallin verifiointi vaaditaan myös.

Simulaatiomalli toteutettiin MathWorksin Matlabilla ja Simulinkillä. Simuloidun järjestelmän rakenne perustuu useaan Danfoss Editronin todelliseen projektiin, koska mallin pitää olla sovellettavissa erilaisiin järjestelmiin. Olemassa olevia simulaatiomalleja ja niiden osia käytettiin työssä sekä suuntaohjeina että varsinaisina komponentteina. Mallin logiikka ja säännöt pohjautuvat Danfoss Editronin sisäisiin ohjeisiin, manuaaleihin ja tietoihin.

Lopputulos esitellään osissa. Simulaatiossa on generaattori-, energiavarasto-, kuorma-, tehotasapaino- sekä DC-linkkimallit. Jokaiselle osiolle esitetään sisään- ja ulostulosignaalit sekä olennaiset yhtälöt. Mallia testattiin jatkuvasti sen kehityksen aikana ja lopullinen versio verifioitiin parametrisoimalla se vastaamaan olemassa olevaa laivaa ja vertaamalla mallin antamaa dataa mitattuun dataan. Mallin valmistelussa tarvitut olennaisimmat parametrit listattiin verifiointiprosessin aikana ja nämä listat esitellään työssä. Simuloidun ja mitatun datan suhteellisten pienten eroavaisuuksien perusteella tämän työn aikana rakennettu simulaatiomalli soveltuu kätettäväksi käyttöönottoa edeltävissä parametri- ja ohjauslogiikkatesteissä. Jatkokehitysvaiheissa malliin voitaisiin esimerkiksi lisätä PLC-malli, tarkemmat diesel- ja akkumallit, enemmän ohjauslogiikkavaihtoehtoja, sekä kehittää käyttöliittymää.

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Venla Holttinen
Lappeenranta, January 2022

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SYMBOLS AND ABBREVIATIONS

Symbols

C	Capacitance
Cap	Capacity
E	Energy
I	Current
J	Moment of inertia
K	Gain
N	Number (of)
n	Speed
P	Power
R	Resistance
s	Laplace variable
SOC	State of charge
T	Torque
t	Time
U	Voltage
α	Angular acceleration
Δ	Change
τ	Time constant
ω	Angular speed

Units

A	Ampere
Ah	Ampere hour
°C	Celsius degree
F	Farad
K	Kelvin
kg	Kilogram
m	Metre
Nm	Newton-metre
pc	Percent
pu	Per-unit
rpm	Revolutions Per Minute
rad	Radian
s	Second
V	Volt
W	Watt
Wh	Watt-hour
Ω	Ohm

Abbreviations

AC	Alternating Current
BMS	Battery Management System
CAN	Controller Area Network
CSV	Comma-separated values
DC	Direct Current
DCDC	DC-to-DC
DP	Dynamic Positioning
ES	Energy Storage
G	Generator
GI	Generator Inverter
genset	Diesel, generator, and inverter(s)
HAT	Harbour Acceptance Tests
HV	High Voltage
ICE	Internal Combustion Engine
LNG	Liquefied Natural Gas
LV	Low Voltage
M	Motor
OC	Overcurrent
OM	Operation Mode
OV	Overvoltage
OVC	Overvoltage Controller
P	Propulsion
PI	Proportional Integral
PLC	Programmable Logic Controller
PWM	Pulse-Width Modulation
SAT	Sea Acceptance Tests
SLD	Single-Line Diagram
SoC	State of Charge
SRPM	Synchronous Reluctance assisted Permanent Magnet
T	Thruster
UPS	Uninterruptible Power Supply
UV	Undervoltage
UVC	Undervoltage Controller

Subindices

1	Previous value
2	New/current value
AC	Alternating Current
batt	Battery
cell	Battery cell
chrg	Charging

DC	Direct Current/DC-link
DCDC	DCDC converter
diesel	Diesel
disch	Discharging
error	Error, difference
gen	Generator
genset	Generator and diesel/shaft
GI	Generator Inverter
i	Integral
int	Internal
load	Load
max	Maximum
mech	Mechanical
min	Minimum
nom	Nominal
oc	Open-circuit
p	Proportional
par	Parallel
PI	Proportional Integral controller
ref	Reference
ref used	Final, used reference value
ser	Series
start	Starting value
sys	System
UDC	DC-link voltage

1 INTRODUCTION

The electrification of travel and transport is booming, as new technologies are being developed and interest in energy efficiency grows. In marine vessels this trend manifests itself in diesel-electric, hybrid, and full electric power systems. The growing demand for on-board energy storages for hybrid and full electric applications can be seen from the 2021 ship order book in Figure 1.1.

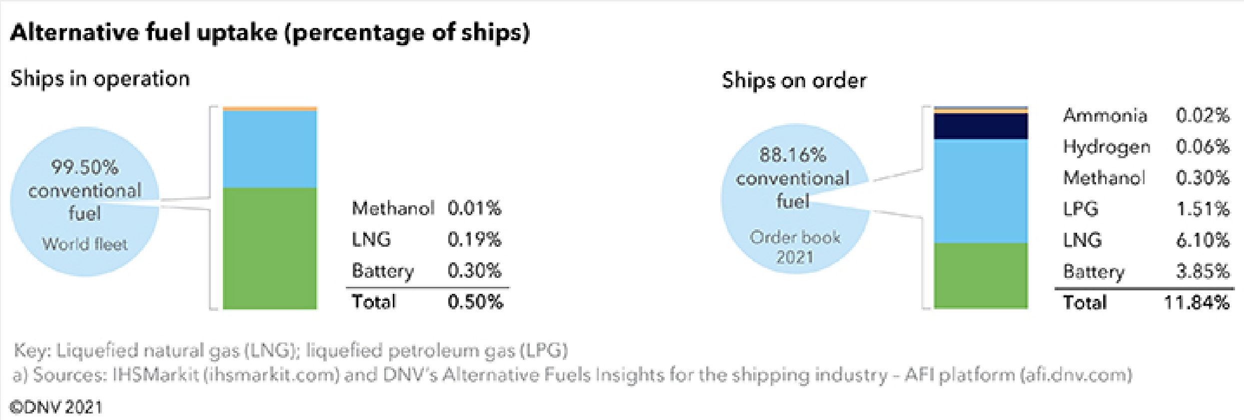

Figure 1.1. Alternatives for conventional fuels are gaining popularity, as can be seen from the 2021 orders collected by DNV. Compared to existing vessels, new ship orders have more variety of alternative energy sources and a larger number of vessels utilizing them. Among other emerging sources, the popularity of batteries is also on the rise. [1]

One of the possible reasons behind this trend is the decrease in operational costs, which hybrid and full electric systems can bring. As presented in Figure 1.2, full electric and diesel electric systems are estimated to be more cost effective solutions than a traditional diesel system in the long run in one example application. This particular full electric ferry has also reported 85 % energy efficiency from grid to propeller, describing it over twice as high compared to a diesel ferry's efficiency from tank to propeller. Savings in carbon dioxide emissions are calculated to be 2520 tonnes in a year. [2]

1.1 Marine hybrid system characteristics

Hybrid and full electric marine vessels can roughly be divided into alternating current (AC) and direct current (DC) systems, from which the latter has started gaining more popularity after a long time of AC being the standard solution. Both have their pros and cons, DC's advantages include not having to worry about frequency control or harmonic distortion. This improves the power quality,

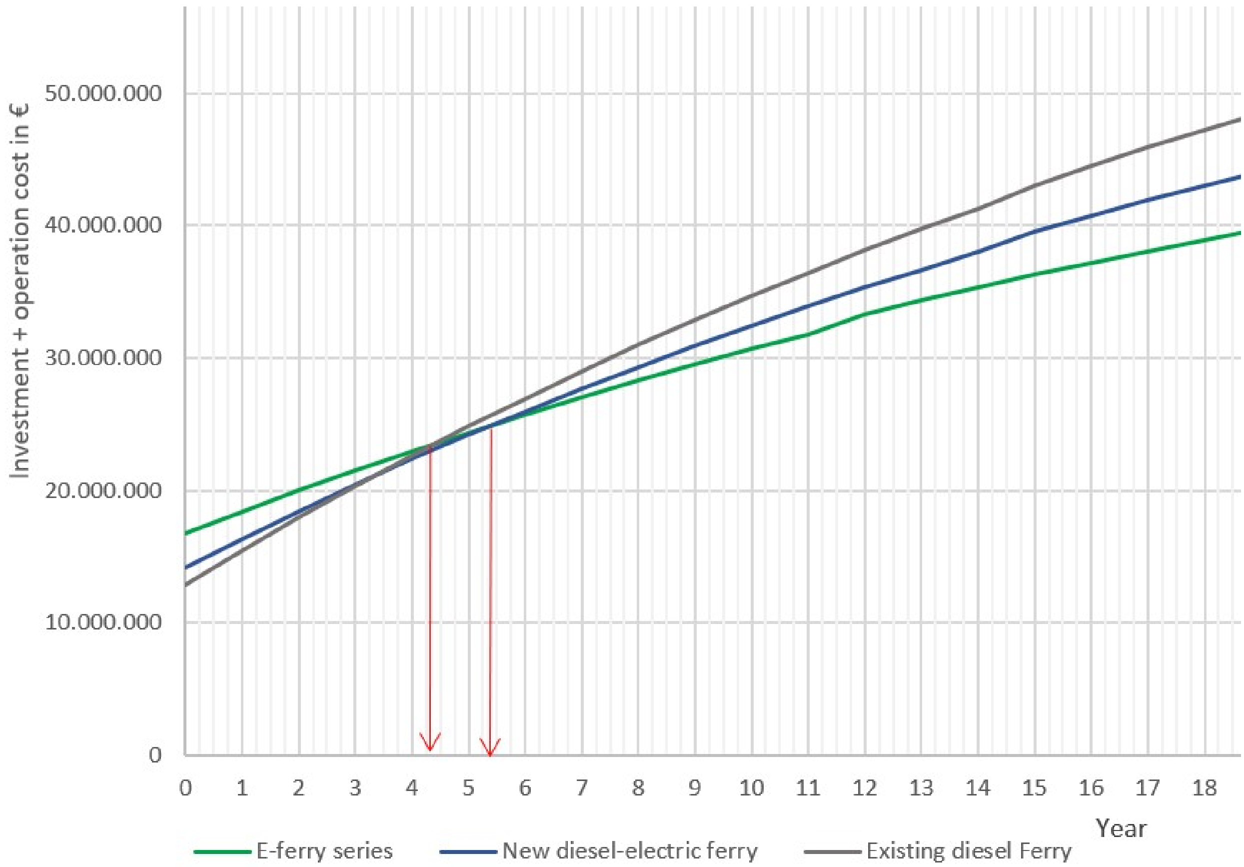

Figure 1.2. Even though the initial investment for a diesel-electric or hybrid vessel is higher compared to a diesel ferry, the operational costs are estimated to be lower over the course of time for this ferry application. [2]

but also makes it easier to control multiple generators and loads as their power electronics don't interfere with each other. From a fuel economy viewpoint, having the freedom to run generators at variable speed means having the generators and diesels adjust to the instantaneous power demand. DC systems end up being lighter since they don't need as many filters and transformers, and not needing to take reactive power into account when dimensioning cables also helps. Having a DC-link reduces complexity when connecting energy storages (e.g. batteries and supercapacitors) to the system, because they store energy in DC. [3]

Optimizing the system to its full potential can reduce the fuel consumption, emissions, and need for service, as the equipment run in optimal points. Even though fine-tuning can be done on board with the real system, ship building is a time-critical and expensive business and anything short of mandatory will not be added to the commissioning schedule. As digital tools are also on the rise, testing different parameter sets beforehand would be possible with an accurate enough simulation model. This would also allow to test difficult and unwanted situations in a safe manner.

Danfoss Editron delivers hybrid and full electric marine systems as a part of their portfolio and mission to lead the electrification movement. The electric machines, power electronic devices, control logic, and software in these systems are also manufactured and developed by them, which makes fine-tuning the system easier and more coherent.

1.2 Objectives and delimitations

The main objective of this thesis is to create a hybrid vessel simulation model for equipment parameterization and control optimization purposes. The model is based on Danfoss Editron's generic system layout and not on any existing vessel to allow versatile testing and reuse in coming projects. This will also include editable input parameters for each simulation run. This idea is very close to a digital twin.

The simulation model is intended for pre-commissioning use, especially for fine tuning the parameters before acceptance tests. The emphasis is on preparation for harbour acceptance tests (HAT) and sea trials, which usually concentrate on system stability and failure handling. The third and final step in commissioning are the sea acceptance tests (SAT), at which point the system should already be quite stable. Producer priorities should be able to be explored through the final simulation model. In practice this would mean giving consumers vital or non-vital labels depending on their function, to allow testing of different failure scenarios.

The research questions of this thesis are based on these above-mentioned requirements:

- Is it possible to create a realistically working marine hybrid system simulation model that could be used in equipment parameter testing without complex electrical or mechanical models?
- What are the minimum requirements for such a model and its parameters to have them match a real system within reasonable accuracy and with reasonable effort?
- Can this model be verified to function realistically?

Although the model is intended for optimization use, no real-system optimization will be done in this thesis. Tests like crash stop are not included in this version since they would require additional functions in the model. The effect of weather is also excluded, and if needed, it could be addressed by adding wave oscillation into the load model to simulate heavy seas, since that is how the hybrid system would see it. System cooling is assumed to be working and no thermal models are included. The responsibility of designing the cooling loop falls on the shipyard, but the equipment's thermal limits and performance should always be taken into account. Some electrical phenomena within power electronics are left out or simulated by averaging their values to keep the model as light and simple as possible, but also due to limited time and resources. Electric machine field-weakening was also deemed too rare in the inspected marine systems to be included. This simulation and its results also don't take into account or comment on how the captain should ultimately sail their ship.

1.3 Research methods and resources

Matlab Simulink by MathWorks was chosen as the platform for this project. Matlab provides a textual programming and calculating interface, while Simulink allows the developer to present models in a graphical way with model blocks. The visual presentation of the model was one of the key factors when making the decision, as it would help the user navigate the model. Seeing how the blocks are connected with signals gives a more concrete view on how different operations and phenomena affect other parts of the simulation. Matlab M-file provides a clean way of listing the simulation model parameters and adding comments for the user. The two parts play well together and are easy to install and start using at the same time, especially with MathWorks' comprehensive block library and article base.

Existing public simulation models were assumed to be scarce, since these are company proprietary projects. Leaning too heavily on ready-made models or components could also bring more problems than quick solutions, since they might be too set-up specific or detailed. Nonetheless, existing models should be searched and evaluated before starting to work on any of the blocks or modules. MathWorks' block library is one of the available sources.

The simulation model verification was chosen to be done against real measured data from an existing marine system. This comparison vessel would not affect the basic model composition as this should be a general model, but instead the model should be adaptable to the vessel. This would allow the testing of model versatility and adaptability, but also show how realistic the simulation results are.

1.4 Structure of thesis

Specifications of research are first defined, these include the requirements and limits given by different parties, as well as a foundation from existing works. Used unit conversion terms are also clarified.

The simulation model structure and necessary background information for components are explained. Input and output signals of the simulated modules are given.

Testing and verification methods are presented. Final system testing results are shared and examined. The benefits of this thesis are considered with the objectives and requirements, and how well they were met.

2 SPECIFICATIONS OF RESEARCH

This project follows a general software development process closest to a waterfall: after defining the needs and resources a draft of the system is made, after which development, testing, and verification follow. Knowing what kind of an environment the hybrid system operates in real life helps to define model limits and interfaces. This research concentrates on marine vessels with DC distributed diesel hybrid systems of around 1 MW and under 1000 V_{DC}, meaning that these are low voltage systems. The DC system is modelled with a common DC-link to which all producers and consumers are connected. An example of a generic DC system is shown in Figure 2.1.

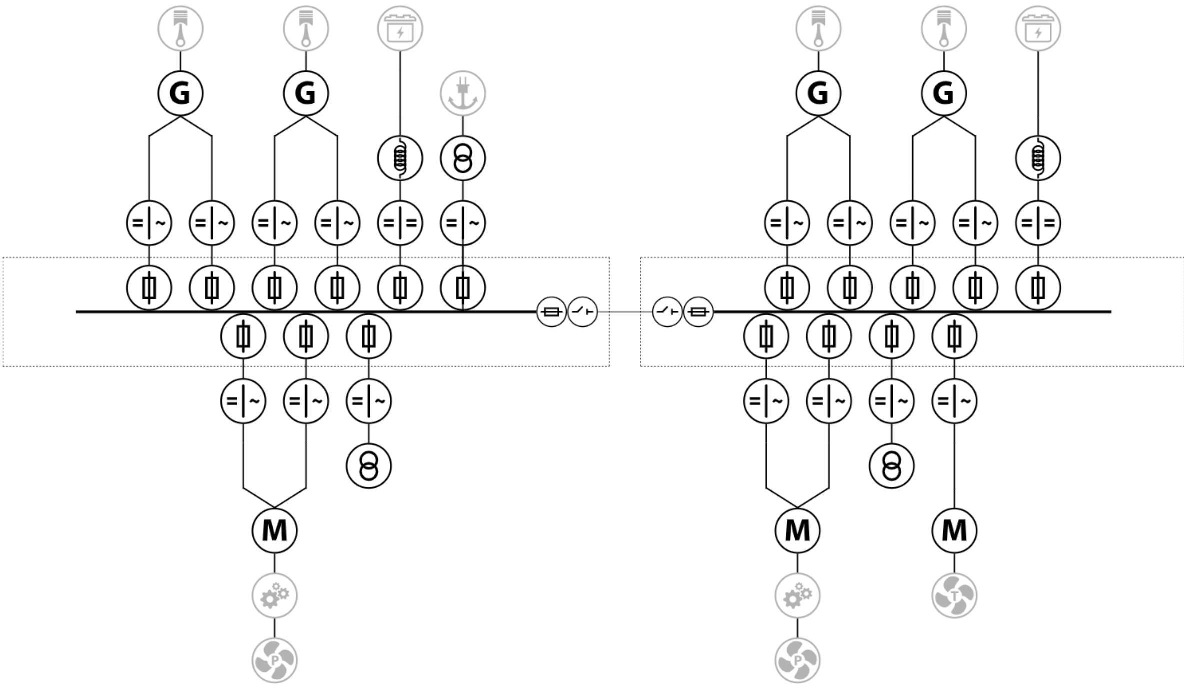

Figure 2.1. A single-line diagram of a generic DC system. The DC-link is represented by a vertical line split in two: the fuses and switches enable the splitting of the DC-link. Splitting the link into two independent systems creates system redundancy, which is discussed further in Chapter 2.4. Producers are shown above the DC-link and consumers below it. G signifies generator and M motor. The generators are mechanically connected to ICEs, and in this example they are dual generators with two AC-to-DC inverters each. P signifies propulsion and T thruster in the motor models, both types have DC-to-AC inverters running them. On the producer side, battery systems are also included with DCDC converters and coil boxes. A shore connection meant for battery charging is shown with a transformer and AC-to-DC inverter. On the consumer side two hotel inverters are marked with DC-to-AC inverters and transformers. There are also fuses between each component and the DC-link. This diagram was created with the Danfoss Editron Electrification Tools eCalculator and is presented with the permission of Danfoss Editron, no further use of this image or design is permitted. [4]

The single-line diagram (SLD) shown in Figure 2.1 has a DC-link represented by a vertical line with all producers above it and consumers below. This representation isn't based on any real vessel, it merely has the usual amount of the most common components. Vessel refers to small ships and ferries in this thesis. Producers are limited to diesel generator sets (genset) in the hybrid power plant and batteries in the energy storage (ES) system. Each genset comprises one internal combustion engine (ICE), one electric generator, and one, two or four generator inverters (GI) depending on whether the generator is a single, dual or quadruple model. Gensets are assumed to have identical specifications and set-ups. ES consists of a battery system and DC-to-DC (DCDC) converters. This simulation model supports having only one battery string per DCDC. Consumers are limited to electric propulsion motors, electric thruster motors, and hotel inverters which feed the vessel's AC grid. Any quantities or powers are not predetermined.

2.1 Existing works

System control algorithm and fine-tuning is usually considered a competitive advantage for a company, so coming by a published and complete model, or even sections of it, is not common. Novelty of digital twins also limits the amount of available data. Comparative studies can still be made.

Batteries have an important role in vessel control optimization. They can be utilized as spinning reserves and also in peak shaving, load levelling, enhanced dynamic performance and ride through, strategic loading, and zero emission operation. Spinning reserve means taking one genset offline and having the battery ready to respond to load peaks with a very short response time. Peak shaving happens when the generators are kept at a constant and optimal operation point and sudden consumption peaks are handled by the batteries. Load levelling is closely related to peak shaving, but instead of keeping the diesels at a strict operation point, the load variations are only smoothed out a bit. Enhanced dynamic performance, also known as rapid load response, takes care of transients during diesel acceleration, while enhanced ride through provides uninterruptible power supply (UPS) as a short time backup. Strategic loading helps to optimize the diesel usage, for example by absorbing excess energy. Zero emission operation or silent sailing means having the whole system powered from the batteries for a limited duration, which allows clean and quiet operation in harbour. All of these can be added to system logic individually or together. Their benefits range from more stable operation to reduced genset online time, which alone means less fuel consumption, emissions, and maintenance. [5, 6]

A battery study by ABB, in which a hybrid icebreaker's simulation model results were compared to measured operational data, shows support for these claims. The studied vessel was equipped with four liquefied natural gas (LNG) gensets and one battery bank, which was intended especially for peak shaving, enhanced dynamic performance and spinning reserve use. No control optimization was included. The measured maximum genset load peak was at 20 MW, and the load variation was notable. According to their simulation results, a 4.5 MWh battery would stabilize and optimize the engine operation and reduce the number of gensets online. The reduction potential for one day was estimated at 12 % for fuel, 12 % for carbon-dioxide, 32 % for methane, and 46 % for engine hours. [5]

Considering the actual benefits of dynamic battery usage in advance is important, as Godjevac et al. prove in their study. Two different diesel-electric vessels that use dynamic positioning (DP) were simulated, and fuel saving possibilities were investigated with both a spinning reserve as well as peak shaving and load levelling. With their specific vessels, spinning reserve looked promising with 15-20 % fuel saving possibilities, while peak shaving results were basically 0 %. [7]

As for the actual simulation, Lana et al. have compiled process instructions for creating a model. To start with, the operating profile and possible loads of the vessel under investigation should be known. Fundamental knowledge of the system architecture and individual components' specifications enables analysing the efficiencies of the power plant. Together with the vessel characteristics (such as dimensions, capacity, and intended use) this will allow reflection of different hybrid system implementations and the changes they would bring compared to the old system. On top of these, the different operation modes (OM), their contents, and rules for each operational scenario should be known. These initial data will have to be adjusted, possibly several times iteratively, after the simulation model has been developed enough to be tested and compared to real-life measurements. [8]

2.2 Customer requirements

Shipyards usually emphasize safety, blackout prevention, diesel protection and fuel consumption reduction in system design, to name a few. Safety aspects and blackouts are considered in Chapters 2.3 and 2.4. Diesel protection is simulated by not allowing any power to be fed back to the diesels, which is often the situation in real life as well. Fuel consumption is given as one of the output values and reducing it is possible through control algorithm optimization. Optimization is not included in this thesis.

Customer requirements also include having different OMs in the model. These OMs are dictated by the vessel control system, which is the highest level of control in the vessel right after the captain. OMs have to follow different standards depending on the situation they are made for.

2.3 Model limitations and risk management

The simulation model's runtime is negligible since this model will only be used in development work and not on board of any vessel. Communication delays are not included in the model even though they do affect the physical systems, which should be remembered when looking at the results. This means that the simulated system can react faster than the physical comparison system, especially if the simulation time step is shorter than the communication delays in a physical system. Currents were excluded from the genset model, both the electric generator's internal currents as well as the inverter's limits. Including them would have required electric models on top of the basic physics models, which would have made the model a lot more complex. Pulse-width modulation (PWM) signals were also naturally excluded, as no power electronic switches were simulated.

Power outages leave a vessel without its main power supply and much of its functions and are sometimes hard to recover from as they can damage equipment. These situations are usually called blackouts or dead ship in marine terms. Blackout is more often used to describe a power outage when the hybrid system might still be able to recover by itself, whereas dead ship is a more severe condition that requires an emergency generator to be started. As dead ship recovery uses equipment outside of the hybrid system, it is not included in the scope of this thesis. Blackouts in the powertrain and AC grid are caused by redundancy failures or power imbalance: when a power plant and its control don't react fast enough to a consumption peak, the voltage in a DC-link drops below system's nominal value and equipment either goes to a fault state or disconnects from the DC-link. Blackout detection is one of the fundamental functions of the simulation model and it is implementation is described in Chapter 3.3.

Fire on board would be one of the most dangerous and life-threatening situations that there is for marine vessels. Taking into account the added dangers of burning batteries, it's crucial to follow limits and operation condition requirements for each piece of equipment. Having a perfect model even with the devices' limits isn't possible, and thus fire prevention actions are left to physical installations and checks. Electrical faults caused by bad practices such as insufficient grounding or disregard for electromagnetic compatibility are also naturally left out of this work's scope.

2.4 Standards

Classification societies oversee and approve a ship's design and function before the vessel is handed over to the owner. Classification of a vessel is not required, instead it's always requested by the customer or their insurance company. Out of the many existing societies, DNV (previously known as DNV GL, Det Norske Veritas and Germanischer Lloyd) is chosen as the example in this thesis because of their recognizability and freely available documents. Their rules for DC system marine vessels are used to define limits in the simulation model. Exceptions to these rules can be accepted by a society in certain cases but for the accuracy of this study the strictest possible guidelines are used.

Redundancy is a significant safety factor on board. DNV defines redundancy as "the ability to maintain or restore a function when one failure has occurred." Redundancy can be achieved through duplicate equipment, known as component redundancy, or by dividing the system into two or more parts which can be used jointly or independently, known as system redundancy. Duplicated systems' output power shouldn't drop below 40 % of nominal power during a single active component failure, or component redundancy will need to be added. Other rules regarding redundancy and steady operation include having at least one independently driven piece of equipment if there are multiple ones with identical function, and not interrupting the propulsion or steering in any way during an operation mode switch. Redundancy shouldn't be confused with reliability or repairable equipment, as the former means not having any failures within a specific time window, and the latter requires manual labour to fix the issue instead of relying to the system design and automation. [9]

The main functions of a ship should always have redundancy. Producers and consumers included in main functions are power generation (including transformers and power electronics), propulsion, steering, drainage, bilge pumping, ballasting, and anchoring [10]. These main functions need to restore their function in 10 minutes (redundancy type 2), unless they support the propulsion system or them being off-line or partly in operation can cause a safety hazard, in which case they should resume normal function in 30 seconds (redundancy type 1) [9]. In a case of component failure, power generation system should be able to continue providing power to safe propulsion operation, largest essential electric motor start-up, functions like heating and ventilation, duplicated essential auxiliary equipment like pumps, and dead ship recovery [11].

For blackouts DNV instructs that "at least two generator sets, connected to separate main busbar sections, shall be arranged with systems for starting in a blackout situation." Severe situations like blackouts should absolutely be avoided. The system should give out warnings and automatically decrease some of the loads if it detects a power imbalance and there's a risk of overload. This is known as load shedding, load reduction, or load tripping. Normally only non-essential consumers can be tripped, but if there are already two or more generators needed to meet the power demand, also essential consumers can be tripped. However, normal operation should never cause a warning, even during manoeuvring or rough weather conditions. Warnings for regenerated power are not needed in any operation modes. [9, 11]

Different OMs can have their own requirements. For example during manoeuvring, usually in a harbour area, generators can't be shut down based on any load factors. There should be at least one genset online per each main busbar while manoeuvring, and if a generator is detached from the system for some reason, load shedding is allowed and even expected if safe manoeuvring could otherwise be compromised. [11]

DC ships are often classified with case by case limits, because most written rules concentrate solely on AC systems. For example, in contrast to AC systems, continuous operation limits are used for inverters instead of strict percentage limits. Producers don't need to be detached in undervoltage (UV) situations, since unlike AC systems, DC systems don't need to worry about frequency. Detachment in such a situation would only lead to a blackout. Stopping the inverter's modulation, known as tripping, is usually enough for most faults. Selected faults can also cause the isolators on the AC side of the inverters to open. With overvoltage (OV) a warning is given when the DC-link voltage (U_{DC}) OV controllers (OVC) are activated. If the U_{DC} OVC is not enough and the voltage keeps rising, an OV trip is triggered. The limits for these are given by the customer. If the inverter flags a current limit, it's a signal that the device is nearing overcurrent (OC) or overload. Similarly warnings for UV or OV situations in the DC-link are given as UV or OV flags. In a DC UV situation load is shed by UV controller (UVC) and in a very grave situation with UV trips. In an OC situation an OC trip is activated. The diesel engine's torque limit controls operation, so as long as the electric generator is correctly dimensioned and parameterized the system should never end up in a situation where the generator is being overloaded.

It's important to note that all hybrid vessel systems should be designed right from the beginning to follow the standards and rules given by the inspecting classification society and this simulation only checks some of the input parameters for any discrepancies. The responsibility can also be given to the higher level control system or ship automation, in which case the hybrid power system only follows commands and doesn't comment on whether they are in accordance with the rules or not.

2.5 Unit conversions

No two ships are alike. Comparing and controlling diverse machines and power electronics is hard when the power levels differ noticeably. Scaling the physical values of interchangeable devices to fit a common range lets the user make more intuitive control choices, as for example steps for the speed reference value have the same effect despite the changes in the rpm reading not being equal. This also allows the use of a single control model in multiple projects. Scaling of the physical values allows the model to support multiple different configurations, and it can be done by per-unit (pu) conversions or percent scaling (pc). The latter is used in this simulation.

Pc values are scaled by setting the nominal value of the physical quantity as 100 %, which is marked as 1 pc. The pc value for any given physical quantity is then calculated with Equation 1. [12]

$$\text{pc value} = \frac{\text{physical value}}{\text{nominal value}}. \tag{1}$$

It should be noted that the pc values of the the genset variables are mostly bound to the nominal values of the generator. Similar nominal base values are unavailable in the ES system and thus pc values can't be utilized there.

3 SIMULATION MODEL

The finished product consists of a Matlab M-file and a Simulink model. The M-file is used for parameterization and fetching data, while the Simulink file contains the actual logic and calculations of the model. Powertrain Blockset toolbox was used on top of the usual Simulink and Simulink Coder components.

The Simulink model is made of simulation blocks which communicate with each other via signals. The model has multiple nested layers: the high-level presentation shows only the main purpose of each section, for example "genset", while the lowest levels consist mainly of logical and mathematical operations, like unit conversions and acceleration calculations. The amount of layers and subsystems depends on the complexity of each section and block, and is not universally the same for all parts of the model. A global fixed time step is used. This is of course a simplification of the real-life situation, in which the equipment have their own control algorithms instead of one common model and communicate via controller area network, known as CAN bus.

The high-level sections and their main components in this simulation are

- DC-link model,
- Energy storage model (battery, battery management system, DCDC),
- Load model and power balance calculation,
- Genset model (generator, generator inverters, internal combustion engine), and
- Verification graphs.

This model has one DC-link model with no splitting options and thus also only one load model, multiple verification graphs, one energy storage model with one battery string for one DCDC converter, and five genset models with one ICE, one generator, and four generator inverters per each set. This layout is presented in Figure 3.1. The system configuration was decided based on existing Danfoss Editron marine systems, and the number of active sections in this first version was set to match the verification data background. The user can choose the number of active gensets by setting the genset start ramp times as they wish.

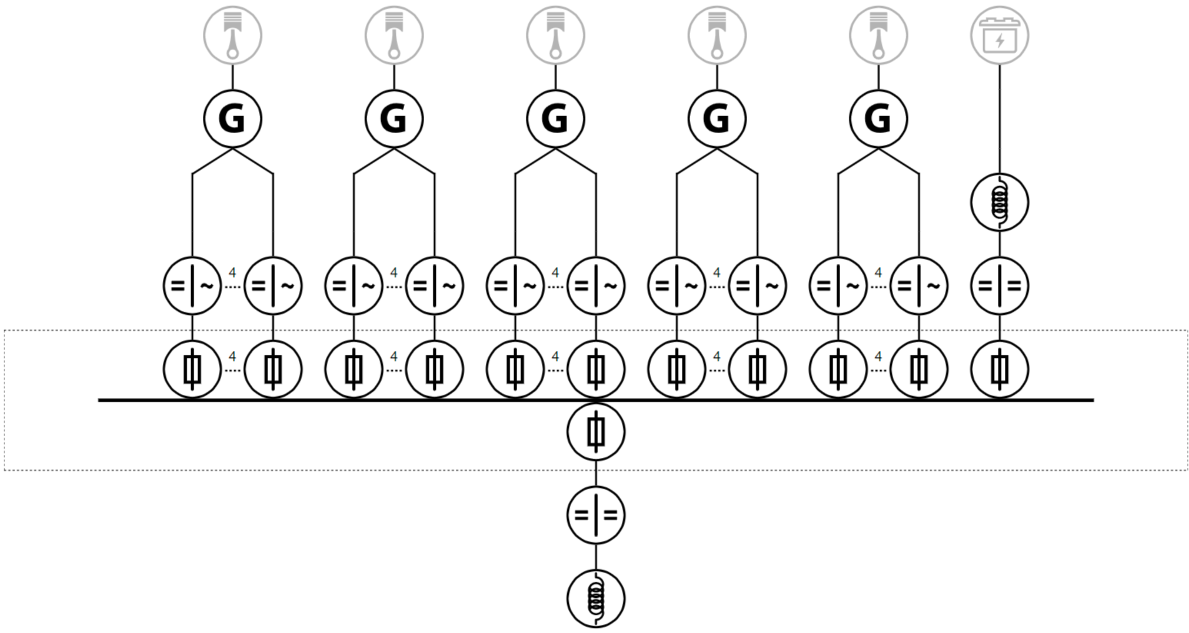

Figure 3.1. An SLD of the simulated DC system. The DC-link is represented by a vertical line. The five gensets and one ES are presented at the top, and a DC-load is shown at the bottom of the figure. Four inverters are shown for each generator to signify a quadruple set-up, but the user can also decide to use only one or two inverters for single and dual set-ups respectively. Fuses are presented as they would be in a real physical system, but they are not simulated. A similar fault to blowing a fuse could be simulated by stepping down one or more inverters' run command. This diagram was created with the Danfoss Editron Electrification Tools eCalculator and is presented with the permission of Danfoss Editron, no further use of this image or design is permitted. [4]

The system model includes multiple feedback signals. To prevent an algebraic loop where the simulation would try to call or use a value that has been calculated on that same simulation step, Simulink Unit Delay blocks are used as recommended by MathWorks [13]. They delay the signal by one simulation time step and require a starting value from the M-file parameters. These and other starting values should be taken from measurement data if available, or iterated with a couple of test runs to see where a specific signal settles.

High-level presentation of the simulation model with the above-mentioned sections can be seen in Figure 3.2. This is based on the presentation Lana et al. produced in their research [8].

Even though DCDCs and GIs are very similar, there are differences in the way they and their modules operate as a part of the system. Both the batteries and the converters communicate directly

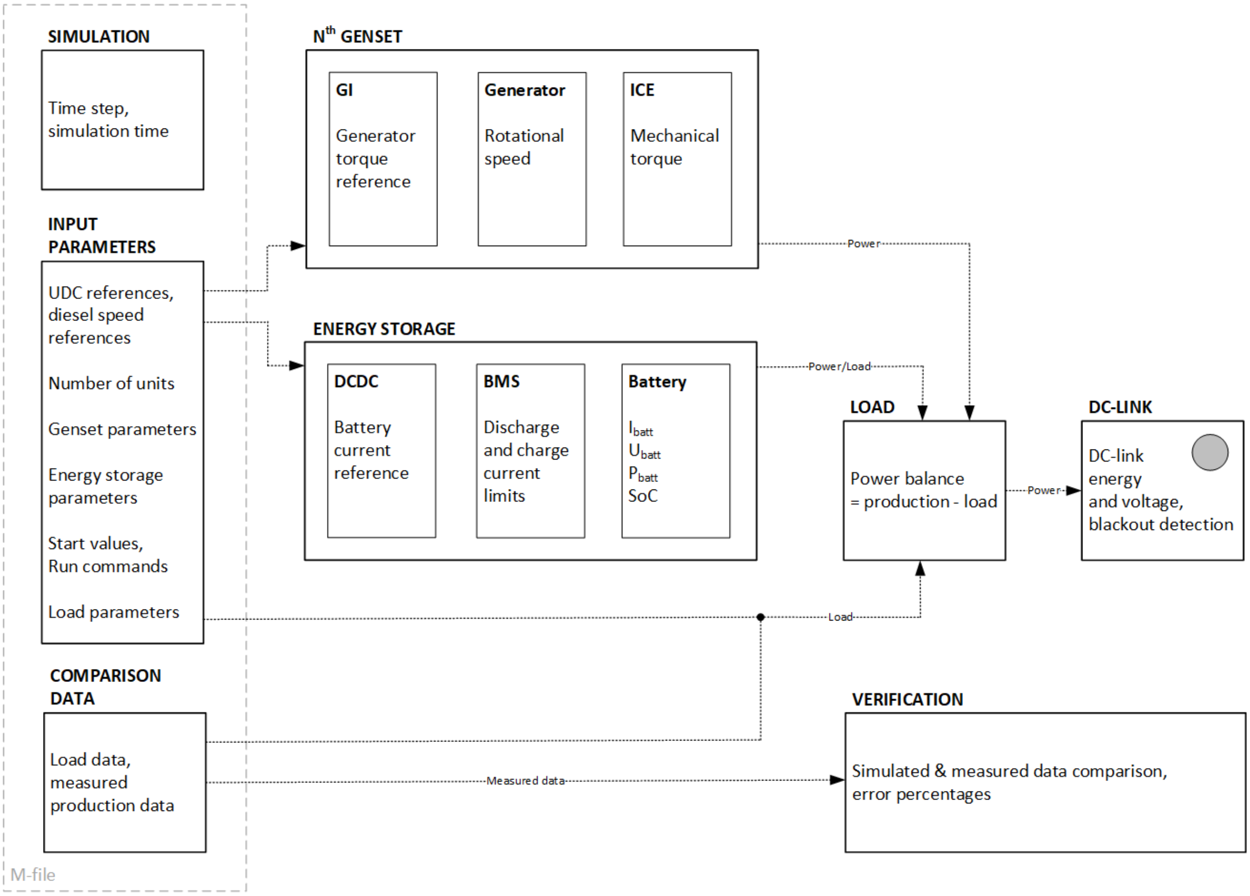

Figure 3.2. Simplified presentation of the simulation model, with only one of the identical gensets shown. M-file functions are separated from the Simulink model with a dashed line. Each block has a list of its most important output signals to show what information they provide for the whole model. Only few signals between sections are shown for readability purposes: input parameters are used to parameterize the production and load to match a specific vessel, production power is calculated for each genset and energy storage unit and then added to the power balance calculation, power balance defines how the DC-link voltage behaves, load data can come from measurements or it can be parameterized, and finally measured data can be used for model verification. Feedback loops are not shown.

with the programmable logic controller (PLC) in charge of the whole hybrid system, whereas generators don't have their own controllers and all information to and fro goes through the GIs. Another important difference to note is that the DCDC converters have high voltage (HV) and low voltage (LV) sides to manage, while the generator inverters are only concerned with their output voltage regulation to keep the U_{DC} at reference value. This leads the DCDC converters to have OVCs and UVCs for both voltage levels.

All the producers are controlled by U_{DC} references set in the parameters. Drooping of this reference allows different producers to communicate and balance the load between each other. This is discussed more in Chapter 3.4.3.

3.1 Simulation model control and input parameters

Due to Danfoss Editron's highly versatile systems, the simulation model must have modifiable input parameters to define the specific system set-up for each simulation run. Simulation minimum input parameters are listed in the appendix. The signal names used in the appendix tables match the simulation model's signal naming, but more commonly known variable symbols will be used elsewhere in this thesis. Minimum required control parameters for the simulated system are given in Table 1 in the appendix.

The simulation's runtime is determined by the user and is given in seconds in the M-file. The only exception to the runtime can be made by the blackout stop described in Chapter 3.3. In this thesis the longest presented simulation time is 180 seconds, since system stability can be observed reliably enough at that point – the most crucial moments are during transients and while running against limiters. The fixed simulation step size can also be changed by the user, but it should be noted that if the step size is smaller than the parameterized integration times of the proportional integral (PI) controllers, the model will not function properly. Other general control parameters are the U_{DC} references given to the control devices: GIs and DCDCs.

3.2 Load model

The power balance of a system means that ideally the production would be equal to the system load. This balance can be slightly off during load changes or when producers are started or shut down, but it should be able to regain itself and keep the offset relatively close to zero. The simulated load model sums the produced power and subtracts load from it to find the power balance error of the system, as shown in Figure 3.3. From the perspective of the DC-link model, positive offset means the link gets charged and negative means it gets discharged. Gensets always produce positive power but a battery can act as both producer and consumer, changing the sign of its power.

The load can be given as a constant value or it can be uploaded from a comma-separated values (CSV) file as measured data, the user has the option to switch between these in the parameters. A constant load was found most useful when tuning the different Simulink blocks' operating logic, since any changes in signals were caused only by the model. System tuning and parameter testing,

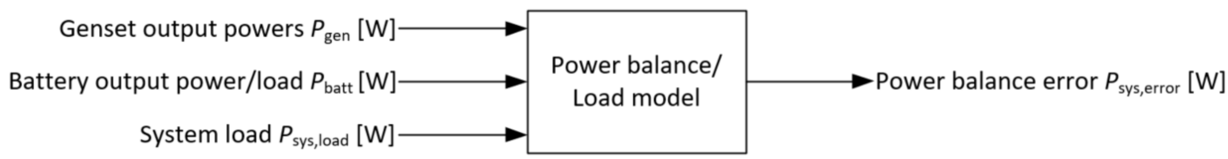

Figure 3.3. Power balance and load model input and output signals.

on the other hand, strives for a set-up that can adapt to changes. In that case measured data should be used. If a specific vessel's operation data isn't available, other existing data can be tuned with a coefficient parameter to match the desired load power level. This coefficient and the load type parameters are listed as the minimum required parameters in Table 2 in the appendix.

3.3 DC-link model

The heart of a DC system is its DC-link. It connects all the producers to all the consumers physically and transfers power between them. Consequently, DC-link voltage is one of, if not the most important signal to follow. If it's significantly lower than the U_{DC} reference, there's too much load compared to production. If it shoots up or oscillates, something is wrong with PLC control algorithms, motor parameters, or limits. The reason behind oscillation could also be bad PI controller parameters. All in all, U_{DC} is a good starting point when diagnosing system problems.

The simulation has a DC-link model that takes the power balance error calculated by the load model and calculates the current value of U_{DC} based on it. These two are the only input and output signals of the DC-link model, as presented in Figure 3.4.

Figure 3.4. DC-link model input and output signals.

The DC-link stores energy with its capacitance. This capacitance value and the starting voltage of the link are defined as minimum required parameters for the DC-link model, as listed in the appendix, Table 3. The amount of stored energy E_{DC} in the beginning is calculated with

$$E_{\text{DC,start}} = \frac{1}{2} C U_{\text{DC,start}}^2, \tag{2}$$

in which $E_{\text{DC,start}}$ is DC-link energy on the first simulation step, C is DC-link capacitance, and $U_{\text{DC,start}}$ is the DC-link voltage starting value. The maximum value for U_{DC} is 1050 V, which is the maximum allowed voltage for Danfoss Editron inverters stated in Chapter 3.4.3, Table 3.2. The DC-link section sees the power balance of the system and calculates the change in stored energy based on it:

$$\Delta E_{\text{DC}} = P_{\text{sys,error}} \cdot \Delta t, \tag{3}$$

in which ΔE_{DC} is the change in DC-link energy and $P_{\text{sys,error}}$ is the power balance error of the system. $P_{\text{sys,error}}$ is zero if the production and consumption are perfectly balanced, and either positive or negative if there's too much production or too much load respectively. Δt is the simulation time step. This change is either added to or subtracted from the previous simulation step's E_{DC}:

$$E_{\text{DC,2}} = E_{\text{DC,1}} + \Delta E_{\text{DC}}, \tag{4}$$

in which $E_{\text{DC,2}}$ is the DC-link energy during the current simulation step and $E_{\text{DC,1}}$ is the previous step's energy. The result is limited to the minimum and maximum values of DC-link energy with a saturation block and finally it gets saved for next step as $E_{\text{DC,1}}$.

To convert energy to U_{DC}, Equation 2 is rearranged to

$$U_{\text{DC}} = \sqrt{\frac{E_{\text{DC}}}{1/2 \cdot C}}, \tag{5}$$

in which U_{DC} equals the DC-link voltage that gets used as the actual or measured U_{DC} feedback in the rest of the simulation model.

The model monitors the U_{DC} at all times and will stop the simulation if an AC grid blackout seems imminent, as without an automatic blackout recovery there isn't any additional information to be found after it. A red indicator light in the Simulink model will inform the user of the blackout, its position is shown in Figure 3.2 as a grey circle. The default limit for the blackout stop parameter was chosen to be 500 V just to be sure that the simulation is definitely running towards a blackout situation. In order to create a 400 V main voltage AC grid the hotel inverter needs as much DC voltage as the AC peak would be:

$$400\text{V} \cdot \sqrt{2} \approx 566\text{V}_{\text{DC}}. \tag{6}$$

The exact value of 566 V could be used as the blackout stop limit if stable operation would be more relevant than the certainty of the blackout. In this thesis the focus is on verification and not parameterization, so blackout should be unavoidable before stopping. Depending on minimum voltage limits and undervoltage controllers some equipment might trip much earlier than this on the DC-grid side, for example the propulsion inverters. If the user would like to draw the line at completely normal and undisturbed operation, an even higher blackout stop limit should be decided based on these equipment limits.

3.4 Hybrid power plant model

The hybrid power plant model consists of multiple identical genset models. Each genset model includes an ICE model, an electric generator model, and a generator inverter model. Even though the genset models have identical structures, they can be run differently: not all of them need to start at the same time, and their U_{DC} reference values can also differ. By giving the generators their run commands with Simulink Step blocks, different starting times can be achieved.

3.4.1 ICE model

The role of an ICE in a genset is very simple: to produce torque for the generator, which will turn it into electricity. In the engine room of a ship the ICE gets commands only for its own functions and doesn't really know what the generator is doing, it's the generator's job to adjust.

The simulated ICE works a bit differently, since calculating the same shaft speed twice for both the engine and the generator wouldn't make sense. Instead the ICE model's input signals are speed reference from the parameters and shaft speed from the generator block, from which it can calculate its speed reference error. The model outputs mechanical torque, load percent, and fuel consumption data. Mechanical torque feedback is then used by the generator model to determine its torque reference error. These input and output signals are also shown in Figure 3.5. In this thesis a diesel model is used, but knowing these outlines it's possible to insert for example an LNG engine model into the simulation set-up.

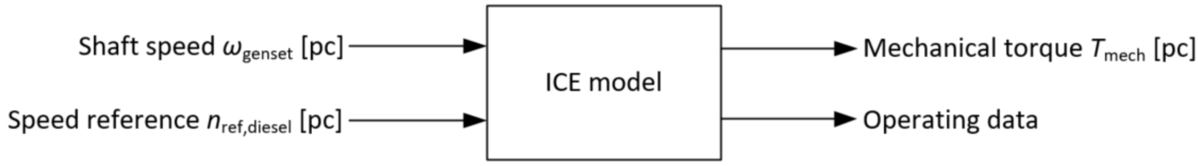

Figure 3.5. ICE model input and output signals.

The internal function of the diesel model is split into two independent parts: the mechanical torque calculation chain and data logging. Data logging handles both the consumption and load data. These two are only for the user's information and not used by the simulation. They were not fully implemented and tested due to limited verification possibilities.

The diesel model's torque calculation was developed throughout the project, first versions failing because of their complexity and the final version being a simplification of existing work. A notable aspect of vessel parameterization is seeing the surrounding systems as black boxes. Descriptions of other manufacturers' equipment and their inner logic are mostly not shared, only the necessary input requirements and available outputs are defined. This caused the detailed versions to fail, as characteristic parameters for engine models (such as time delays and constants) are not easily available and are thus against the objectives of this work.

In the end, a satisfying diesel model was achieved by modifying the diesel prime mover block diagram by Thebou et al., presented in Figure 3.6. Speed governor logic was implemented similarly with error calculation and a PI controller with filter, and actuator and combustion system were also included in the model. The first order filter and actuator were initially parameterized by iterating, but later removed to minimize the amount of needed parameters. The filter and PI controller combo was thus adjusted from Equation 7 to Equation 8 by implementing a basic Simulink

PID Controller block as a PI controller. [14, 15]

$$G_{\text{PI},1}(s) = \frac{K_{\text{i,diesel}} + sK_{\text{p,diesel}}}{s(1 + s\tau)}, \tag{7}$$

$$G_{\text{PI},2}(s) = K_{\text{p,diesel}} + K_{\text{i,diesel}}(\frac{1}{s}), \tag{8}$$

in which G_{PI}(s) is the diesel PI controller equation in Laplace domain, s is a Laplace variable, $K_{\text{p,diesel}}$ and $K_{\text{i,diesel}}$ are gains for the PI controller, and τ is a time constant.

The removal of the filter and actuator didn't have a significant impact in a simplified model like this, as was observed from the output signals during development testing, but it did leave a potential need for more time delay in the model. The combustion system delay could be increased or a rate limiter block could be added for the speed reference.

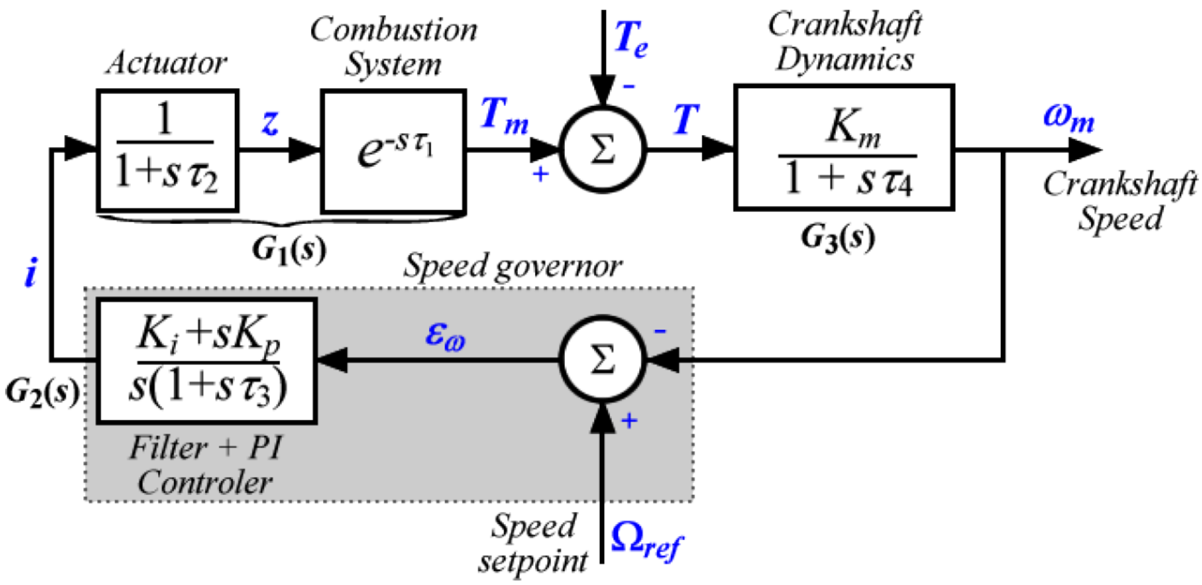

Figure 3.6. A diesel prime mover block diagram model by Thebou et al., which was used as guidance for the torque calculation chain. First order functions are used to describe the actuator, the delay caused by the combustion system, and the crankshaft dynamics. The diesel speed governor is presented as a combination of error calculation and a PI controller. [14]

The PI controller and combustion system remained as the main components. The combustion system is simulated with a Simulink Transport Delay block, which slows down the changes to simulate a more realistic diesel. Torque error calculation, crankshaft dynamics, and speed calculation were included in the generator model and duplicating them wasn't necessary in the diesel model. Instead a performance limiter was added to the end of the torque calculation chain. It matches the current speed to a maximum torque based on performance data from parameters and compares this value to the torque calculated earlier, smaller value wins. This allows the engine model to be closer to its real-life counterpart. The last addition was a torque limiter block, which saturates the diesel output torque to user-defined minimum and maximum values, in case the whole performance range of the engine is not in use.

On top of these, the generator inverter has a limiting mechanism to prevent the diesel from stalling in transient states. This ICE controller is discussed further in Chapter 3.4.3.

To sum it up, the diesel model requires speed-torque performance and ICE controller curves, mechanical torque minimum and maximum limits, combustion system time delay and inertia values, speed controller parameters, and gains $K_{\mathrm{p,diesel}}$ and $K_{\mathrm{i,diesel}}$ for the PI controller. These are also given in the appendix, Table 4, as the minimum required parameters that should at least be checked, if not updated, to be close to the compared real-life system.

The tuning of the model was done by iterating the gains to match measured comparison data from an existing vessel. Measured and simulated generator speeds were used in the tuning, and the gains were changed in turns, always checking the result between changes. The goal was to have the measured and simulated speed curves match as closely as possible, which they did after approximately six iteration rounds. This is presented in Figure 3.7. The same method will need to be used if another diesel model is required and there are no readily available PI controller parameters for it.

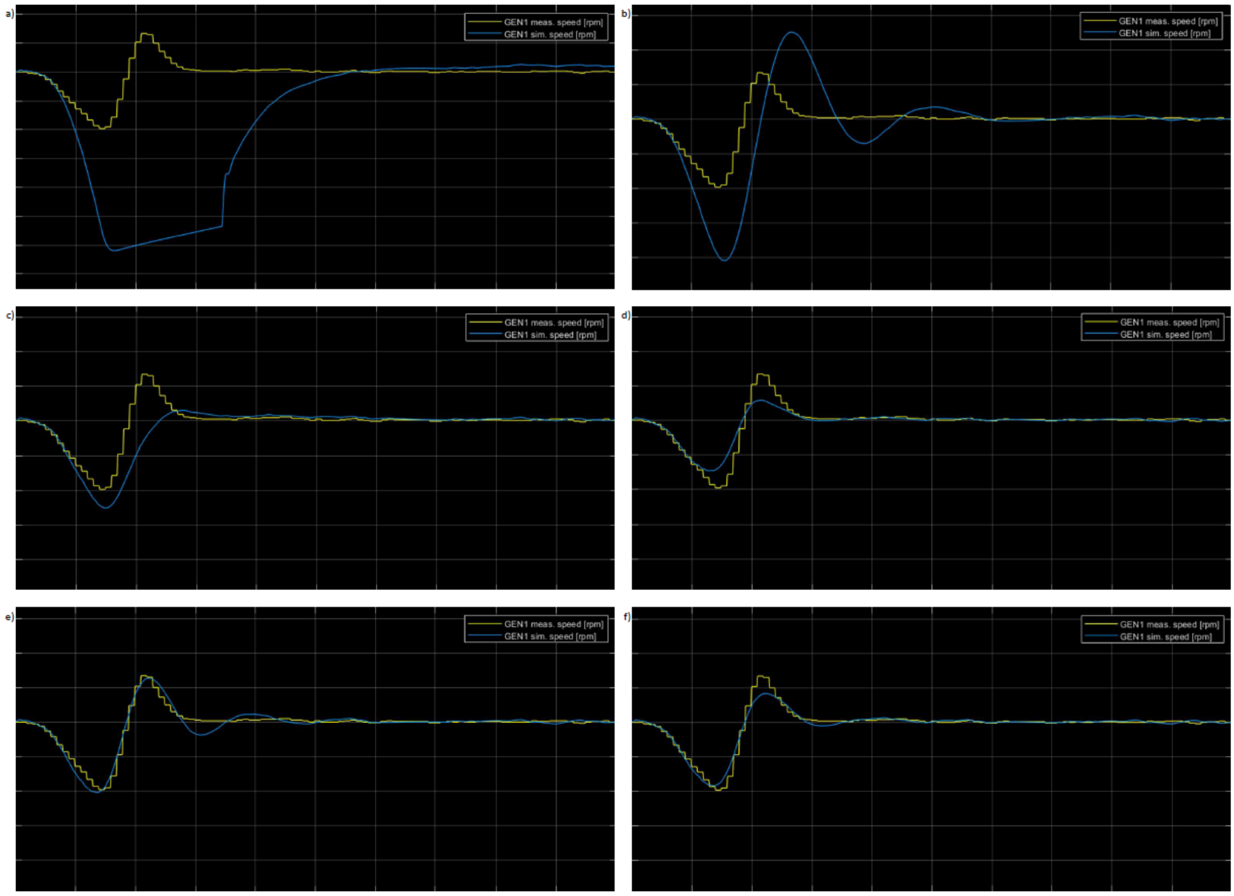

Figure 3.7. Iteration steps for tuning the diesel model. Each plot has the measured generator speed in yellow and simulated in blue. Generator is used instead of diesel, because the diesel block doesn't even output speed as their speeds are the same. The values of $K_{\mathrm{p,diesel}}$ and $K_{\mathrm{i,diesel}}$ during different steps from left to right are: a) previous ICE model values, b) $K_{\mathrm{p,diesel}} = 2.3$ and $K_{\mathrm{i,diesel}} = 0.25$, c) 4 and 0.25, d) 4 and 0.1, e) 3 and 0.12, f) 3.5 and 0.12. The value for $K_{\mathrm{p,diesel}}$ needed to be adjusted very slightly during later testing, and the final value ended up being 3.4. Otherwise the diesel tuning proved successful.

3.4.2 Generator model

A generator is an electric machine that is mechanically attached to a diesel engine via a common shaft and electrically attached to one or multiple inverters. It converts the ICE's mechanical torque into AC voltage, which is then rectified by the GI into DC voltage for the DC-link. Danfoss Editron motors and generators can run in all four quadrants of the torque-speed plane. On top of the normal rotation and torque direction, either or both variables can change direction and move the operation from one quadrant to another. Naturally with generators the motoring modes are avoided, but sometimes briefly utilized to maintain system stability. The operation modes are defined with speed and torque as shown in Figure 3.8. [16, 17]

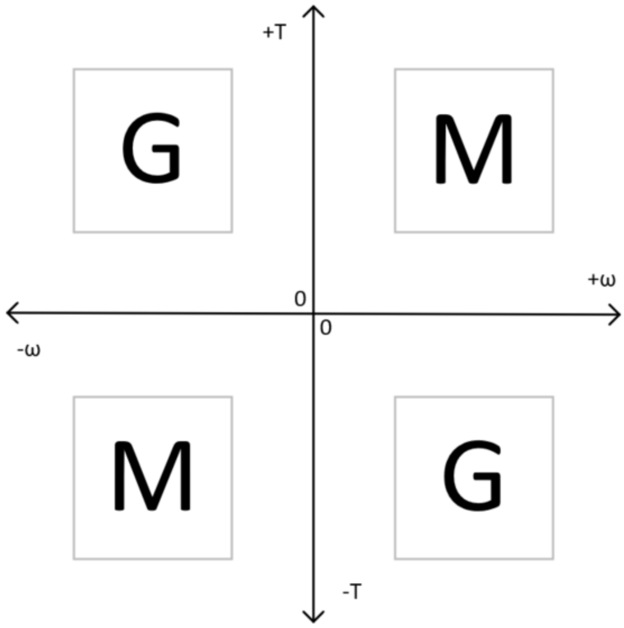

Figure 3.8. The four-quadrant speed-torque plane of an electric machine.

In physical systems all the generator's control logic is in the GI, the generator merely spins the same speed as the diesel does and creates as much power as the inverter requests. The generator speed is estimated by the inverter. Differing from this, the simulated generator block calculates its own speed, which removes the need to loop that estimation through the inverter. Simplicity is also achieved through not needing to convert the GI's torque reference into current, which would be the case with physical equipment. Instead the block receives a torque reference from the GI and mechanical torque value from the diesel model, and torque reference error is calculated from these. The reference error is fed into inertia model which includes both the diesel and generator inertias, and through acceleration, the current generator speed is calculated. With speed and torque, output power can also be calculated. These inputs and outputs are shown in Figure 3.9.

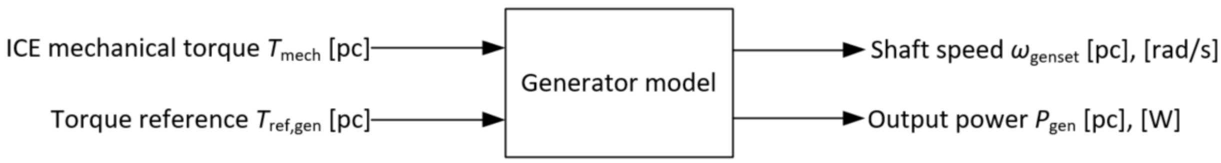

Figure 3.9. Generator model input and output signals.

While the torque reference error T_{error} is the difference between torque measurement and reference with the correct sign, angular acceleration is calculated with Equation 10:

$$T_{\text{error}} = J_{\text{genset}} \cdot \alpha_{\text{genset}}, \tag{9}$$

$$\alpha_{\text{genset}} = \frac{T_{\text{error}}}{J_{\text{genset}}}, \tag{10}$$

in which α_{genset} is the generator's and diesel's angular acceleration and J_{genset} is the combined inertia of generator and diesel. Angular shaft speed is calculated with Equation 12:

$$\alpha_{\text{genset}} = \frac{\omega_{\text{genset,2}} - \omega_{\text{genset,1}}}{\Delta t}, \tag{11}$$

$$\omega_{\text{genset,2}} = \alpha_{\text{genset}} \cdot \Delta t + \omega_{\text{genset,1}}, \tag{12}$$

in which $\omega_{\text{genset,1}}$ is the shaft speed of last simulation step, and $\omega_{\text{genset,2}}$ is the new value calculated on the current step. Δt is the simulation step. A starting value given in the parameters is used for $\omega_{\text{genset,1}}$ during the first step, after that the new value of last round is used.

Compared to the diesel engines the electric generators have a much quicker response, and thus no delay is added to the generator model block. The calculated speed is given to the ICE block and produced power is calculated for the power balance block:

$$P_{\text{gen}} = T_{\text{gen}} \cdot \omega_{\text{genset}}, \tag{13}$$

in which P_{gen} is the generator output power, T_{gen} is the generator torque, and ω_{genset} is the genset shaft angular speed.

Necessary unit conversions within the generator block are done with nominal values in pc-system. Nominal values for the generator are given as listed in Table 3.1, these already include the nominal power. Nominal angular speed is calculated with

$$\omega_{\text{nom}} = \frac{n_{\text{nom}}}{60} \cdot 2\pi, \tag{14}$$

in which n_{nom} is the nominal speed. Nominal torque is calculated from nominal power and nominal angular speed with

$$T_{\text{nom}} = \frac{P_{\text{nom}}}{\omega_{\text{nom}}}, \tag{15}$$

in which P_{nom} is the nominal power, T_{nom} is the nominal torque.

Danfoss Editron EM-PMI375-T1100-1800-DUAL is used as an example generator in this thesis. It is a synchronous reluctance assisted permanent magnet (SRPM) machine, which is optimal for marine use thanks to its compact size, good power-to-weight ratio, and high efficiency for the whole operation range. As stated in the type code, it is a dual machine that has two galvanically isolated stator windings and is normally run by two inverters. In this example the generator is run by just one inverter, in real life this would mean that the windings are connected together. The power of a generator's output or a motor's input is limited by the inverter's current limit. The example inverter used in this thesis is Danfoss Editron EC-C1200-450-L+MC350, which is limited to a nominal AC current of 350 A [18]. Using two of these inverters with a dual machine would increase that limit. A dual machine with two inverters would also add redundancy to the system because it can still be run at half power if one of the inverters trips. On the other hand, having a dual machine with just one inverter reduces the current per cable compared to a single machine, which in turn reduces the temperature and thus increases the lifetime of the cables. At the same time, output power is not increased unnecessarily due to only having one inverter. [19]

This simulated generator model supports single, dual, and quadruple machines, the user can switch between these in the M-file parameters. Setting up a dual drive requires some care with the machine parameters, as the total nominal current and total nominal power need to be divided by two when parameterizing the inverters. In that case the torque from one inverter's viewpoint would also be just 50 % of the total nominal torque.

The generator has functional limits to prevent damaging itself or other components in the DC-link during use. These limits are overseen by the generator inverter and discussed further in Chapter 3.4.3. Overall, most of the user-defined parameters for a generator-GI pair are for the GI, the minimum required parameters of the generator being inertia, initial speed and power values, and

Table 3.1. Nominal datasheet values for the EM-PMI375-T1100 generator, also known as the name plate or rating plate values. It should be noted that the machine parameters are read from the +40 °C coolant column in the datasheet, as this will allow for a better performance. Current and power should be divided by two if two inverters were used. [19]

Quantity	Value	Unit
Nominal voltage	500	[V_{AC}]
Nominal current	305	[A]
Nominal power	243	[kW]
Nominal speed	1900	[rpm]
Maximum speed	3600	[rpm]

nominal nameplate values given in Table 3.1. These requirements are also given in Table 5 in the appendix. Generator thermal limits are excluded from this work, as sufficient cooling should always be available when the machine is running. This also means excluding any temperature related derating ramps.

3.4.3 Generator inverter model

The generator inverter is the brains of the generator both in the real world and in this simulation model. It can control the generator with DC-link voltage reference, speed reference, or torque reference. All of these are rotor flux oriented current vector controls. Only DC-link voltage control is included in the scope of this work. [18]

In a marine system, the GI gets an U_{DC} reference from the PLC and converts it to a torque reference for the generator. The AC voltage created by the generator also gets rectified into DC voltage by the inverter. Before the reference is given to the generator in the form of current, it goes through a limiter chain. The limiter chain has also been implemented in this model, but variables like the generator speed and power that would be estimated by the inverter are being fed to the inverter block as feedback signals. This removes the need of calculating the same thing twice, since generator already has to estimate these values. The input and output signals of the inverter model are presented in Figure 3.10. The values needed to parameterize the model and especially the limiter chain are given in Table 5 in the appendix.

The GI limiter chain contains limits for the U_{DC} reference itself, these are in place just to have a

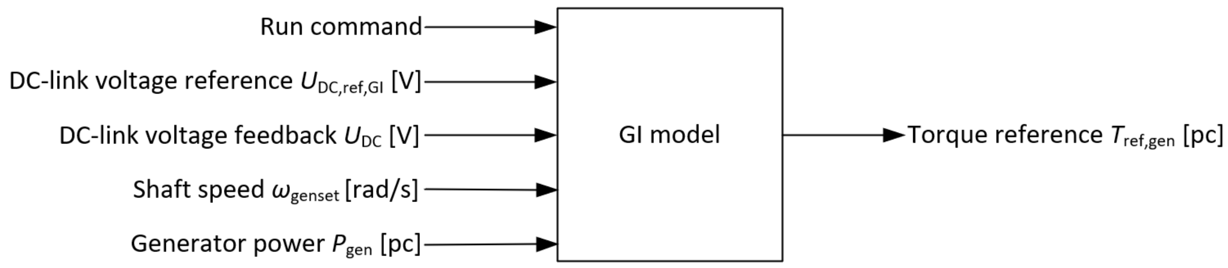

Figure 3.10. Generator inverter model input and output signals.

sanity check for the reference, and also to limit its rising or falling rate to prevent diesel stalling and OC trips. The reference also gets drooped to balance out the load-sharing between multiple producers. The drooping gets more significant as the generator gets more load: if in a two generator scenario the other generator gets loaded more, its drooping will intensify and decrease the inverter's U_{DC} reference. The less-drooped generator will then have to carry a larger portion of the load, and it will in turn get drooped more. This way the two gensets will unknowingly communicate with each other and balance out the load. The same goes between gensets and the ES. Drooping also prevents oscillation, as it will bring the references closer to one another in case one of the gensets wants to bring up the output voltage and the other wants to decrease it due to differences in the U_{DC} measurement. In the simulation the user can choose between torque or power droop. Torque droop is based on the torque value calculated in the last cycle, in the first cycle a starting parameter value is used instead. The drooped U_{DC} reference for the generator is calculated from

$$U_{\text{DC,ref used,GI}} = U_{\text{DC,ref,GI}} - T_{\text{gen}} \cdot \text{droop rate}, \tag{16}$$

in which $U_{\text{DC,ref used,GI}}$ is the DC-link voltage reference actually used in the control, $U_{\text{DC,ref,GI}}$ is the reference value given by the PLC, and T_{gen} is the actual torque value from the last cycle in pc units. The droop rate is given as [V/T_{nom}]. The power droop formula is very similar:

$$U_{\text{DC,ref used,GI}} = U_{\text{DC,ref,GI}} - P_{\text{gen}} \cdot \text{droop rate}, \tag{17}$$

in which P_{gen} is the actual generator output power value from the last cycle in pc units. The droop rate is given as [V/P_{nom}].

On top of these U_{DC} reference limiters, the DC-link voltage also gets protected by undervoltage and overvoltage controllers. UVC reduces motoring side torque and OVC generating. It should be noted that this model only supports a linear OVC with start and end values of the torque-voltage ramps given by the user. UVC is quite often disabled in marine GIs, and thus only OVC is implemented in the GI model. When the DC-link voltage reaches the ramp start value, the controller gets activated. It will lower the torque reference according to the voltage ramp until the DC-link voltage hits "zero torque", at which point the torque reference has been reduced to zero. This ramp is illustrated in Figure 3.11. The user may also limit the amount of motoring torque OVC can use, which would ideally be zero, but from the control's point of view zero is very hard to work with and a better option would be for example 0.05.

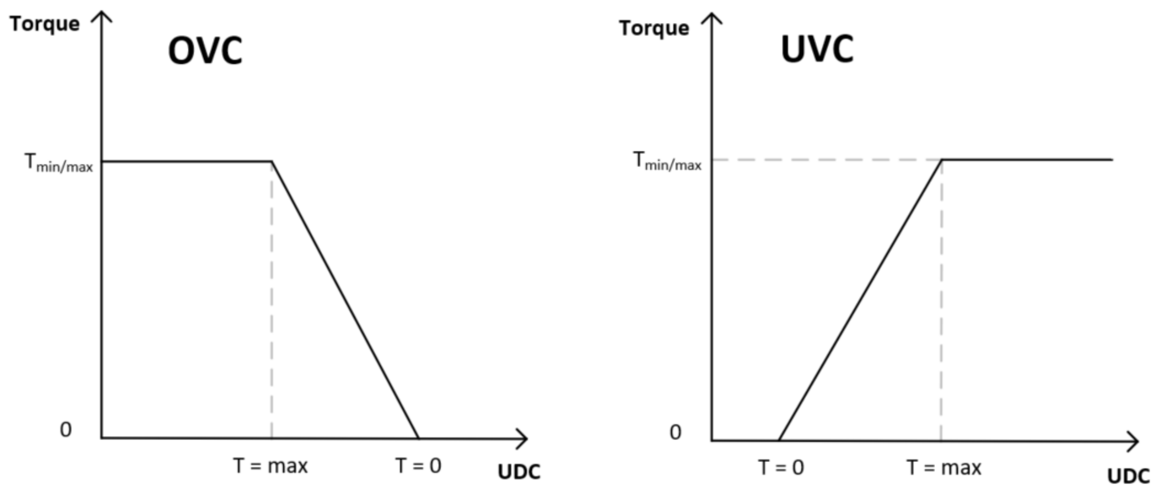

Figure 3.11. The U_{DC}-torque ramps of OVC and UVC.

The limiter chain also has protections for the ICE and the generator when calculating the generator torque reference. The ICE controller checks the current speed provided by the generator model and matches it to a maximum ICE torque value on a speed-torque lookup table. The ICE curve is model specific and needs to be given by the user. The generator performance limiter has likewise a model specific speed-torque lookup table, but it's also bound to a current limit.

Limits that protect the equipment and surrounding system mechanically are power limiter, torque limiter, and rush controller. Power and torque limits can be defined by the user to match the generator's, ICE's, and attached mechanical parts' performance limits. Rush controller activates only if other control method than speed is used, and if the generator speed is over limits. It will bring the speed back to limits by modifying the torque reference of the generator. The AC current would also be limited in a real system, but current limiters have been excluded from the scope of this thesis.

For the generator, the U_{DC} PI controller is the main controller. It takes in the U_{DC} reference error, calculated as the difference between the U_{DC} reference and the U_{DC} value from the previous simulation step, and gives out power reference for the generator.

Tuning the $K_{\mathrm{p,UDC}}$ and the $K_{\mathrm{i,UDC}}$ is a good way to adjust the GI's behaviour. An anti-windup needed to be implemented in the controller after running into a problem in the testing phase. Anti-windup prevents the integral term from increasing uncontrollably, which can be a problem in real-life, non-linear systems. If the system has any limits, be it limiter chain blocks or physical limits, at some point the PI controller will run into them. When a limit is reached before the reference value, error will continue rising while the system output stays saturated to a value. This will cause the integrator part to stray further and further from zero, and once the limit is lifted or the reference value decreased it will take a long time to rewind the I-term. One anti-windup method is to limit the integrator's action when certain conditions are met, also known as clamping or conditional integration. [20, 21]

The inverter also has functional limits just like the generator, but there are less of them. In the model, only the current and voltage limits are used: maximum current defines the generators performance curve, and maximum voltage sets a boundary for the U_{DC}. Cooling is assumed to be sufficient whenever the inverter is online, not just when running, so temperature limits are not included in the scope of this work. Hardware limits for model EC-C1200-450-L+MC350 are stated in Table 3.2.

Table 3.2. Limit values for the EC-C1200-450 inverter from the device's datasheet. [18]

Quantity	**Value**	**Unit**
Maximum HV side voltage	1050	[V_{DC}]
Maximum current	350	[A]

3.5 Energy storage model

Marine energy storages can be for example batteries, fuel cells, or supercapacitors. This thesis concentrates on batteries, but knowing the outlines of the battery simulation model, other equipment models could also be placed between the DCDC converter and the power balance block. In a marine system, a battery communicates only with its battery management system (BMS) and not directly with a DCDC or PLC, even though it's electrically connected to the DCDC. BMS relays statuses and measurements to the PLC, for example state of charge (SoC), current limits, faults, single cell temperatures and voltages, and the status which can be pre-charging, online or offline. PLC only sends commands and fault clears to the BMS. The DCDC converter gets updated U_{DC} reference and current limit information from the PLC, as these can change dynamically. It will then give a charging or discharging current reference to the battery based on these values.

Compared to the creation of the genset model, the ES simulation model wasn't as straightforward. More guesses and estimations had to be made due to the larger number of unknown factors, which in turn affected the accuracy of the end result. Battery data and BMS logic are proprietary to each battery manufacturer, and only the system interface and connections are well known. The ES model was made as general and parameterizable as possible, and the final product was tuned to be as close to the example ship's operation as possible. Realistic ES operation was prioritized over getting an exact copy of any existing system, as that would be more valuable for future parameterization testing with other vessels.

3.5.1 Battery model

A Datasheet Battery model from Simulink's block library was chosen as the core of the ES system. The most important selecting criteria was the possibility of parameterization with datasheet values, which this battery model has. The required parameters are listed in the appendix in Table 6. The model would require a temperature measurement input, but since temperatures were excluded from this work as a whole, a constant room temperature value of 298.15 K is fed to the input for now. This needs to be paid attention to when giving the temperature-resistance-SoC matrix in the parameters, as only the data for this one specific temperature will be used. The library block gives out multiple output signals, out of which battery output current, output power, output voltage, and

SoC measurement are used, as shown in Figure 3.12. [22]

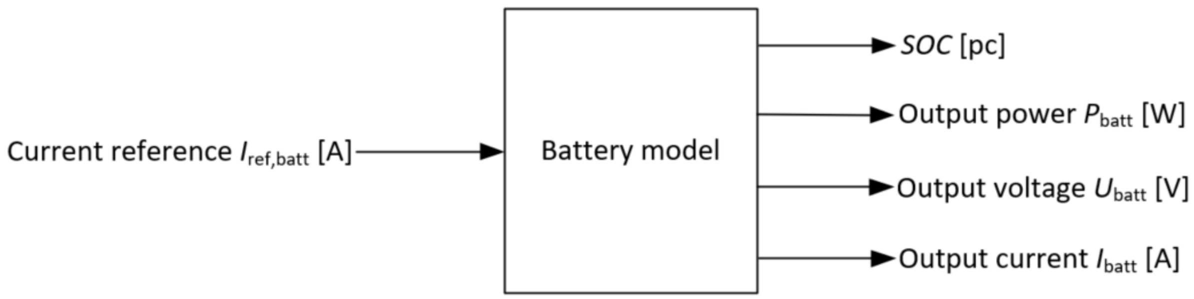

Figure 3.12. Battery model input and output signals.

The equations for the model outputs are given below.

$$SOC = \frac{1}{Cap_{\text{batt}}} \int_0^t I_{\text{batt}} dt, \tag{18}$$

$$I_{\text{cell}} = \frac{I_{\text{batt}}}{N_{\text{par}}}, \tag{19}$$

$$U_{\text{cell}} = U_{\text{oc}} + I_{\text{cell}} \cdot R_{\text{int}}, \tag{20}$$

$$U_{\text{batt}} = N_{\text{ser}} \cdot U_{\text{cell}}, \tag{21}$$

$$P_{\text{batt}} = -U_{\text{batt}} \cdot I_{\text{batt}}, \tag{22}$$

in which *SOC* is battery state of charge, Cap_{batt} is battery capacity, t is time, I_{batt} is battery current, I_{cell} is cell current, N_{par} is the number of cells in parallel, U_{cell} is cell voltage, U_{oc} is cell open-circuit voltage, R_{int} is cell internal resistance, U_{batt} is battery output voltage, N_{ser} is the number of cells in series, and P_{batt} is the battery output power. [22]

Status information isn't given, as the battery is assumed to always be online. Information isn't looped unnecessarily through the BMS block just to mimic the real-world ship system, instead only SoC is given to the BMS while output power and voltage signals are routed directly to the

DCDC. The battery output power is also used by the power balance calculation block, both negative and positive power are accepted since the ES can switch between a producer and a load. Output current is only used in verification.

3.5.2 BMS model

The BMS model has far less tasks compared to an actual BMS, but the one less remaining responsibility is also one of the most essential: controlling the charging and discharging currents based on the SoC level of the battery. This main responsibility can also be seen from the model block's input and output signals in Figure 3.13.

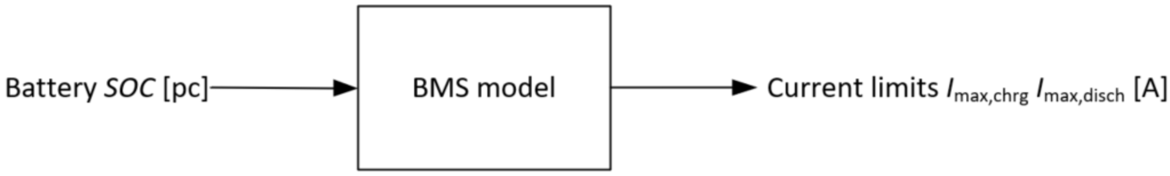

Figure 3.13. Battery management system model input and output signals.

The user can give SoC limits for both maximum charging and maximum discharging currents, and as long as the SoC stays between these values the DCDC can use maximum current for both operations. If either limit is reached, the BMS will start limiting the current reference that the DCDC gives the battery with a linear limiter, that is analogous to the linear behaviour of OVC and UVC presented in Figure 3.11. The current limit will be ramped from its maximum value to a zero as a function of the SoC, the lower SoC limit at which the current will drop to zero can be defined by the user just like the ramp start value. These ramp parameters are listed in Table 7 in the appendix. The SoC limits for charging and discharging are usually given by the battery manufacturer, as they know the battery's optimal operation range and safety limits the best. The same goes for the maximum current values for both charging and discharging, although the converter's functional limits should also be kept in mind when choosing the parameter values.

Something to be noted about the trio's communication is that the battery model and DCDC see current and power directions the opposite way. The battery model's direction was left as it is in the library version, and BMS was built to match the battery. The DCDC converter's direction was kept the same as its real-life counterpart's, and thus the signals' signs need to be inverted between the blocks. DC-link sees the direction of the power the same way as the battery and for that reason no inversion is needed between the battery block and the power balance calculation block.

3.5.3 DCDC converter model

DCDC converter and battery dynamic is very similar to that of a generator inverter and a generator. In this simulation model both control devices only give out one reference signal, but they get a lot of information from around the whole system, as can be seen in Figure 3.14. In physical installations DCDC converters are paired with an external inductance unit to filter the output PWM signal and store energy during the switching cycle. This is left out of the simulation due to the simplified DCDC model that doesn't give out a PWM voltage, but instead a current reference in amperes. [18]

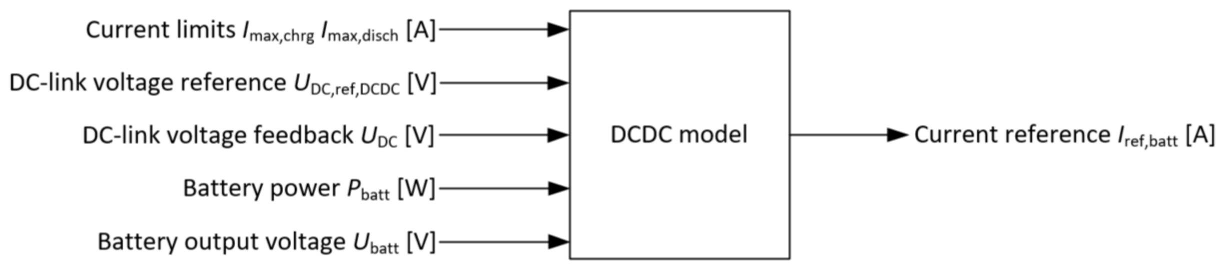

Figure 3.14. DCDC converter model input and output signals.

The DCDC converter has the same limiters for the U_{DC} reference as the GI: sanity check and rate limiter. The DCDC also has drooping just like the GI but the the only mode option is power, see Equation 17. It should also be noted that the unit for DCDC droop is V/kW. Since this first simulation model version only has one ES unit, the droop of the DCDC will try to balance the load between the gensets and the ES.

DCDC has to watch over two different sides with different voltage levels, HV and LV, DC-link and ES. This causes the undervoltage and overvoltage controllers to double in numbers, all the variants are listed in Table 3.3. Otherwise their function is similar to the OVC and UVC in GI, explained in Chapter 3.4.3. The battery's current reference can be thought as analogous to the generator's torque reference.

When power flow goes from HV to LV the operation mode is called buck, and in the opposite case of power flow from LV to HV the mode is known as boost. The power flow is controlled with the LV side current via PWM. Creating a higher LV side output voltage compared to the battery output voltage will make current flow towards the battery. Reversing the direction of current will reverse the flow of power as well. [16]

Table 3.3. DCDC undervoltage and overvoltage controllers for both DC-link side and ES side.

Controller name	**Side**	**Function**
HV OVC	DC-link (boost)	Protects the link from overcharging and overvoltage.
HV UVC	DC-link (buck)	Protects the link from draining.
LV OVC	ES (buck)	Protects the battery from overcharging.
LV UVC	ES (boost)	Protects the battery from deep discharge.

DCDC's current reference is also limited by power and current limits. Saturation block is used for power limiting, naturally the current reference needs to be converted into power before and after the block. The current limiter is a combination of a dynamic limiter and a saturation block, the former applying the BMS current limits and the latter user-defined. The dynamic limiter receives the upper and lower limits as input signals from BMS, but both are also limited to maximum value parameters.

The DCDC converter's U_{DC} PI controller model is the same as the GI's. In practise, DCDC converters' PI controllers are parameterized to be more aggressive, because there are no mechanical parts like couplings that would be affected by swift control changes. So even though the PI controller blocks are the same, the K_{p} and K_{i} can be very different between a DCDC and a GI in the same system.

To sum it up, the most relevant parameters for the DCDC block are the OVC and UVC parameters, output power limits, and U_{DC} PI controller gains. Nominal current, voltage, and power of the DCDC are also needed. These are listed as the minimum required parameters of the model in the appendix, Table 8. The nominal values for the Danfoss Editron EC-C1200-450-L+DC400 converter used in this simulation are stated in Table 3.4.

Table 3.4. Nominal values for the Danfoss Editron converter model EC-C1200-450-L+DC400. [18]

Quantity	**Value**	**Unit**
Nominal current	400	[A_{DC}]
Nominal voltage	750	[V_{DC}]
Nominal power	240	[W]

4 VERIFICATION OF SIMULATION MODEL

In this thesis, the target was to create an easily modifiable and realistic enough simulation model of a hybrid marine system, more specifically concentrating on the production side equipment and its parameterization test use. The realistic function of a basic system model was deemed more valuable than a model with more details and functions but possibly less verified modules. Due to the high value and expectations of the model's realistic behaviour, constant testing of the model and re-evaluation of requirements were conducted throughout the development phase.

Some features had to be simplified or completely dropped because of schedule or resource limitations, but these decisions were only made for modules that weren't part of the core model, to not affect the main target of this project. As the rest of the model verification is mainly about its functional testing and requirement compliance, other end result quality related topics like model versatility are discussed here. For example simulated load with consumer models was left out, since it's additional value for the whole system wouldn't have been enough to justify compromising the production side verification. Creating propulsion and thruster motor models could be done based on the existing generator model in the future, which would be a lot easier than creating the whole generator model from zero was. PLC model development was also dropped midway, when it came clear that verifying it wouldn't be easy with the same data that was going to be used for the production model. One of the possible usages of this model is to test different PLC control logics, so it could also have been unnecessary work that would have been replaced straight away by a different model under testing. Signal inputs are already in place for a PLC model to be added. Active limiter data, warning signals, and faults were left out due to time limitations, but the model would be ready for adding them in the future. Simulated trips would be possible to do with the model by stepping down GI run commands or U_{DC} references, but those functions were not verified. Producer priorities and OMs had to also be dropped, as they would have required a working PLC model. ES models weren't duplicated during this project because of limited comparison data for the verification, so only one exists, but based on the experiences during genset model duplication it would be an easy addition in the future. On top of these cuts, some unused features were also created. The first detailed diesel model required time to be implemented, but in the end proved to be unsuitable for the model's needs. Diesel speed controller was also developed and preliminarily tested to be working, but needed to be removed from the version that was verified due to differing control logics between it and the ship system that the simulation model was compared to. These resource misuses didn't affect the target of the project, but they still had an impact on the project itself, especially time-usage wise.

4.1 Testing principles and methods

A basic testing process starts with a test plan, after which a testing environment is created, tests are conducted, and finally the results are evaluated. Focusing on the target is important, in this case it's the model's realistic operation. It's also important to remember that even though testing reveals faults, tracking the source of the problem and fixing it are their own separate processes. Having no bugs also doesn't automatically mean that the end result is what was requested or needed. With these in mind, the plan was to do functionality testing as much as possible during the development phase, and the final verification testing was done against the business need. This way tracking the fault sources and re-testing would be faster. No separate performance testing was planned, as the main requirement for usability was automatically fulfilled when the model was developed with the same equipment that it should be able to run on. User experience was kept in mind during the development, but it was also excluded from the testing contents. Clear division between the parameter file and the simulation itself was kept to help other users navigate the model, and commentary was added both for the parameters as well as the Simulink model blocks.

It's impossible to test all possible scenarios, but on the other hand using the same test case over and over again won't reveal any new bugs. To cover most possible scenarios this model could encounter in normal use, a couple of distinct measurement sets were chosen to be used at different development stages. These data sets present different operation scenarios on board of the comparison ship, and are described more in detail in Chapter 4.2. Using real measured data automatically limits the tested scenarios into realistic situations that the model should be able to handle.

The development and tests were conducted with a V-model: the project started with functional specifications that were refined into more and more detailed model plans, and the testing was done the other way around from smaller sections into module and finally system testing. Lowest level component testing was done as soon as a subsystem was ready to run, as this reduced the amount of components that could be causing issues in the results. No measured comparison data was used for component or subsystem testing, as constant input values could already show the stability of the block. Simulink scopes were used to check not only the final output of a single block, but also the signal form and behaviour between smallest possible components inside it. This eliminated the possibility of not noticing a controller fault because of saturation limits after it. Module testing was conducted separately on the genset model and DCDC model, before testing their compatibility. Highest level system functionality was tested last, first with just one genset and one ES with adjusted comparison load, and finally with the complete set-up of five gensets and one ES. All three steps included repeated testing with updates on the blocks and parameters in between. Comparison data was present in last stage module testing and during the whole system testing.

The last acceptance tests were done completely with comparison data. Verification testing environment was created within the model: the initial parameter file was parameterized anew with the comparison vessel's own parameters and the output data was compared directly in Simulink scopes with measurement data from the ship. Even though the realistic model behaviour was also the passing criteria for functional testing during the development, the specifications were tightened towards the end when nearing the last verification tests. The things that were looked for were deviations from the specifications, lack of function, wrong function, or model parts that couldn't be adjusted to match a specific real-life set-up. Verification test results were evaluated together with Danfoss Editron.

4.2 Model verification

Verification testing was done completely with simulated and measured data side-by-side. Measured data was acquired from an existing Danfoss Editron hybrid marine system. The first data set that was used was best for general genset testing, as it contained pretty standard genset running with no unusual signal changes or operating against limits. The second data set was for genset boundary testing, as it included running the GI against parameterized limits. This was used to perfect the function of the genset module. The third measurement data set was used for ES and complete system testing, because it had the most transient situations for both producer types.

Component, module, and system testing results were evaluated in meetings with Danfoss Editron. Only complete system results will be presented here as their initial requirement is that the previous stages were already successful.

The third measured dataset characteristic are presented in Figure 4.1. This test run was done on board of a real vessel. The three graphs show how the load is increased and all producers respond to the change accordingly. The U_{DC} measurement stays relatively stable throughout the measurement sample, as it should, and the system doesn't start oscillating with a steady load. This is how the simulation model is expected to function as well.

The selected simulation model output graphs are presented in Figures 4.2-4.10. The amount of graphs is limited due to some of them having more fine-tuning information than system functionality value, and some containing information only valuable for Danfoss and not model verification. Diesel engine operating data is not included in the verification, as no measured comparison data was available for consumption or load percentage. A global fixed time step of 0.001 seconds was used for the verification simulation run, whereas the measured data has 0.01 s steps. Thus, it should be noted that the roughness of measured data curves compared to the simulation curves is caused by CAN sample time and not the hybrid system's function. The measured U_{DC} also shows the 1 V resolution of the inverter's CAN communication. Both of these add to the calculated error signals.

Figure 4.2 shows the power production and consumption balance in the simulation model. Gensets 2, 4 and five can be seen starting during the first 30 seconds, and the effect of growing load starts limiting the battery charging power after 40 seconds. When diesels are accelerated around the 50 second mark, DCDC takes momentarily more charging power. The power balance error oscillates quite a bit, even though it stays close to zero most of the time. This is probably caused by load measurement resolution, evidence for that is shown in a zoomed version of the scope in Figure 4.3. The load curve can be seen to have steps in it, this reflects onto the genset output powers and their summed difference causes the oscillating pattern in the error.

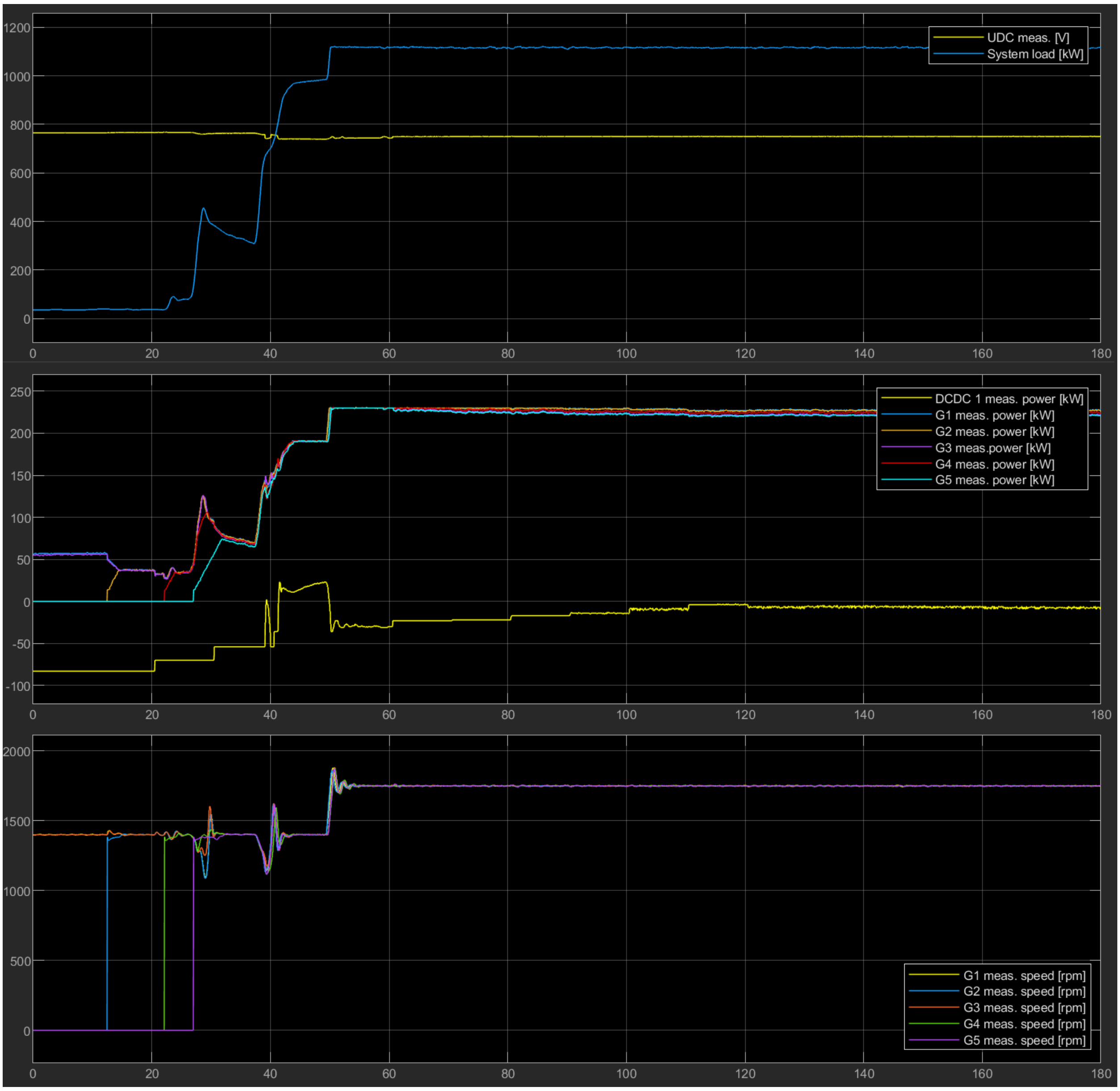

Figure 4.1. Measured real-life comparison data. The top graph shows how the consumer load is increased during 20-50 s but U_{DC} stays stable. The middle graph displays the output powers of the producers, in this case that includes one ES and five gensets. Generators 1 and 3 are online right from the start, G2 starts at around 10 s, G4 and G5 start between 20-30 s as the load increases. All generators' output powers follow the load curve above once online. The DCDC starts by charging the battery pack, but eases its share in the total load once the consumer load starts increasing, momentarily discharging the battery during 40-50 s to fill in while the gensets are increasing their output powers. After 110 s the battery pack is full and the system doesn't require ES assistance either. The bottom graph has the genset speeds, each measurement is the same for both the diesel and generator in that particular set. The speeds show the starting times and load changes even more clearly than the output power curves.

The most noticeable differences between the simulated and measured ES data in Figure 4.4 are the differences in charging power and SoC. As explained in chapter 3.5, the battery and BMS logic

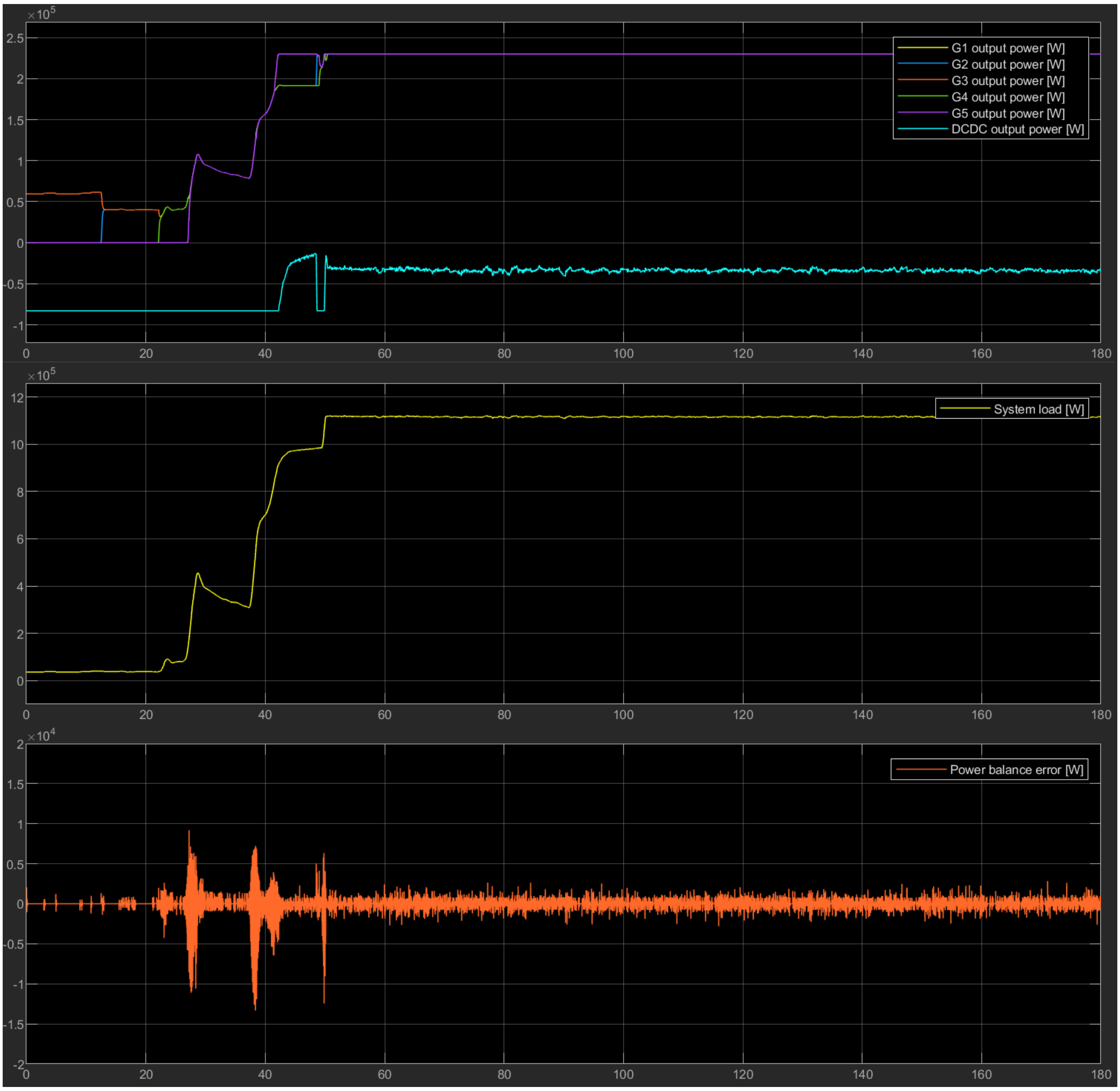

Figure 4.2. Simulation power balance. The scope shows the production modules' output powers on top, load in the middle, and power balance error at the bottom.

outside of their communication with the Danfoss Editron marine system is not well known. Because of that, getting the ES model perfectly right wasn't realistic, and that can best be seen in the battery SoC comparison. Even though the battery model was parameterized to be the same size as it would be on board of the comparison vessel and the DCDC parameters were copied from the ship system, the BMS logic didn't match and the battery couldn't be parameterized to start with the same SoC as the data would require, as that caused the model to be out of boundaries. The battery model needed to start emptier compared to the measured data, which allowed the simulation model

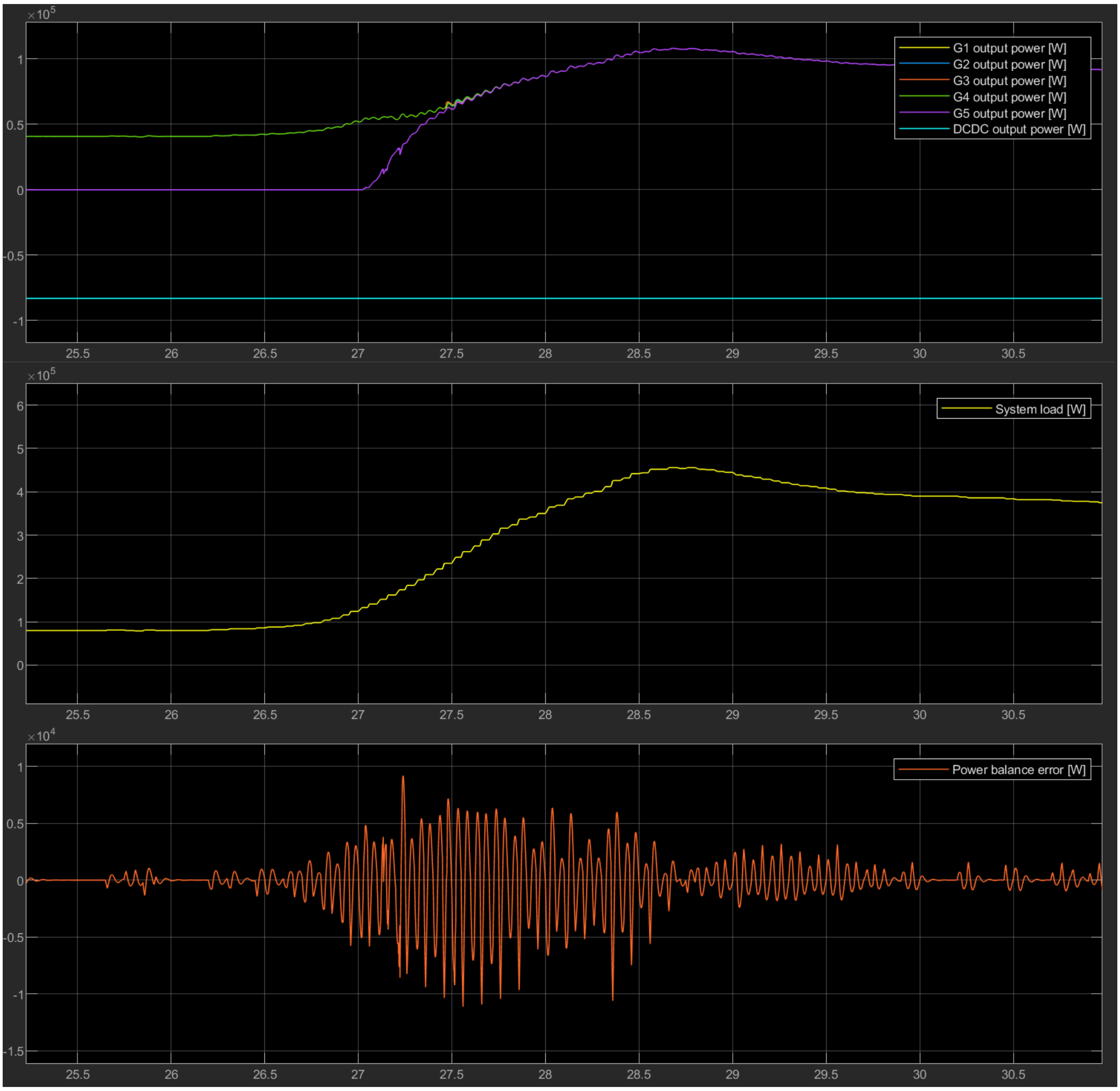

Figure 4.3. Zoomed picture of the power balance graphs. Steps in the load data possibly affect the production power curves and cause the error to oscillate.

to charge it more. As can be seen from the scope, the measured battery is getting quite full with its SoC at 94 % and it can't be charged as much as the simulated battery at 70 % SoC. This also affects the output power and current graphs at the top, as well as the U_{DC} in the bottom left, since there is more load. The U_{DC} measurement and simulation values start deviating around the same time as battery charging powers, which is also speaks for the ES model's effect.

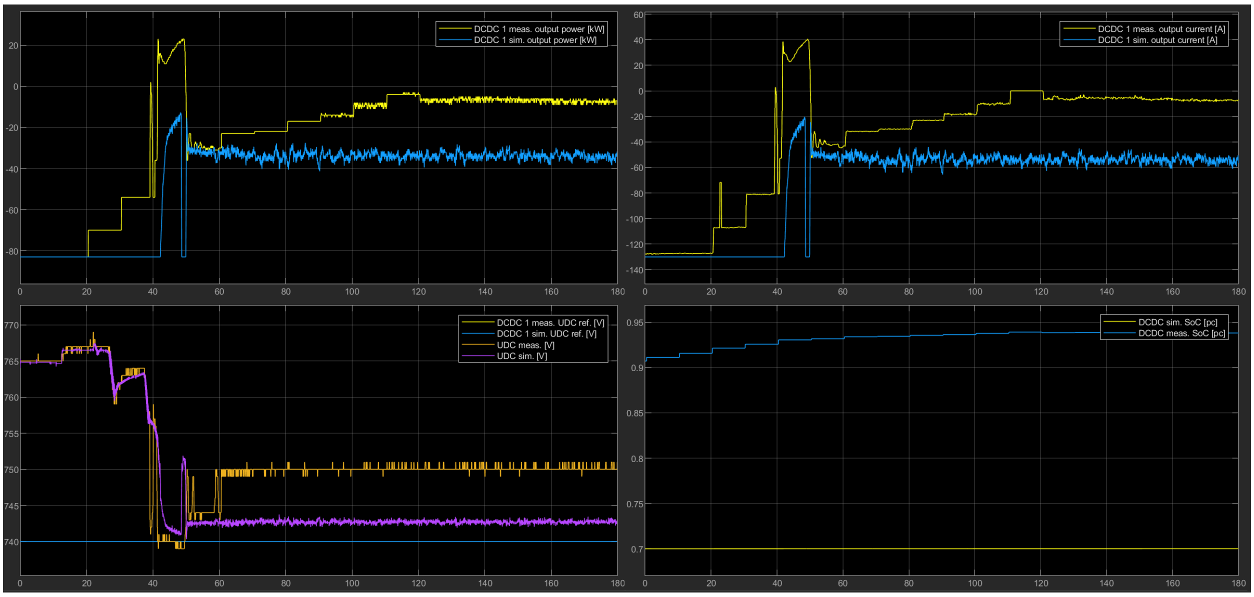

Figure 4.4. Simulated ES characteristics compared to the measured data.

The five simulated gensets are compared to measurement data in Figure 4.5. All of them follow the same patterns, although the simulated signals react a bit faster and with less ramping. A good example of this is seen in genset 2 starting, where the simulated power does a step and the measured data follows a ramp, and also especially in genset 5 data in the top right corner. This is most probably caused by limiting of the gensets on board of the comparison vessel, as according to the measurement data, limits were active during the transients shown in this figure. Similar ramping or acceleration limiting could also be added to the model, if necessary. Part of the issue is that even though the diesel speed reference of the simulation model is the exact same as measured on board of the ship, the generators still manage to achieve a higher speed and thus also output power faster. The reason for this can be found with a deeper look into the generator data.

In Figure 4.6, the same differences in power production can be seen more zoomed in. The maximum error is 16 %. If compared to Figure 4.7, a connection can be seen: the simulated genset model accelerates faster, and faster speed allows more output power. The speed error reaches the high values that it does because the simulation model gets a head start.

If the generator speed data is zoomed in, more details of the diesel differences are found, as shown in Figure 4.8. Even though both diesels get the same speed reference at the same time, it's clear

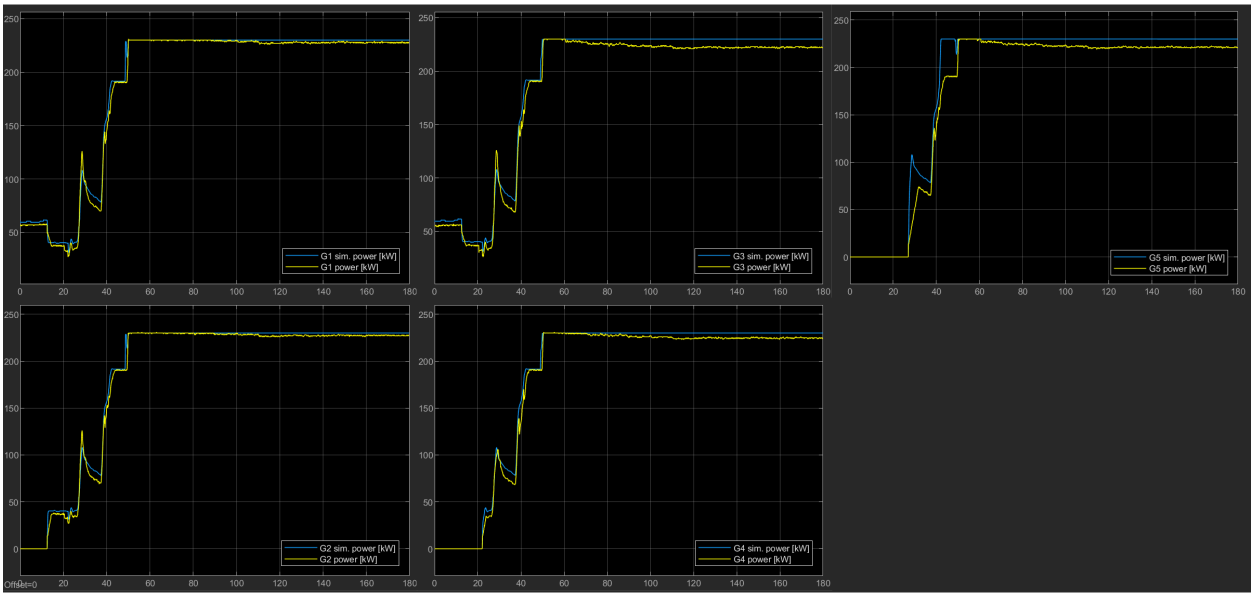

Figure 4.5. Simulated genset output powers compared to the measured powers.

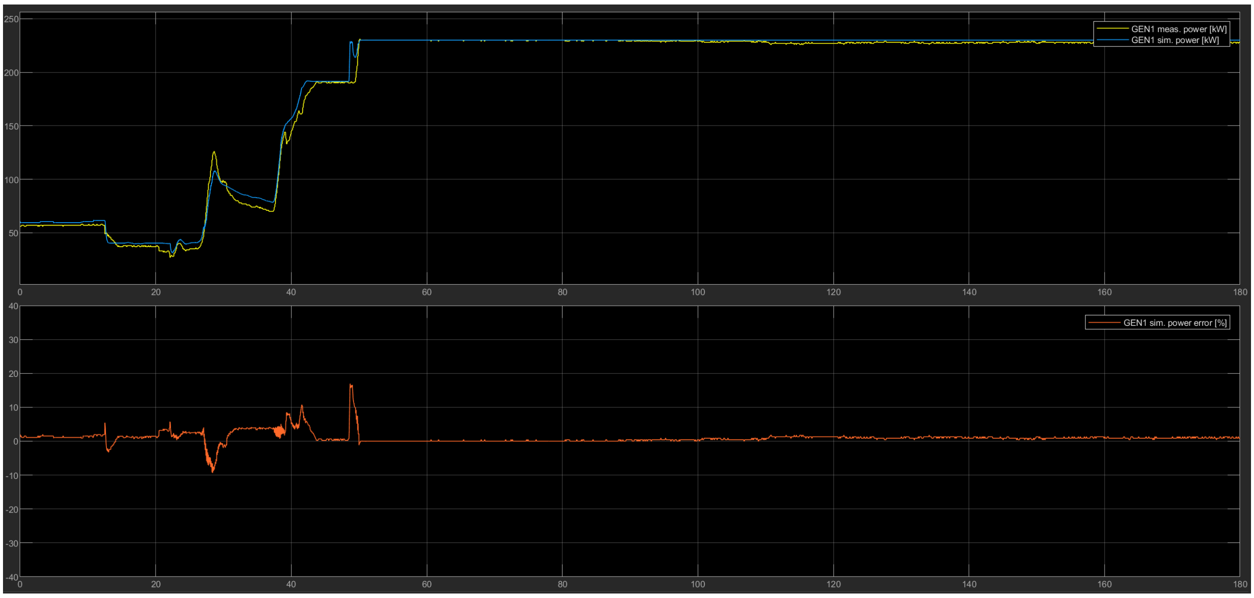

Figure 4.6. Simulated generator output power compared to the measured data.

that the simulated diesel model reacts faster, despite the tuning in Chapter 3.4.1. There are multiple possible reasons behind this, one of which could be a rate limiter in the measured system. The more linear rise of the measured speed would support this assumption. A rate limiter would also make sense protection-wise in real life, and so more delay could be added to the diesel model as well, as already considered in Chapter 3.4.1. Losses, slowness caused by mechanical parts, and inertia could also affect the physical diesel. Even though inertia is included in the model as well, it's only a value taken from general datasheets. Another reason could be communication delays,

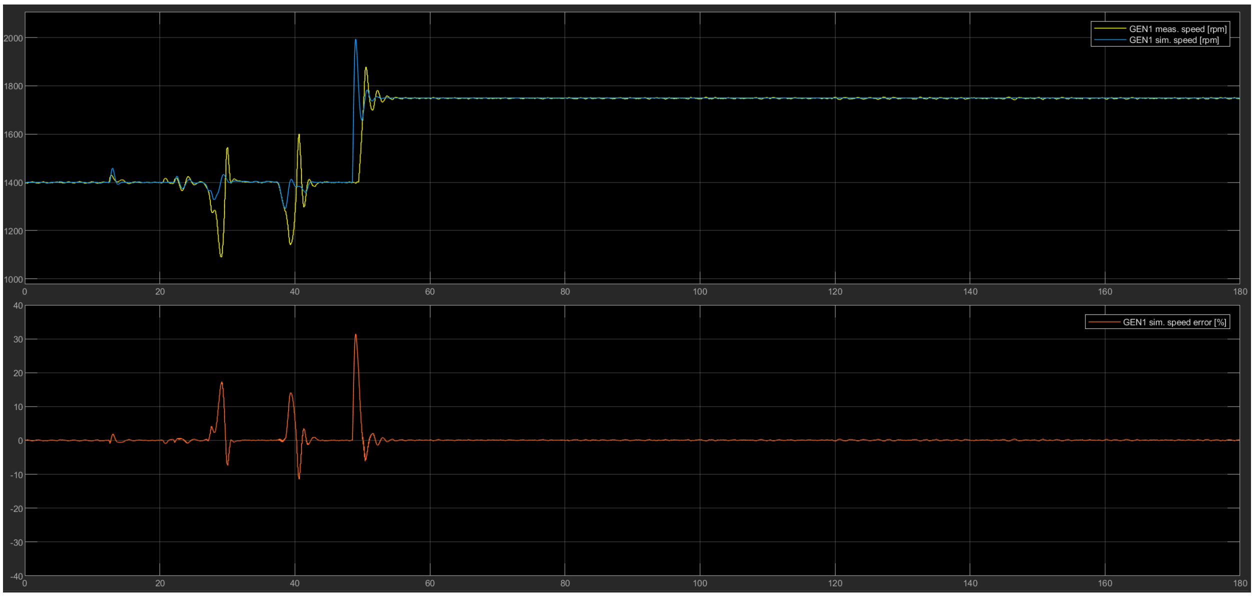

Figure 4.7. Simulated generator speed compared to the measured data.

as the difference seems to be quite exactly one second.

The third and final generator data comparison in Figure 4.9 shows the generator torque. If looked back on the genset speed data in Figure 4.7, it can be seen that the measured speed oscillates more than the simulated speed. This causes difference in the two torques, if power is kept relatively stable, which it is based on the error signals of power, speed, and torque. From error signals it can be seen that power has the smallest difference out of the three.

The last verification figure was also the most used during testing, and is probably the most important: DC-link voltage, shown in Figure 4.10. There are two main differences between the two signals: the steady state error and the jumps in the measured U_{DC} at around 40 seconds. The steady state error could be caused by the difference in ES operation. While the measured ES on board of the comparison vessel eases its load at around 60 seconds, the simulated battery continues drawing more energy from the DC-link. Both systems have the same load, but the simulated system also has the additional load caused by the ES. The measured jumps at around 40 seconds can be seen in multiple scopes: the load starts rising, the genset output powers respond to it, and the ES eases its load (Figures 4.1 and 4.4). Even if the simulated components see the same changes, the U_{DC} doesn't drop similarly to the measured U_{DC} in Figure 4.10. The reason for this could be found

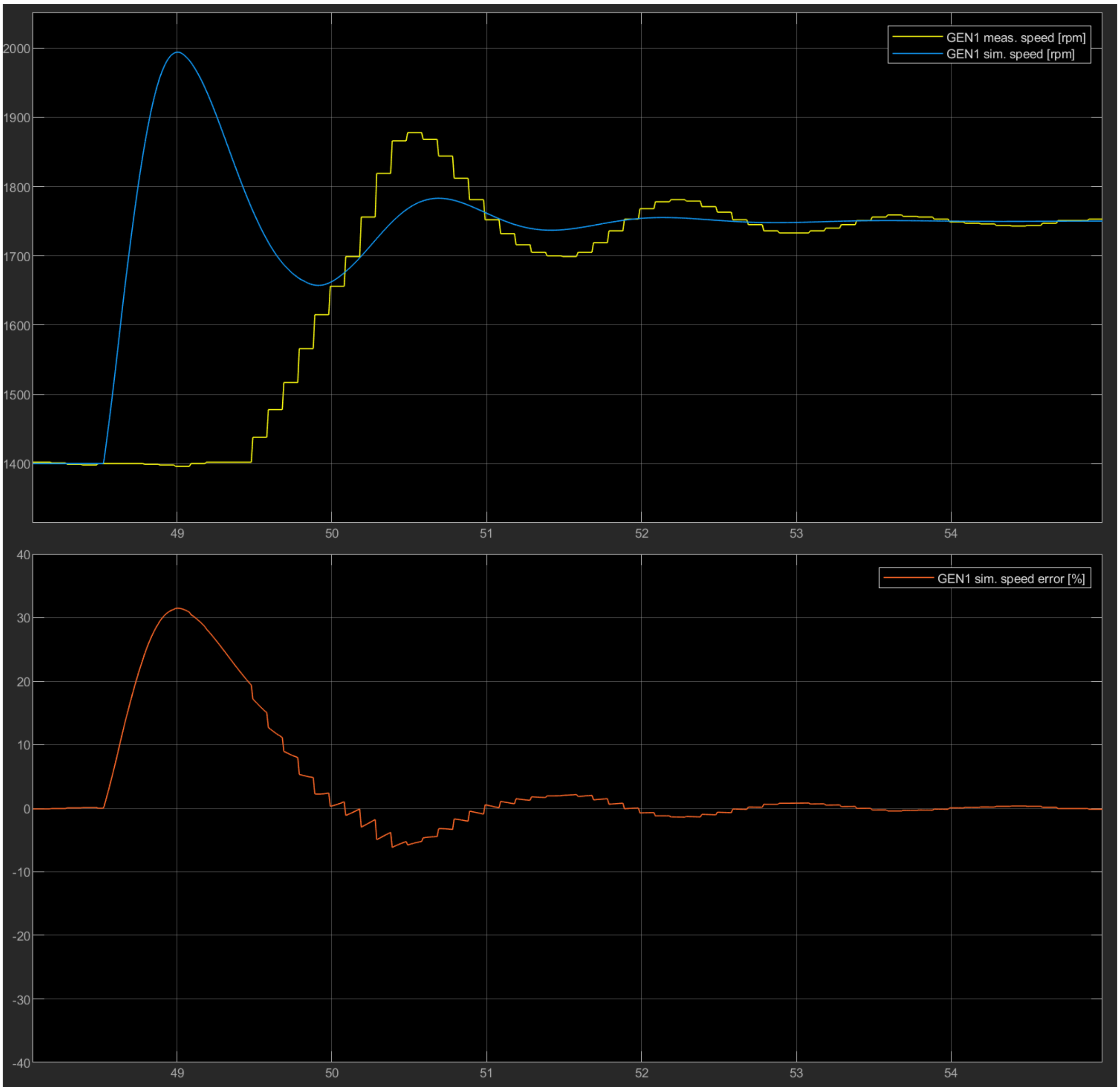

Figure 4.8. Zoomed in picture of the genset speed signals.

from the load data, that is being fed to the simulation model. The load data is the sum of all consumers' output data, which means that it already includes the consumer's reaction to the changing situation. The propulsion motors in the physical ship's engine room have their own UVC's which will react to a dropping U_{DC}, but the measured U_{DC} still needs to drop before the propulsion starts decreasing its power demand. This means that while the real system's U_{DC} shows the events just before and during the consumers' reaction to the dropping U_{DC}, the simulation sees only the outcome, meaning the final output power of the consumers. One related cause for this jumping could

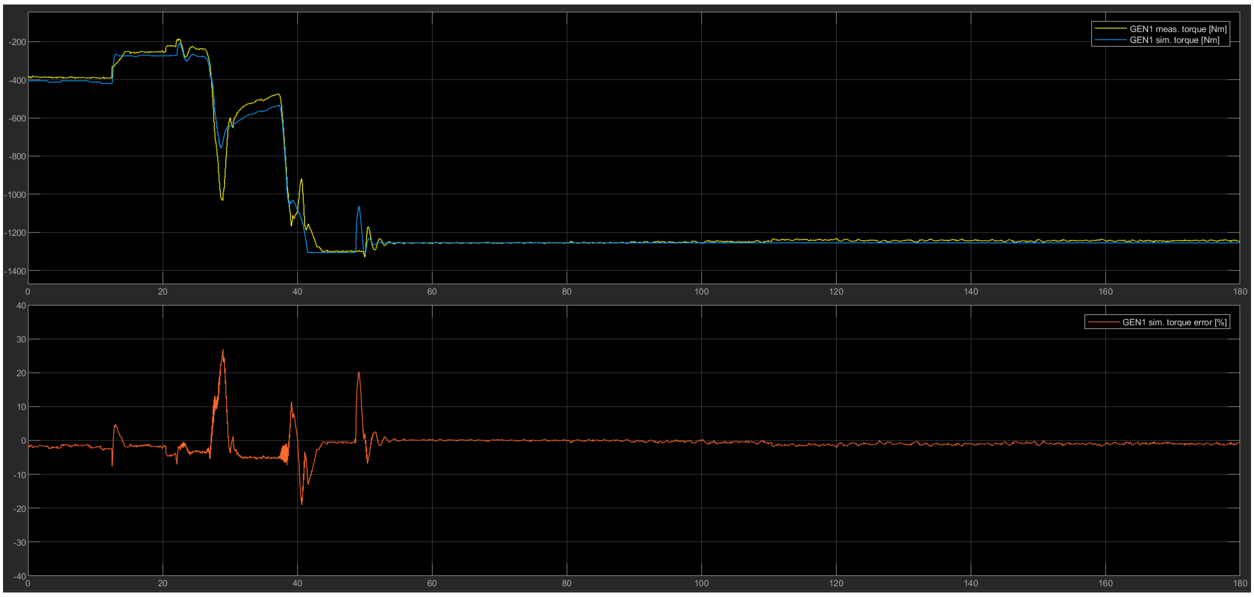

Figure 4.9. Simulated generator torque compared to the measured data.

also be the inverters' estimation errors. While the simulated model calculates with exact values, the multiple inverters in a physical system might see and record slightly different values compared to each other, which could cause different limiters to activate if the devices are running close to limits to begin with. This could cause twitching in the measured U_{DC}, while still maintaining the overall balance.

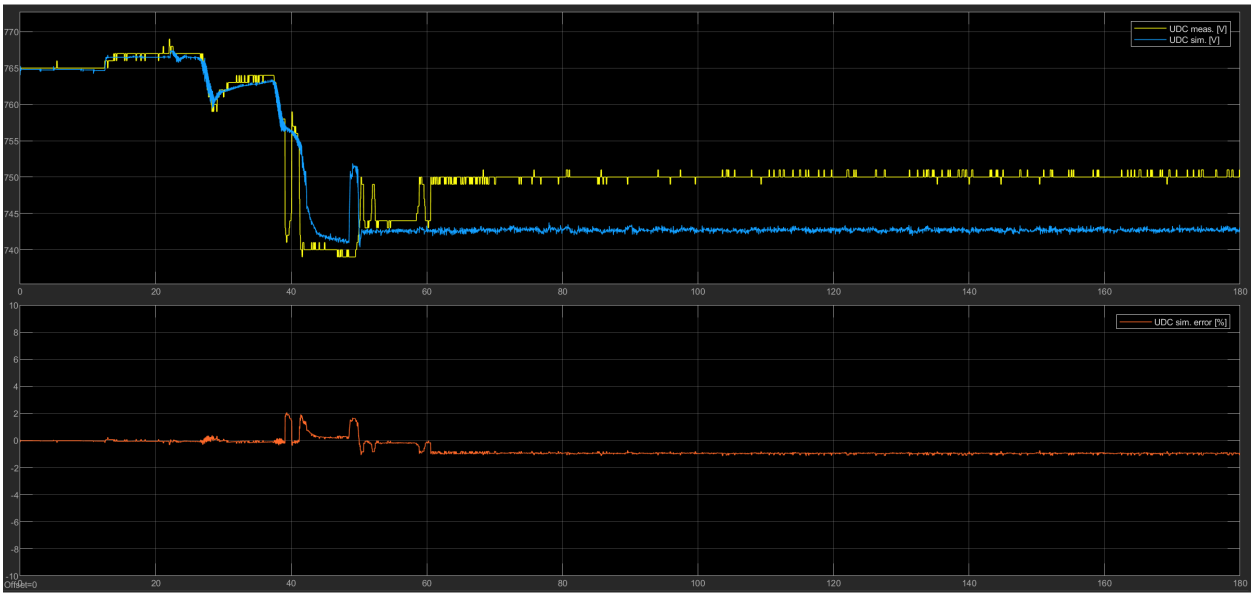

Figure 4.10. Simulated U_{DC} compared to the measured U_{DC} data.

4.3 Model validation

Verification testing revealed some aspects that would still need developing and fine-tuning, for example the diesel model speed response and BMS control logic. These affect the accuracy of the results, but not the functionality or the stability of the system. The results were examined together with Danfoss Editron and found to be realistic. Errors between measured and simulated signals were deemed acceptable.

5 CONCLUSION

Considering the objectives of this project, a general hybrid system model was successfully created. The model can be parameterized to match a specific marine vessel, and it is ready for a PLC module addition and control logic testing. Minimum required parameters were discovered during the testing phase, and verification of the model was possible. The system was tested to be stable in transient and active limiter situations. In those aspects both the requirements and business needs were met.

Some requirements were partly realized. The implemented failure handling includes a blackout stop but is missing equipment faults and trips, as well as blackout recovery. Individual consumer models were replaced by a single load signal. System redundancy required by the standards was partly implemented with the multiple producers and multi-inverter generators, but the DC-link can't be split into two in the name of system redundancy. Existing equipment redundancy and separate run commands for different inverters would allow the testing of device trips mid-run, but this was not tested or verified. Diesel speed controller was created and preliminarily tested, but not verified due to unavailable comparison data.

The biggest unfulfilled requirements are a PLC model, OMs, and priorities, out of which the latter two couldn't be implemented due to the missing PLC model. The development work for the PLC model was already started and it could be finished at a later time. However, if the model would be used in control algorithm testing, a default PLC model wouldn't even be necessary.

On top of these features, future development could include multiplication of the ES module and sanity checks for the input parameters. The former could be reasonably easy based on the experiences while multiplying the genset module into five, and the latter could help make the user experience better. The diesel model could be developed to be more realistic with delays, and the BMS model would require more testing to find out the current and SoC limits that are closer to real-life control logic. Life cycle models, thermal model, and current data could also be considered, as they could increase the amount of useful output data. Weather conditions and unusual operation situations could be added as available test run options, the same way as different OMs.

These additions should be done in small modules and with comprehensive testing right from the start to make finding the minimum required parameters and suitable default parameters easier.

The results achieved in this thesis show that relatively realistic results can be simulated with a simple hybrid system model. The model would benefit from more field testing with different comparison systems, but it could also possibly benefit the development of these systems in turn, as feedback for parameter changes is comparatively fast and clear with the output signal scopes. Complete system start and stop testing could also be useful, since as of now there is no data of the model's reliability in those situations. More extreme producer starting and stopping could also be experimented with, to really test the stability of the model and parameters. Different size gensets and ESs should also be tried out, to map out the optimum system size range of the model. Having multiple users try out the model could also be a good way of finding out different opportunities as well as places that still need development, especially regarding the user interface. All in all, more diverse testing would be valuable and needed.

Development of digital tools like this model will hopefully benefit the electrification market in the long run. Testing out different hybrid set-ups digitally could lower the threshold for new customers, as it is rather risk-free. Concrete data like consumption differences and equipment running hours are a good selling point, if the data can be produced reliably. By making the electric system design even more approachable and attractive, traditional technologies of travelling and transportation can be challenged and the future can be electrified.

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APPENDIX

The simulation model can be parameterized with the Matlab M-file. While all parameters listed in the file don't need to be changed in normal testing, the minimum required parameters listed in the tables below do need to be checked and possibly updated to match the real-life system as closely as possible. Default parameter value suggestions are given in the M-file. Battery and diesel data can be especially hard to find, in which case the default settings can be used if there's no discrepancy between them and the rest of the system. Battery, BMS, and DCDC are closely related to each other and always need to be parameterized in sync. The same goes for diesel, generator, and GI. It's recommended to run the model for only a few seconds in the beginning during parameterization, as wrong initial values or unsuitable controller settings start causing disturbance in the output data quite quickly. After the minimum parameters are set, the system fine-tuning with all parameters can start.

Table 1. Minimum required parameters for system control. Parameters marked with * need to be given for each genset separately.

Signal name	Description	Unit
DcdcUdcRefV	DCDC U_{DC} reference.	[V]
DcdcUdcRefStartV	DCDC U_{DC} reference initial value.	[V]
*GenUdcRefV**	Genset U_{DC} reference, separate for each genset.	[V]
*GenUdcRefStartV**	Genset U_{DC} reference initial value, separate for each genset.	[V]
SimTimeS	Simulation run time.	[s]

Table 2. Minimum required parameters for load model. A constant load value only needs to be given if constant load model is selected with *SysLoadSelection*, and if measured load is selected, the correct data will need to be uploaded via the M-file. Measured load data might also need to be tuned with the coefficient parameter.

Signal name	Description	Unit
SysLoadSelection	A selection switch for constant load value or measured load data.	-
SysConstLoadW	A constant load value.	[W]
SysMeasLoadCoef	Measured data coefficient for system capacity adjustment.	-

Table 3. Minimum required parameters for DC-link model.

Signal name	Description	Unit
DcLinkCapF	DC-link capacitance.	[F]
UdcStartV	DC-link voltage initial value.	[V]

Table 4. Minimum required parameters for diesel model. PI controller integration time will be converted into I gain in the model. Speed control type parameter switches between a constant reference value and a controller model, only one of them needs to be parameterized. A third option for speed controller is to use measured data directly in the Simulink model, as was also done during the model verification. ICE controller is used by the GI but is still included in the diesel parameters since it's based on the diesel performance.

Signal name	Description	Unit
DieselInertiaKGM2	Diesel motor inertia.	[kg·m^2]
DieselTimeDelS	Combustion system delay.	[s]
DieselConPGain	Diesel PI controller P gain.	-
DieselConITimeS	Diesel PI controller I time.	[s]
DieselSpeedConType	A selection switch for diesel speed control type.	-
DieselConstSpeedRefRPM	A constant speed reference value for diesel.	[rpm]
DieselSpeedConPowerW	Speed controller power-speed curve, power vector.	[W]
DieselSpeedConSpeedRPM	Speed controller power-speed curve, speed vector.	[rpm]
DieselSpeedConMaxRPM	Maximum speed limit for speed controller.	[rpm]
DieselSpeedConMinRPM	Minimum speed limit for speed controller.	[rpm]
DieselPerfSpeedRPM	Performance limiter speed-torque curve, speed vector.	[rpm]
DieselPerfTorqNM	Performance limiter speed-torque curve, torque vector.	[Nm]
DieselMaxTorqNM	Performance curve upper extrapolation limit.	[Nm]
DieselMinTorqNM	Performance curve lower extrapolation limit.	[Nm]
IceConChartSpeedRPM	GI ICE controller speed-torque curve, speed vector.	[rpm]
IceConChartTorqNM	GI ICE controller speed-torque curve, torque vector.	[Nm]

Table 5. Minimum required parameters for generator and GI models. Dual and quadruple type switches increase the amount of active GI models per one generator. PI controller integration times will be converted into I gains in the model. Parameters marked with * need to be given for each genset separately.

Signal name	Description	Unit
GenTypeDual	An on-switch for the 2nd inverter per genset.	-
GenTypeQuad	An on-switch for the 2nd, 3rd, and 4th inverters per genset.	-
GenInertiaKGM2	Generator inertia.	[kg·m^2]
GenNomCurA	Generator nominal current.	[A]
GenNomPwrKW	Generator nominal power.	[kW]
GenNomSpeedRPM	Generator nominal speed.	[rpm]
GenNomVoltV	Generator nominal voltage.	[V]
GenSpeedConPGain	Generator speed PI controller P gain.	-
GenSpeedConITimeS	Generator speed PI controller I time.	[s]
GenSpeedMaxRPM	Generator maximum speed limit.	[rpm]
GenSpeedMinRPM	Generator minimum speed limit.	[rpm]
GenPerfSpeedRPM	Performance limiter speed-torque curve, speed vector.	[rpm]
GenPerfTorqNM	Performance limiter speed-torque curve, torque vector.	[Nm]
GenPerfCurA	Performance curve current limit.	[A]
GenPwrMaxKW	Generator maximum power limit.	[kW]
GenPwrMinKW	Generator minimum power limit.	[kW]
GenUdcConPGain	U_{DC} PI controller P gain.	-
GenUdcConITimeS	U_{DC} PI controller I time.	[s]
*GenSpeedStartRPM**	Initial value for speed, separate for each genset.	[rpm]
*GenPowerStartW**	Initial value for power, separate for each genset.	[W]

Table 6. Battery model minimum required parameters.

Signal name	Description	Unit
EsNomCapAH	Battery nominal capacity.	[Ah]
EsCellNumSer	Number of battery cells in series.	-
EsCellNumPar	Number of battery cells in parallel.	-
EsOcvDataVoltV	Voltage-SoC curve, open circuit cell voltage vector.	[V]
EsOcvDataSocPC	Voltage-SoC curve, battery SoC vector.	[pc]
EsResDataIntResOHM	Resistance-temperature-SoC curve, resistance vector.	[Ω]
EsResDataTempK	Resistance-temperature-SoC curve, temperature vector.	[K]
EsResDataSocPC	Resistance-temperature-SoC curve, SoC vector.	[pc]
EsStartCapAH	Battery capacity initial value.	[Ah]
EsStartVoltV	Battery output voltage initial value.	[V]
EsStartPwrKW	Battery output power initial value.	[kW]

Table 7. BMS model minimum required parameters. Charging and discharging ramps start from the maximum current and end to 0 A current.

Signal name	**Description**	**Unit**
EsChrgMaxCurSocLimPC	Charging current ramp down, SoC for ramp start.	[pc]
EsChrgMaxSocPC	Charging current ramp down, SoC for no charging.	[pc]
EsChrgMaxCurA	Maximum charging current.	[A]
EsDischMaxCurSocLimPC	Discharging current ramp down, SoC for ramp start.	[pc]
EsDischMinSocPC	Discharging current ramp down, SoC for no discharging.	[pc]
EsDischMaxCurA	Maximum discharging current.	[A]

Table 8. Minimum required parameters for DCDC model. PI controller integration time will be converted into I gain in the model.

Signal name	**Description**	**Unit**
DcdcNomCurA	DCDC nominal current.	[A]
DcdcNomVoltV	DCDC nominal voltage.	[V]
DcdcnomPwrKW	DCDC nominal power.	[kW]
DcdcPwrMaxKW	ES maximum output power.	[kW]
DcdcPwrMinKW	ES minimum output power.	[kW]
DcdcEsOvConVoltRampStartV	LV/ES side OVC ramp start.	[V]
DcdcEsOvConVoltRampEndV	LV/ES side OVC ramp end.	[V]
DcdcEsUvConVoltRampStartV	LV/ES side UVC ramp start.	[V]
DcdcEsUvConVoltRampEndV	LV/ES side UVC ramp end.	[V]
DcdcUdcConPGainKWPERV	DCDC U_{DC} PI controller P gain.	[kW/V]
DcdcUdcConITimeS	DCDC U_{DC} PI controller I time.	[s]