

The Design and Development of Test Benches

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EXAMENSARBETE

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Abstrakt

Testbänkar används av WE Tech Solutions för att säkerställa funktionaliteten för deras lösningar i en småskalig och säker laboratoriemiljö innan implementering ombord på fartyg. Eftersom företaget utvecklar skräddarsydda lösningar för varje projekt är laboratorietester nödvändiga för att verifiera prestanda och tillförlitlighet.

Detta examensarbete fokuserar på design och utveckling av nya testbänkar som uppfyller nuvarande funktionskrav samtidigt som laboratoriets testkapacitet utökas. Testbänkarna och tillhörande tillverkningsdokumentation skapas med EPLAN, och tillverkningen utförs av ett företag som specialiserar sig på tillverkning av elskåp.

I examensarbetet går kraven genom för funktionalitet, designprocessen och hur dessa krav uppfylls av den utvecklade lösningen.

Resultatet av projektet är färdiga testbänkar som ökar laboratoriets testkapacitet och är lätt att modifiera enligt lösning som skall testas. Den är även förberedd för framtida anpassningar med extra rum.

Språk: Engelska
Nyckelord: Frekvensomriktare (VFD), Generator, Testbänk

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Tiivistelmä

Testipenkkejä käytetään WE Tech Solutions yrityksessä heidän ratkaisujensa toiminnallisuuden varmistamiseen pienimuotoisessa ja turvallisessa laboratorioympäristössä ennen käyttöönottoa aluksilla. Koska yritys kehittää jokaiseen projektiin räätälöityjä ratkaisuja, laboratoriotestaus on välttämätöntä toimivuuden ja luotettavuuden varmistamiseksi.

Tämä opinnäytetyö keskittyy uusien testipenkkien suunnitteluun ja kehittämiseen siten, että ne vastaavat nykyisiä toiminnallisia vaatimuksia ja samalla laajentavat yrityksen laboratoriotestauksen kapasiteettia. Testipenkit ja niihin liittyvä valmistusdokumentaatio laaditaan EPLAN-ohjelmistolla, ja valmistusprosessi ulkoistetaan erikoistuneelle sähkökeskusvalmistajalle. Työssä esitetään vaatimukset ja niiden täyttäminen sekä valmistusdokumentaation suunnitteluperiaatteet.

Työssä kuvataan määritellyt vaatimukset, suunnitteluprosessi sekä se, miten vaatimukset toteutuvat kehitetyissä ratkaisuissa.

Projektin tuloksena syntyy joukko valmiita testipenkkejä, jotka lisäävät laboratoriotestauksen kapasiteettia ja ovat helposti muunneltavissa.

Kieli: Englanti

Avainsanat: Testipenkki, taajuusmuuttaja (VFD), generaattori

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Abstract

Test benches are used by WE Tech Solutions to ensure the functionality of their solutions in a small-scale and safe laboratory environment before on-board implementation. As the company develops custom-tailored solutions for each project, laboratory testing is essential to ensure functionality and reliability.

This thesis focuses on the design and development of new test benches that meet current functional requirements while expanding the company's laboratory testing capacity. The test benches and associated manufacturing documentation are developed using EPLAN, and the manufacturing process is outsourced to a specialized electrical cabinet manufacturer.

The requirements and how they are met will be explained in the thesis as well as the design of the manufacturing documents.

The thesis describes the defined requirements, the design process, and how the requirements are fulfilled through the developed solutions.

The result of the project is a set of completed test benches that increase laboratory testing capacity and are easily modifiable.

Language: English

Key words: Test bench, frequency converter VFD, Generator

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Abbreviations

VFD – Variable Frequency Drive

PM – Permanent Magnet

RPM – Revolutions Per Minute

DC – Direct Current

AC – Alternating Current

SG – Shaft generator

HV – High voltage

LV – Low voltage

MV – Medium voltage

PLC – Programmable Logic Controller

FAT – Factory Acceptance Test

PWM – Pulse Width Modulation

CPP – Controllable Pitch Propeller

FPP – Fixed Pitch Propeller

1 Introduction

Test benches are essential equipment because they enable verification of software and hardware functionality and safety in a controlled test environment. If a system functions correctly in a test environment, it is much more likely to perform reliably in a real-world application. In some cases, testing the real application may be time-sensitive, so it is essential to thoroughly test most functionality beforehand to ensure the system operates as expected.

The term "test bench" is broad and refers to setups used to test various types of equipment or software. In this thesis, the test bench refers to an electrical panel used for software testing.

1.1 Project

The project involves planning new test benches for WE Tech's laboratory. The scope of the project included planning, preparing manufacturing documents, following the manufacturing process, and putting them into use. Since application engineers are the primary users of these test benches, the project will be conducted in close collaboration with them. There will be regular follow-ups to ensure all functionality is met.

The solutions provided by WE Tech Solutions are on a large scale, which cannot easily be tested before the system is up and running. Most solutions are project-specific, and to ensure they work, these test benches are required. With these benches, it is possible to test functionality at a smaller scale in a safe environment before the real system is installed.

The real application cannot be tested until everything is connected, and by then, there is usually little time left. This is why a laboratory with as realistic a simulation as possible is necessary.

1.2 Background

WE Tech Solutions offers environmentally friendly solutions for ships through technology. There is no standard solution that can be tested and verified to work across all solutions, as they are custom-tailored to each ship. This means that every solution must be tested

and verified to work in the laboratory. The simplest way to test different solutions is with test benches, where it is possible to connect the different solutions and simulate different scenarios.

WE Tech Solutions already has a laboratory containing test benches for this purpose. The capacity of the test benches is too low due to the company's growth. To continue testing all solutions and verifying their functionality, new test benches must be acquired. The older test benches have been modified since they were built, as the solutions have evolved over time. This means that new test benches must be developed and designed to support current and future solutions.

1.3 Goal

The goal of this project is to design and develop new test benches for the laboratory that can handle solutions developed by WE Tech Solutions and increase the laboratory's capacity to test more solutions simultaneously. New components are also being used with the new test benches, ensuring they work when integrated into solutions.

The manufacturing documents must be prepared and saved for future modifications of the test benches, along with the electrical files.

1.4 Client

WE Tech Solutions Oy is a company working towards zero-emission shipping through technology. They have been around since 2010 and have so far provided solutions for more than 250 projects. They specialize in using variable-frequency drives, permanent magnet generators, and DC-link technology to deliver cost-effective, environmentally friendly solutions for the shipping industry.

They are a company specializing in planning and developing solutions. These solutions are tested in their own laboratory in Vasa to ensure their functionality by simulating the solution.

2 Theory

This theory will briefly explain the main parts used in the test benches as well as the tool used to develop the manufacturing documents. This will be done to improve the understanding of this thesis.

2.1 AC generator

A generator converts mechanical energy into alternating current. It does this by using magnetization, because a changing magnetic field is what induces voltage in a conductor. When the magnetic field from the generator's field windings sweeps across the armature windings, it creates an electrical current by forcing electrons in the wire to move. (Electrical4U, 2024)

Field windings are the part of a generator responsible for creating the magnetic field, while the armature windings are the coils where electrical power is produced. (Nasir, 2024)

An AC generator produces an alternating current, often represented by a sine wave (example in figure 1). The current rises to a peak, reverses direction, and falls to the opposite peak. One period is completed when the sine wave goes through a full cycle of 360 degrees and returns to its starting point.

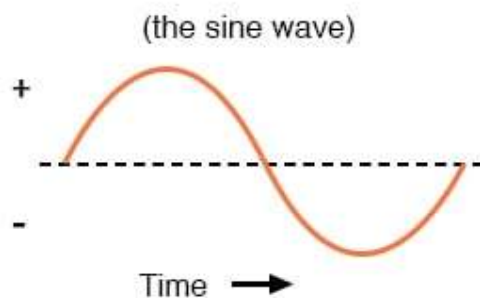


Figure 1 AC Sine wave (All About Circuits, n.d.)

The number of periods completed in one second depends on the generator's rotational speed and the number of pole-pairs it has. This is called the frequency, measured in hertz (Hz). In other words, the frequency of an AC generator is determined by how fast it rotates and how many poles are on the rotor.

Generators create magnetization by using either field windings supplied with current or permanent magnets to produce a magnetic field.

2.1.1 Permanent magnet generator

A permanent magnet generator is a type of generator that uses permanent magnets instead of field windings to create the magnetic field needed for electricity production. Because the magnets provide a constant magnetic flux, PMs do not require an external power source for excitation, making them simple, reliable, and highly efficient.

Thanks to its permanent magnetic field, the generator continuously induces voltage during rotation, and the output voltage rises proportionally to the rotational speed.

2.2 VFD – Variable Frequency Drive

Different terminologies are used for systems that alter the frequency. The most common are “Adjustable frequency drive”, “Frequency converter”, and “Variable frequency drive”. For this thesis, the term “variable frequency drive (VFD)” will be used.

The intermediate circuit has many names. In Danfoss's “Facts Worth Knowing about AC Drives” it is referred to as an intermediate circuit, in Figure 2 it is referred to as DC BUS, and in this thesis, it will be referred to as DC link.

The VFD can be split into different voltage categories: LV is up to 1000V, MV is from 1000V to 35kV, and HV is above 35kV. Even though they are divided into different categories, they still utilize the same working principle.

VFD's are used to adjust the speed of an electrical motor with high accuracy (Danfoss Drives, 2019). They convert power at one frequency to power at a desired frequency. For example, if an electrical motor must spin at a certain speed, it can be adjusted with a VFD. This brings down costs by allowing the motor to match the demand instead of running at full speed constantly.

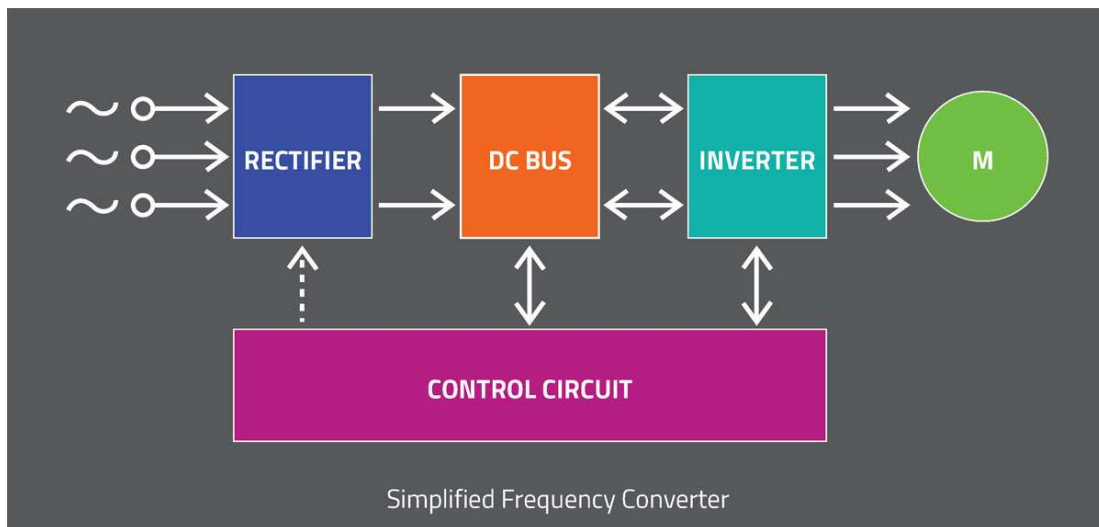


Figure 2 VFD functionality overview (Messung Group, n.d.)

The VFD consists of four main components that will be explained in the sections below.

2.2.1 Rectifier or Converter

A rectifier converts AC (single-phase or three-phase) to DC.

The simplest type is the uncontrolled rectifier, which uses a diode bridge to convert AC to DC. These are commonly used in low- to medium-power applications.

For higher power applications, typically above 37 kW, half-controlled rectifiers are used. They combine diodes and thyristors, allowing partial control of the DC voltage and limiting inrush currents. The maximum DC voltage is similar to that of an uncontrolled rectifier.

Fully controlled rectifiers use only thyristors, allowing full control of the DC output voltage. However, they introduce higher losses and can cause more disturbances on the supply grid, requiring filtering.

Active Front End (AFE) rectifiers use IGBTs to convert AC to DC. They provide precise voltage and current control, reduce harmonic distortion, and can allow bidirectional power flow, enabling energy regeneration. AFEs are common in modern high-performance VFDs. (Danfoss Drives, 2019)

2.2.2 Intermediate circuit or DC BUS

The DC link is the middle part between the rectifier and the inverter that holds the DC voltage before the inverter transforms it to AC.

When multiple units should be controlled with VFDs, it is possible to use a common DC link, where, for example, one rectifier feeds a DC link that has multiple inverters connected to it. An example can be seen in figure 3. (Danfoss Drives, 2019)

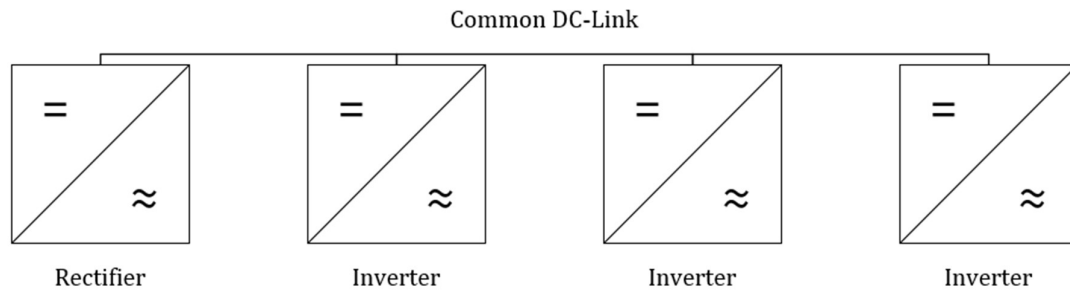


Figure 3 Common DC-Link (author's own illustration)

2.2.3 Inverter

The inverter is the final stage of a variable frequency drive (VFD), and its job is to convert the DC voltage from the DC link back into AC with a controlled frequency and voltage. It does this using power electronic switches, typically IGBTs, that turn on and off rapidly to create a pulse-width modulated (PWM) output. By adjusting the switching pattern, the inverter controls the motor's speed and torque by delivering AC power at the exact frequency and voltage needed. This stage allows the VFD to operate the motor smoothly, efficiently, and with precise speed regulation. (Danfoss Drives, 2019)

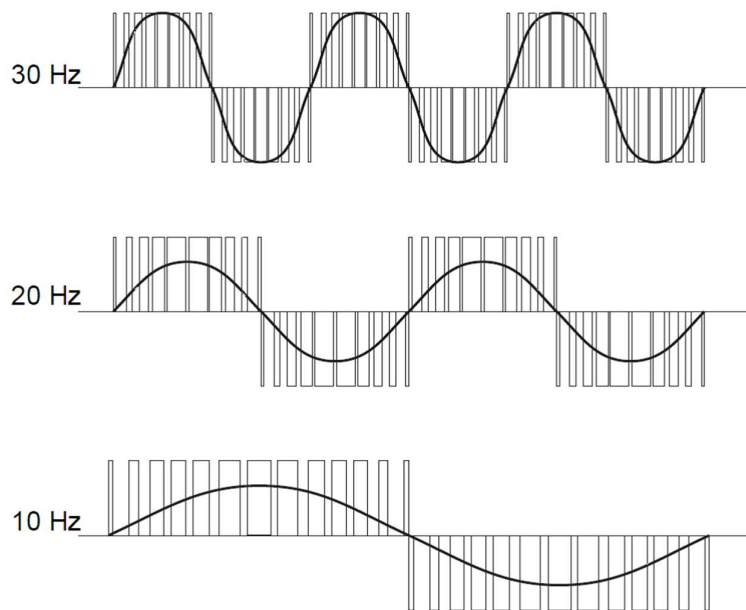


Figure 4 PWM example (Glampe, 2021)

In Figure 4 it can be seen how PWM switches on and off to simulate an AC sine wave at different frequencies. Where the line going up and down is the switching on and off, and the wave is the output from the VFD in a perfect world.

2.2.4 Control circuit

The control circuit is the part of the VFD responsible for monitoring, regulating, and coordinating the operation of the rectifier, DC link, and inverter stages. It consists of low-voltage electronics, sensors, and a microcontroller or DSP that processes feedback signals such as current, voltage, and motor speed. Based on this information, the control circuit adjusts firing angles, switching patterns, and protection functions to ensure stable operation, accurate motor control, and safe response to faults. It is essentially the “brain” of the VFD, managing both performance and protection. (Danfoss Drives, 2019)

2.3 Filter

There are different kinds of filters for drives with different purposes to either protect the motor driven by the VFD or to protect the grid from where the power is taken. VFD’s works by cutting the part of an AC sine wave that they need to produce a DC voltage. This is altering the sine wave form on the grid side, which is called harmonic distortion. The

harmonic distortion can cause issues for other components on the grid, for example, overheating. The harmonic distortion is not only caused by drives but also by all non-linear loads on the grid and these harmonic distortions can be reduced with filters. (Danfoss, n.d.)

Converting DC to AC by using the PWM principle does not create a perfect sine wave, as can be seen in Figure 4. This can cause steep voltage pulses that may damage the motor's insulation, and the high switching frequency can cause EMC disturbances. They can already be filtered in the drives, but in some cases, they must be separately filtered. (Danfoss, 2024).

2.4 Programmable Logic Controller

A programmable logic controller (PLC) is an industrial computer that performs logical decisions based on how it has been programmed. It was originally developed in the late 1960s and 1970s as a replacement for relay-based control systems. Early PLCs provided basic functions such as timers and counters, eliminating the need for complex hardwired relay logic. They were primarily used as on/off logic to control motors, sensors, and other industrial equipment. (Process Solutions, INC., 2025)

As PLC technology has evolved, it has become a crucial component in modern automated systems. Today, integrated control systems allow multiple PLCs to work together to control large factories and processes automatically. Visual indicators such as lamps have largely been replaced by Human-Machine Interfaces (HMIs), which allow operators to monitor and interact with the system. (Schneider Electric, 2025). Through an HMI, users can view data such as tank levels, pipe temperatures, conveyor belt speeds, and other process variables from a single location.

The PLC acts as the “brain” of the control system and contains a number of input and output (I/O) points. Modern PLCs can handle far more I/O than what is built into the base unit. Additional I/O cards can be connected to expand the system as needed. In some applications, I/O devices must be located away from the main PLC. This is achieved using remote I/O racks, which communicate with the PLC via Ethernet or other industrial communication protocols to exchange data reliably. (Antaira, 2025)

2.5 Shaft generator solutions

Shaft generators have long existed, but in the early 2000s, they were most common on larger container vessels that sailed fixed routes. That meant they could maintain a fixed speed with a fixed-pitch propeller and therefore use shaft generators that must rotate at a constant speed to produce a constant frequency. At the same time, controllable pitch propellers could be installed to adjust the speed while the main engine kept a constant RPM. When the price of frequency converters has lowered in recent years, it has allowed solutions where frequency converters can be used with the shaft generators to generate power at different frequencies. This can be utilized with both CPP and FPP. (MAN Energy Solutions, 2021)

Vessels with a fixed-pitch propeller can utilize the frequency drives to produce power at various speeds. This allows the vessel to adjust its speed without the need for additional power generation from a genset, which saves on fuel and emissions. The controllable pitch propeller can already adjust its speed without adjusting the RPM of the main engine, but the efficiency of the propeller is low at low pitch during low loads.

Many different solutions have been designed for the shaft generator. For example, the generator can be mounted on the front of the engine, directly on the shaft, on the shaft with a gear/clutch, and more ways. And since the prices of frequency converters have come down, new solutions using VFDs to either take power from the generator or feed the generator have been developed. These solutions, called PTO and PTI, will be explained in sections below. (MAN Energy Solutions, 2021)

2.5.1 Power Take-Out Solution

The Power Take-Out (PTO) mode is a solution that allows the customer to use the SG as a power source over a wide RPM range by utilizing VFD technology. The VFD draws power from the SG at a wide range of operating frequencies and converts it to the grid's required frequency. Simple illustration can be seen in figure 5. (WE Tech Solutions Oy, n.d.)

With a CPP, it is possible to adjust the propellers so that the ship is not moving. This allows the main engine to keep running during short port visits and while mooring. With a shaft generator solution, it is possible to lower the main engine's RPM to reduce vibrations. This

allows the main engine to keep running and producing power, reducing the need for an additional auxiliary engine during this short period. (GreenVoyage 2050, n.d.)

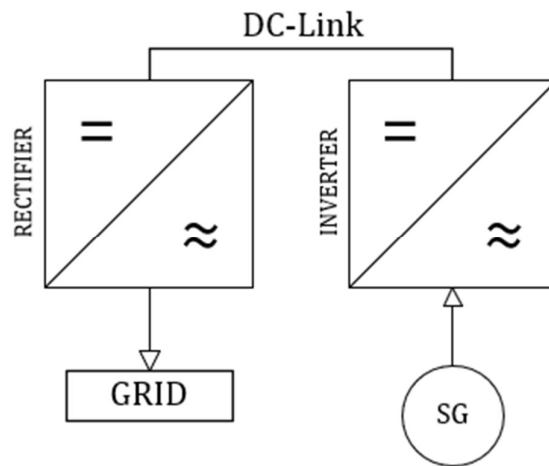


Figure 5 (author's own illustration)

2.5.2 Power Take-In solution

The Power Take-In (PTI) mode is a solution where other power sources, such as batteries or generators, can be used to boost the main engine or drive the shaft itself. A clutch must be installed between the main engine and the shaft generator to allow the shaft generator to drive the shaft directly by itself. When the option to drive the main engine exist it is usually called Power Take-Home (PTH). These solutions can be used when operating in port during low-load conditions or sailing through ice to give extra power to the main engine. (CM Energy, 2025)

With the option to feed the generator and use it as a motor, another solution is possible. A clutch can be added between the main engine and the SG to facilitate the possibility of disconnecting the main engine from the shaft. When the main engine is disconnected from the shaft, it is possible to run the shaft and propeller with just the generator as a motor. If the main engine is locked up and won't rotate, this solution is a good way to reach a safe anchorage place or the closest port.

Figure 6 is an overview of a PTI solution where the power can both go from the SG to the grid and from the grid to the SG.

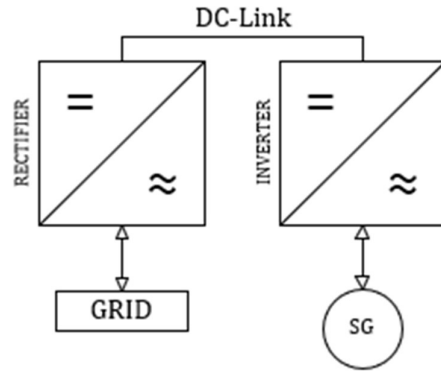


Figure 6 (author's own illustration)

2.5.3 DC-Link power distribution

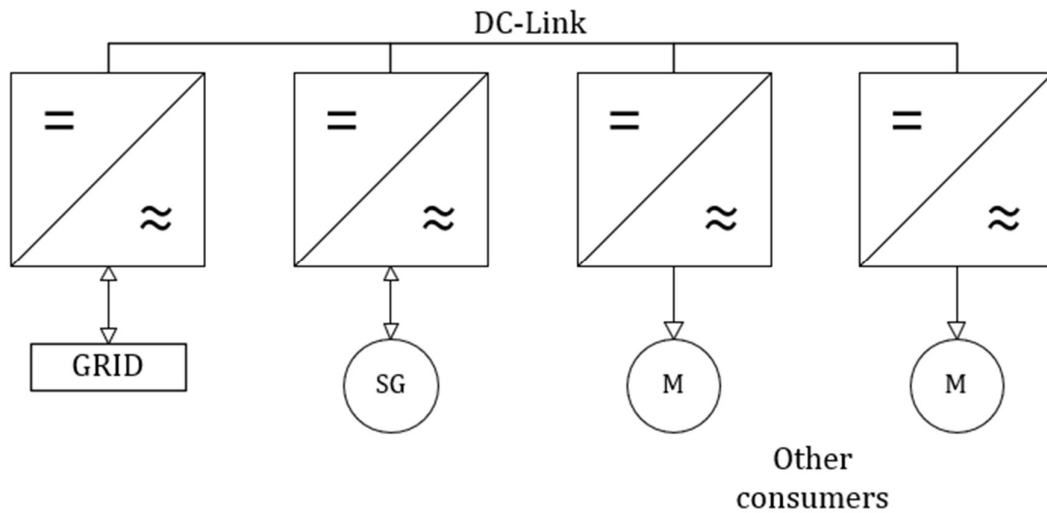


Figure 7 DC-Link power distribution example (author's own illustration)

DC-link power distribution can be combined with either PTO or PTI, offering the possibility of powering and controlling electrical consumers, such as fans and motors, directly from the DC-link as can be seen in a simple overview in figure 7.

2.5.4 Hybrid Electric Propulsion

As previously mentioned, most frequency converters have a DC link. With a DC/DC converter, batteries can be connected relatively simply to the solution. In Figure 8 a simple overview of such a solution is available.

The batteries can be used in ports or for peak-shaving during temporary high loads. Removing the need to start an additional generator for a short, temporary high load.

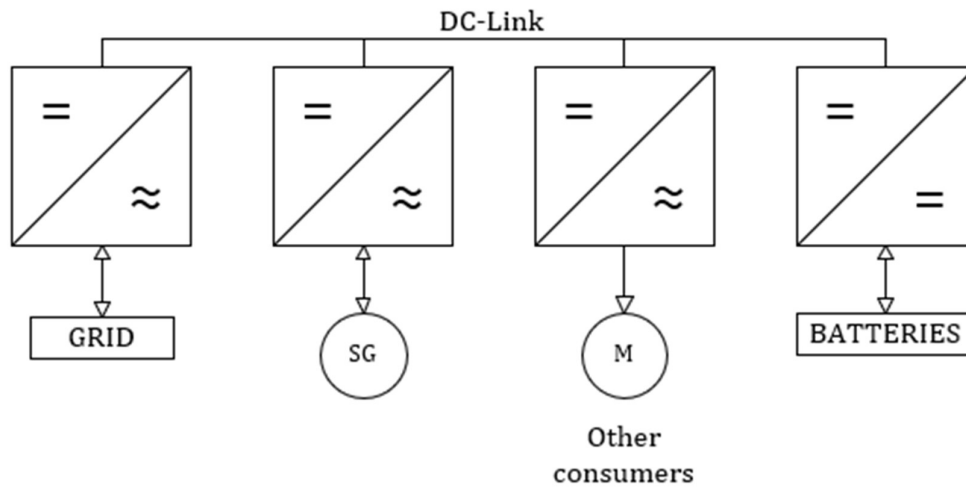


Figure 8 Hybrid Electric Propulsion (author's own illustration)

2.6 EPLAN Electric P8

EPLAN was founded in 1984 by Winfried Müller as a tool to create schematics digitally. Friedhelm Loh invested in the company in 1986, and it has grown into a global company with 50 locations worldwide and 68,000 customers. The Friedhelm Loh Group owns a portfolio of companies, including EPLAN and Rittal. One is a leading supplier of enclosures and related components, while the other is CAD software used to design circuit diagrams and layouts for electrical cabinets. (EPLAN, n.d.)

EPLAN offers a wide range of solutions, from designing circuit diagrams in Electric P8 to creating 3D panels in Pro Panel. While Pro Panel is used for panel design, Electric P8 also supports 2D panel design. Other solutions exist, such as cable proD, which lets users plan cable lengths from the Pro Panel, and Harness proD, which lets users combine mechanical and electrical designs to create cable harnesses. (EPLAN, n.d.)

EPLAN offers a cloud where manufacturers can upload their parts, including 3D models, data, and symbols. This cloud can be used to download the data, which saves time on manually entering it and saves time on 2D/3D models by offering already made models for the components. Manufacturing documents generated with EPLAN use data from the part database, which is updated when data is downloaded from the cloud.

EPLAN Electric P8 automatically connects components when they are placed and automatically updates lists, such as part lists, connection lists, terminal diagram or other affected lists/diagrams.

3 Assignment

The assignment is to develop and design new test benches that must meet specific requirements while increasing laboratory capacity. These requirements ensure that the functionality is satisfactory and that the design is logical, with components at a comfortable height, depending on their intended use.

3.1 Functional requirements

The test benches must be easily modified to ensure that most projects can be tested. The figures below are attached to provide a better understanding of why the benches must be easy to modify and what kind of functionality might need to be tested.

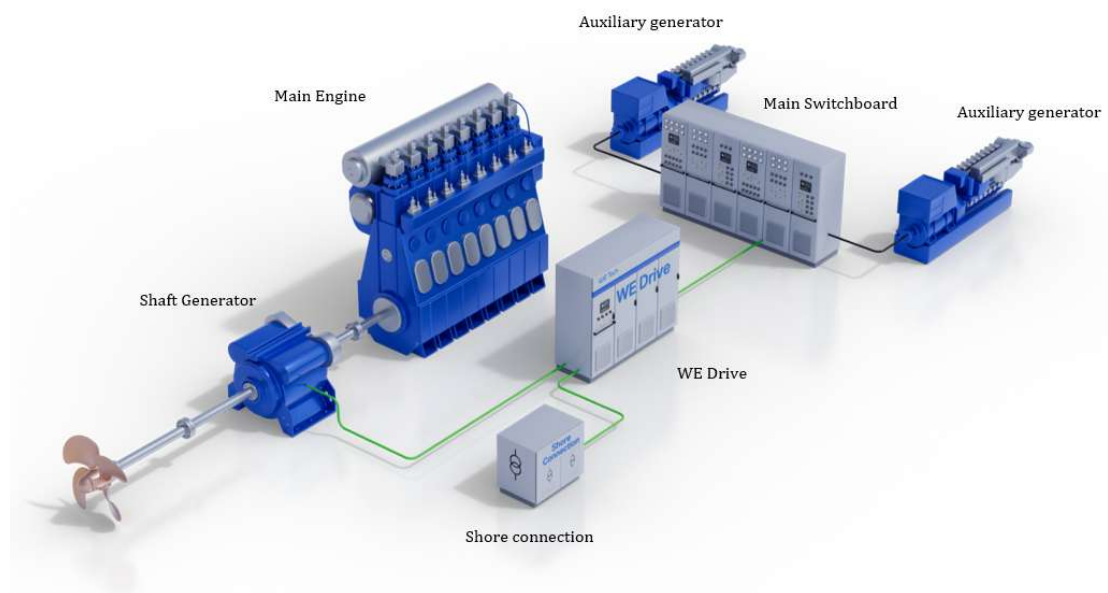


Figure 9 PTO solution overview example (WE Tech Solutions internal documents)

The figure above (figure 9) represents an example of a simple PTO solution that generates power to the grid and might have shore connection supply. This is a system that can be tested in the laboratory and here the “Main Engine”, “Shaft Generator”, “WE Drive”, and “grid” must be simulated.

This means a main engine capable of delivering adjustable RPM is required and must be connected to a PM generator. This main engine must be able to rotate slowly enough for the generator to generate power at the minimum required frequency, and fast enough that the generator can generate power at the maximum required frequency.

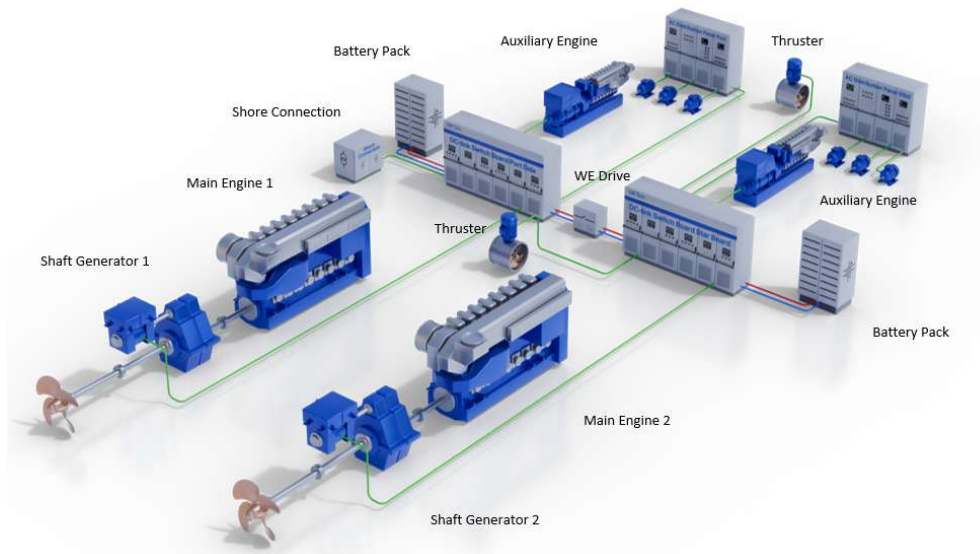


Figure 10 Hybrid Electric Solution (WE Tech Solutions internal documents)

Figure 10 is an example overview of a more complex solution where the WE Drive is connected to battery packs, thrusters, two shaft generators, and a shore connection. This provides a clear understanding of how the test benches must be configurable to support all solutions.

It is also important that the solutions can simulate PTI mode, which feeds power to the shaft generator to simulate a boost or “Take Me Home” mode. If the solution is a “DC-Link power distribution” it must also be able to feed different power consumers, for example, fans or pumps.

3.2 Design requirements

The test benches will be installed in a room with limited space. This means that the test benches and motors cannot be too large, and the possibility of moving them is necessary. The test benches must also be designed to have extra space for modifications since the solutions offered might change and new functionalities can be implemented.

The test bench components must be logically designed, and a clear visual representation of the functionality must be provided on the panel door to make what's happening easy to identify.

3.3 Documentation requirements

Manufacturing documents must be prepared since the manufacturing will be outsourced to a company specializing in manufacturing electrical cabinets. The required documents are the circuit diagram, part list, connection list (including wire markings), terminal diagram, layout scheme, cut-out scheme, and mimic scheme.

All these documents must be prepared in EPLAN Electric P8, and the files must be saved to easily document future changes.

4 Solution & Execution

This chapter will focus on what will be done to meet all requirements mentioned in Chapter 3 "Assignment".

To address the challenge of simulating a main engine and a permanent-magnet shaft generator, two electrical motors will be used. One motor will represent the main engine, while a second (permanent magnet) motor will simulate the shaft generator. The two machines will be mechanically coupled to replicate their configuration on board a vessel. The first motor (main engine) will be controlled by a VFD to produce different RPMs. The permanent-magnet motor will be connected to a separate VFD and operated as a generator to simulate the behavior of a shaft generator under operating conditions.

To simulate a PTI solution boosting the main engine, the PM motor used as a generator will be fed with power. Depending on whether it is PTI or PTH, it will either boost the motor or drive it.

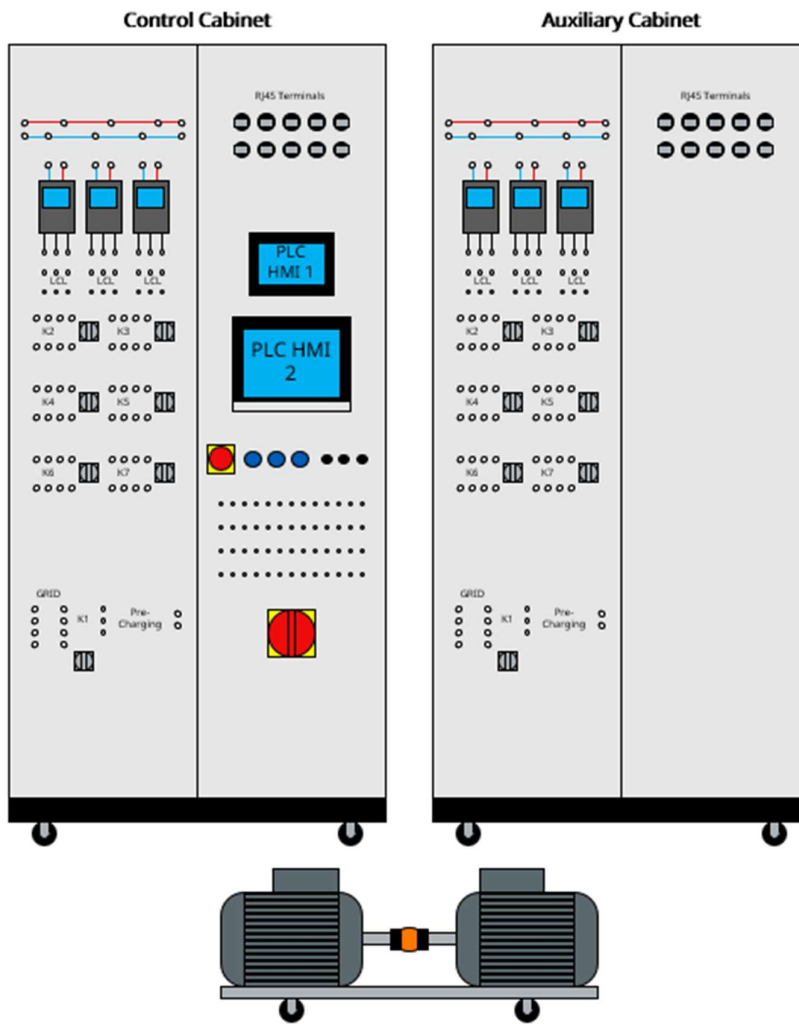


Figure 11 Example overview of test benches. (WE Tech Solutions internal documents)

An example overview is shown in the figure 11 and will be described in this chapter.

4.1 Mechanical design

The test bench will be divided into two electrical cabinets, each containing three drives, resulting in a total of six drives per test bench. Splitting the test bench into two cabinets allows each cabinet to be narrower than a single long enclosure, making the system easier to install logically into the laboratory layout, which has limited space. One bench will work as the control cabinet containing HMI, PLC, and main components, while the second cabinet will work as an auxiliary cabinet carrying parts.

4.2 Electrical configuration

The test benches will include a power cable that plugs into the wall for quick connection/disconnection. Most components with connections that may differ from project to project are connected to banana contacts on the panel door. This is done for the ease of modification that banana plugs provide. They can be easily connected or disconnected to wherever they need to go.

LCL Filters will be installed inside the benches for easy connection with banana plugs. This will prevent the need for external filters, and when installed at the bottom of the cabinet, it will lower the center of gravity. Having these connected to banana plugs will offer the possibility of using the filters or not.

The test benches will be divided into two separate cabinets to simplify installation in the laboratory. This raises a safety concern: if cabinet one is energizing cabinet two and cabinet two is opened, there is a risk of electric shock that could cause serious injury. To reduce this risk, door-operated switches will be installed in both cabinets. These switches will detect when a cabinet door is opened and will immediately trigger the emergency stop circuit, disconnecting power and ensuring safe access.

The smaller VFDs available provide terminals for AC input, AC output, and the DC link, making them particularly well-suited for this application. Depending on the configuration, they can operate as a rectifier, inverter, or frequency converter. All main drive connections will be routed through banana plugs, allowing the number of drives in each configuration to be easily changed or reassigned to different functions.

In addition to the drives, other mains connections will also be routed through banana plugs to facilitate rapid modification. These include connections for contactors (which can be operated either manually or via a PLC), the 400 V grid supply, and protective earth (PE).

Banana plugs connectors provide an additional advantage by simplifying fault-seeking. Troubleshooting inside a cabinet containing many internal conductors is significantly more difficult than performing diagnostics externally, where only the main connections are present. Using banana plugs allows measurements and reconfiguration to be carried out outside the panel, improving accessibility and visibility. This approach also minimizes the

risk of damaging internal wiring during fault-seeking or modifications, as fewer interventions are required inside the cabinet.

4.3 Control system

PLCs will be used to control the test benches, and because two different PLC manufacturers are used, two PLC systems will be installed. Each will have an HMI on the panel for monitoring and control, as in a real application. The PLC will be mounted on the outside of the panel to simplify user access, while the I/O rack will use remote I/O and be mounted inside the panel.

4.4 Manufacturing Documents

The manufacturing of the test benches is being outsourced to a company specializing in manufacturing electrical cabinets. They require the following documents for manufacturing:

The circuit diagram in EPLAN serves as the basis for this project, all lists are generated and updated from it. If something changes in the circuit diagram, it will also change in the lists and diagrams. The circuit diagram will include all electrical components in the test benches and show how they are connected.

The part list contains all the parts in the circuit diagram. When a part in the circuit diagram is defined by a part number, it reads that number from the part database and displays the corresponding information in the part list.

The terminal diagram is a collection of all terminals in the circuit diagram. It can be used as a checklist to see that wires are connected correctly. It also indicates whether any terminals are free, without requiring the cabinet to be opened and checked manually.

The connection list is a list of all wires in the circuit diagram, showing their sizes and where they connect. This list is customized to also display the wire markings, which must be printed and attached to all wires. This must be done in case a wire is removed to easily identify where it came from. Many printers for these markings support lists imported from Excel. With EPLAN, it is possible to export these lists to Excel, which will be done for the manufacturers.

The layout diagram was created in close collaboration with the application engineers, who already had a clear idea of how they wanted the layout. Components were designed at a comfortable height, depending on how often they are used. For example, HMIs, which are often checked, were placed at average face height.

The internal component layout was also designed to simplify the manufacturer's work and align with our needs. Many components lacked suitable 2D models in EPLAN Electric P8, so most were created from scratch.

EPLAN already had the panel in the EPLAN cloud, which simplified the process by allowing it to be dragged and dropped. EPLAN provides a 2-panel layout list from which the remaining components used in the circuit diagram can be dragged and dropped.

The cut-out diagram shows all panel measurements and the locations of each cutout. For the cut-out diagram, the panel was dragged and dropped again into the circuit, and the layout components were copied into the diagram. After being copied, they were replaced one after another with the cutout scheme for that component, as specified in the supplied data sheets.

When creating a cutout scheme or layout, it must be checked whether the internal frame or other structural elements might interfere with the components. The frame was manually drawn on the outside of the panel for these documents to prevent placing components where the structure would interfere.

Mimic diagram

A visual mimic will be implemented to provide a clear overview of the internal cabinet configuration, without requiring circuit diagrams or opening the cabinets. The mimic will indicate how components are interconnected and show their functional relationships simply.

For example, the banana plug connectors will be connected with lines indicating which component they are connected to, and protective earth (PE) banana plugs will be clearly marked with a printed PE symbol. This improves usability, reduces setup time, and enhances safety by minimizing the need for cabinet access.

These were done by copying the cut-out diagram and drawing an overview of what is happening inside. These were exported from EPLAN in an AutoCAD-compliant file format to match the manufacturer's printing process.

4.5 Manufacturing

Manufacturing was outsourced to a company specializing in the manufacturing of electrical cabinets. During manufacturing, a few issues arose due to design errors. On the inside of the panel door, there was a gasket that was not shown in the panel's data sheets or drawings. Components were planned in this place and had to be moved. Some indicator lights were the wrong model due to incorrect part numbers.

Because what it looks like on paper and in reality differs, some components did not fit as planned. These components had to be moved, and the layout, cutout, and mimic had to be updated.

4.6 FAT

A factory acceptance test was conducted once the test benches were built. Functionalities were tested during the FAT to ensure that everything was working properly. Issues found could be corrected before they left the factory.

Issues found were design mistakes, for example, a wire color was set incorrectly in a few places due to a copy-paste mistake. These wires were replaced when the test benches arrived at the laboratory. A switch had an internal jumper that was not accounted for in the design, and it was not noticed before the FAT.

5 Result

The thesis resulted in fully functional test benches now located in the WE Tech Solutions laboratory. They meet the functional requirements and can be easily modified to simulate different solutions. There are electrical motors with banana plug connectors for quick, safe connection, and filters are included inside the panel. They have enough internal space to accommodate future changes, as well as enough space on the panel doors for additional components. They are equipped with three-phase cables that plug into the wall and a set of wheels underneath. Which ensures they are easy to move if needed.

The following documents were created in EPLAN Electric P8 to support the test bench solution and now serve as a reference for future modifications. The documents can also be used when manufacturing new test benches or as a basis for a new test bench design.

- Circuit diagram.
- Part list.
- Terminal diagram.
- Connection list.
- Layout scheme.
- Cut-out scheme.

The part list, terminal diagram, and connection list were less time-consuming than the other parts because of EPLAN Electric P8 automation. It automatically updates the lists once they have been generated. Generating the first version of the lists was the most time-consuming since it required some understanding of how EPLAN works to get the lists as required.

The development of new test benches has increased capacity at the WE Tech Solutions laboratory. The laboratory required minor modifications to accommodate the test benches. Old storage cabinets had to be removed to make room for the test benches, and electrical outlets had to be installed to power them.

6 Discussion

I'm satisfied with the result of the test benches, even though there are some parts that I would do differently if I made them again. And mistakes that should not have happened, but they have been a good learning experience.

This thesis has been a valuable learning experience in planning and design, what to consider, and the importance of reviewing everything again to prevent unnecessary mistakes. It has also shown the importance of not copy-pasting too much.

This was the first time I made a circuit diagram from scratch for a bigger project, the first time I made a layout for any project, the first time I made a mimic for any project, the first time I made a cut-out scheme for any project, and the first time I used EPLAN. Even though there were many firsts with this project, I'm happy with the result.

If I were to remake the test benches, I would use larger cabinets to better fit the components and leave even more room for future add-ons.

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