Rapid Prototyping Systems
In Wärtsilä Laboratory

Tobias Birell

Bachelor's Thesis

Electrical Engineering

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BACHELOR'S THESIS

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Abstract

This Bachelor's thesis was commissioned by Wärtsilä Finland Oyj Engine Laboratory in Vaasa. The goal of the thesis was to get a wider understanding of the rapid prototyping unit on a Wärtsilä 20 engine and to produce a complete documentation of the system, including electrical drawings. It was of great importance to develop a new template for this type of drawings. The system consists of two MicroAutoBoxes from dSPACE GmbH, which control the intake- and exhaust valves electro-hydraulically.

During the Autumn of 2011 a similar system, with briefly the same setup, was constructed on Single Cylinder Engine (SCE) in Vaskiluoto. This system has only one, but more powerful MicroAutoBox unit. The automation cabinet for SCE was planned and designed. Drawings were also made for SCE. After all documentation had been done, the cabinet was also constructed.

Language: English Key words: dSPACE; MicroAutoBox; EHVA; AutoCAD

EXAMENSARBETE

Författare:	Tobias Birell
Utbildningsprogram:	Elektroteknik
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Titel:	Rapid Prototyping System i Wärtsiläs laboratorium

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Abstrakt

Detta ingenjörsarbete är gjort för Wärtslilä Finlands motorlaboratorium i Vasa. Målet med arbetet var att få en bredare uppfattning av vår Rapid Prototyping enhet installerad på en Wärtsilä 20 motor och åstadkomma en komplett dokumentation av systemet, inklusive elritningar. Det var av stor vikt att utveckla en ny botten för den här typen av ritningar. Systemet består av två stycken MicroAutoBox enheter från dSPACE GmbH, som styr insugs- och avgasventilerna elektrohydrauliskt.

Under hösten 2011 konstruerades ett liknande system med motsvarande upplägg för en encylindrig motor, Single Cylinder Engine, på Vasklot. Detta system använder sig utav endast en, men mera kraftfull MicroAutoBox enhet. Automationsskåpet för SCE planerades och designades. Även SCE försågs med ritningar. Med dokumentationen färdig, konstruerades skåpet.

Språk: Engelska Nyckelord: dSPACE; MicroAutoBox; EHVA; AutoCAD

OPINNÄYTETYÖ

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Nimike: Rapid Prototyping Järjestelmiä Wärtsilän Laboratoriossa

Päivämäärä: 29.04.2012 Sivumäärä: 28 Liitteet: 3

Tiivistelmä

Tämä insinöörityö on tehty Wärtsilä Suomi Oyj:lle, moottorilaboratoriossa Vaasassa. Insinöörityön tavoitteena oli saada laajempi ymmärrys Wärtsilä 20 moottorin Rapid Prototyping laitteistosta, ja samalla saada järjestelmä dokumentoitua ja piirrettyä sähköpiirrustuksiin. Oli todella tärkeää kehittää uusi pohja tällaisiin piirrostuksiin. Järjestelmä koostuu kahdesta MicroAutoBox:sta dSPACE GmbH:stä, mikä ohjaa imu- ja pakoventtiilit sähköhydraulisesti.

Syksyn aikana vuonna 2011 vastaavan järjestelmä rakennettiin Single Cylinder Engine:en Vaskiluotoon. Tämä järjestelmälla on ainut yksi, mutta voimakkaampi MicroAutoBoxi. Automaatio kaappi suunniteltiin ja asennettiin. Piirustukset tehtiin myös SCE:lle.

Kieli: Englanti Avainsanat: dSPACE; MicroAutoBox; EHVA; AutoCAD

Arkistoidaan: Theseus.fi

Contents

ABBREVIATIONS

Abbreviation	Description
AI	Analog In
AO	Analog Out
BDC	Bottom Dead Center
CA	Crank Angle
CAD	Computer Aided Design
CR	Common Rail
DI	Digital In
DO	Digital Out
EGR	Exhaust Gas Recirculation
EHVA	Electro Hydraulic Valve Actuation
EVC	Exhaust Valve Close
EVO	Exhaust Valve Open
I/O	Input / Output
ILC	Iterative Learning Controller
IVC	Inlet Valve Close
IVO	Inlet Valve Open
MABX	MicroAutoBox
PLC	Programmable Logic Controller
R&D	Research and Development
SCE	Single Cylinder Engine
TDC	Top Dead Center
TUT	Tampere University of Technology
VIO	Variable Inlet Openining

FOREWORD

I want to thank the whole personnel at the Wärtsilä Laboratory in Vaasa for all the support and help during my work on the thesis and everything else. A special thanks to Guy Hägglund and Tony Glader at the Laboratory and Matts Nickull at Novia for being my contact persons.

29.04.2012

Tobias Birell

1 The Company

Wärtsilä Oyj is a Finnish corporation manufacturing and serving power sources and other equipment in the marine and energy markets. The main products are large combustion engines. The company employed 17,875 workers in more than 70 countries at the end of September 2011. The headquarter is located in Helsinki. Wärtsilä was founded in 1934 in Tohmajärvi eastern Finland. In 1936 Wärtsilä acquired the workshop of "Onkilahden Konepaja" (Onkilahti Engineering roughly translated) in Vaasa. [7]

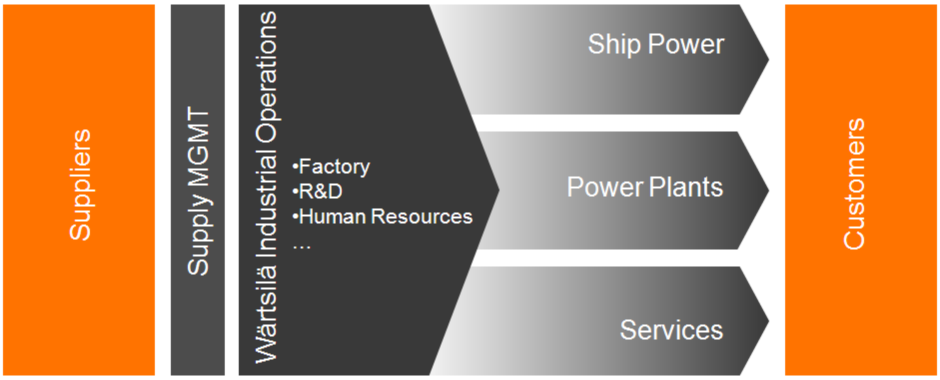


Figure 1. Wärtsilä organisational structure in a customer perspective.

Ship Power is the leading supplier of machinery, propulsion- and maneuvering systems for shipping companies worldwide. Today every third ship worldwide is equipped with a Wärtsilä engine. Power Plants is a significant supplier on the power plant market. About 1 % of the world's energy consumption is produced with power plants made by Wärtsilä. Service provides customer support during the supplied systems' life cycle.

Research & Development, under which the Laboratory is working, is divided into research projects and development projects. The Laboratory has the task of carrying out tests on different engines depending on what is the main concern on that engine. [8][6]

2 Introduction to the Task

The project of installing an Electro Hydraulic Valve Actuation (EHVA) system (chapter 3.1) on the Single Cylinder Engine (SCE) in Vaskiluoto was approaching, and this time we wanted it to be documented. For other engines on which this system has been installed, there have been no drawings or documentation.

My part in this project was to investigate and analyze the existing system and automation cabinet, i.e. to document the system and its functionality, and to make drawings.

With all the drawings and knowledge in hand, I could continue to make drawings for SCE. I have also been involved in the construction of the system, especially the cabinet.

2.1 What Is Rapid Prototyping

Rapid Prototyping is by definition a procedure of creating an object (prototype) according to given instructions. An example of Rapid Prototyping would be generating a 3D model with a 3D printer according to a Computer Aided Design (CAD) drawing. Rapid Prototyping uses additive manufacturing technology for modeling. By additive manufacturing is meant that the object is built by adding material to the object. The opposite is subtractive manufacturing, where material is removed to make the desired shape. Carving wood or stone would be an example of subtractive manufacturing.

2.2 Background

In the Engine Laboratory in Vaasa, the main purpose is to test engines. Research and Development is divided into two groups whose focus is on slightly different approaches. There is research engines on which new concepts and equipment are tested, in order to try to find new and revolutionary solutions and ways to make engines. Then there is development engines that are used for validation and testing of existing products and concepts to ensure that the engines and engine parts last as long as promised. The engine for which this system is used is a W6L20 diesel engine, equipped with Common Rail (CR) injection, twin-turbo and EHVA. This is a typical example of an research engine. It is used for testing new concepts, new components and combinations of these in order to make the Wärtsilä engine comply with for further regulations and demands regarding for instance emissions and fuel economy. Finding optimal settings and timings are another quite significant part of the work on this engine.

2.3 What Was Missing

From the beginning of this project, the electrical part has been made without much planning. People involved have changed over time, and no one has really known exactly what others have done and how. When a new person was involved, usually when something does not work as it should, he would have had to start from the beginning by familiarizing himself with the system, usually with only a few sketches and Excel sheets as guidelines. What was needed was a complete documentation of the system, electrical drawings and some sort of functional description, so that any user unfamiliar with the system can find help on the subject and know where to begin. The functional description will be made with this thesis as a foundation.

3 Theory and Pre-study of Subject

As a first approach to the system, all possible information of the system was collected by talking to the people behind it. All existing documents, manuals, sketches, excel-sheets were collected. In a meeting with Tony Glader it was discussed how the system was working and what he knew about it. All his information, and all these documents helped a lot. Mr. Glader is working as a *Chief Test Engineer in Engine Automation* in the laboratory and has been involved in the project from the beginning. He has also been involved in the development of this system in collaboration with Tampere University of Technology [4].

3.1 EHVA

EHVA is a system that uses hydraulics controlled by electrical signals to operate the valves. Compared to using the engine's camshaft to operate the valves, this method is much more flexible. Changes can easily and rapidly be made, with very high accuracy. [4]

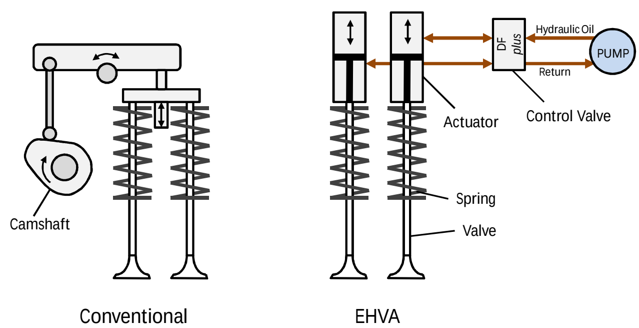


Figure 2. Conventional valve control compared to EHVA.

By using Rapid Prototyping combined with EHVA on a Wärtsilä engine, hundreds of changes and variations of our valves' behavior can be made without replacing a single camshaft. The only thing to be done is making small adjustments to the parameters in the software. Changes in parameters are made within a minute compared to installing a new camshaft, which can take up to several days.

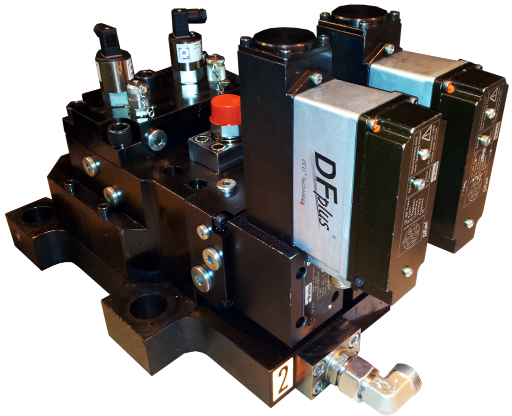


Figure 3. The 80 kg heavy EHVA block for a Wärtsilä 20 engine.

To be able to realize this, some sort of control unit is needed to process the signals. The system chosen is developed by the German company dSPACE. dSPACE offers a few possible alternatives to handle this task, both internal and external hardware. Internal hardware alternatives are not so suitable for on-engine installations, but external devices are. MicroAutoBox is one compact and robust alternative with flexible and high performance hardware. [1]

3.2 dSPACE MicroAutoBox

The Rapid Prototyping unit chosen is a MicroAutoBox of the 1st generation. See figure 4. It is a powerful unit based on IBM's Power PC Processor. Originally it is developed for the automobile industry as an Engine Control Unit (ECU), but with only minor changes in connections it is suitable to be used in a laboratory environment. Wärtsilä engines are originally equipped with their own automation system, UNIC, which may either be used in parallel to MicroAutoBox, or one can choose to have MicroAutoBox control and monitor everything. In this case both systems are connected. UNIC controls the engine as usual and MicroAutoBox controls EHVA. Speed- and phase signals are wired to MicroAutoBox and used for engine positioning in the model.

Figure 4. dSPACE MicroAutoBox 1401/1501 - ©dSPACE GmbH

The model is made in MathWorks MATLAB®'s Simulink Toolbox (or written in C), and downloaded into MicroAutoBox. This gives the user the ability to graphically draw the process without any advanced programming skills. MicroAutoBox is also connected to a PC running dSPACE's own software, ControlDesk®, which works as a user interface for the MicroAutoBox. The user can fully configure and customize ControlDesk for his own needs. More information about ControlDesk and how it works in chapter 6. In this case ControlDesk is remotely controlled via VNC (Virtual Network Computing) from the control room, where from the engine is controlled. In this way no one needs to be in the cell while the engine is running, but this also depends on the maximum length of the cable between the MicroAutoBox and the PC.

4 Documentation for 6L20CR

The engine is a straight six-cylinder W20 research engine. It is a small and stable engine suitable to test new concepts and setups. Wärtsilä automation system UNIC and Modicon PLC controls all automation on the engine. dSPACE is installed in parallel to this and controls only valves with the help of EHVA. Each cylinder has two intake valves and two exhaust valves, which makes a total of 24 valves. Since this is a W20 engine, the spring forces of the springs that close each valve are of such a size that a single EHVA block may control both intake (or both exhaust) valves at the same time. When using dSPACE controlled EHVA on this specific engine in a laboratory environment, all the advantages of customizability are beneficial to Wärtsilä. Specific timings and lift profiles are easy to maintain, and smaller as well as bigger changes are rapidly made. To ensure proper behavior of this system, feedback sensors measure the valves' positions in order to confirm the correct position of the valve.

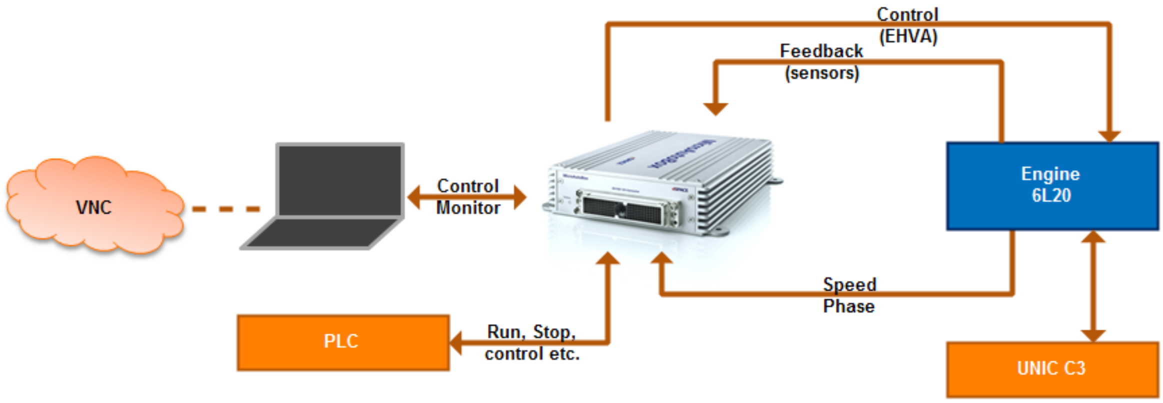


Figure 5. 6L20 automation system and auxiliary systems.

Note: This system is not intended for production engines. It is an outstanding tool for R&D engines in a laboratory, in order to optimize and develop proper configuration. When a proper camshaft profile is found, it can be taken into use by a conventional system.

4.1 I/O Ports and Connections

At a first approach to a system like this, overview and familiarization are important to get an idea of what the system is capable of. What I/Os there are, and what is in use at the moment needed to be specified. By looking through manuals from dSPACE and checking on their web page, a lot of information was found. A lot of information was also found in personal excel sheets, such as the one mentioned in chapter 4.1.1. A detailed technical specification of MicroAutoBox can be found in Table 1. [2]

Table 1. MicroAutoBox - Technical Specifications

MicroAutoBox	**1401/1501**
Revision	18
CPU	800 MHz
RAM	8 MB
Digital In	52
Digital Out	50
Analog In	16
Analog Out	8

4.1.1 dSpace_connections.xls

When the system was planned and built, Mr. Glader had made an excel sheet where all used I/Os were listed. The list became the foundation for what was to be included in the drawings, and the starting point from where to begin. The list was compared to the corresponding pages in the manual *"MicroAutoBox Hardware Installation and Configuration"* by dSPACE. It was also compared to all sketches, hand-drawn material, and to what was actually connected on site. The documents were updated and all information was put onto drawings. [2]

4.1.2 Markings and Numbering

All connection terminals, fuses and relays have to be marked in order to maintain order in the cabinet. Objects are numbered on the drawings and marked with terminal markers in the cabinet. Usually cables are marked with the number corresponding to where the other end of the cable is connected. A system of number series was planned as follows.

Table 2. Number series used for marking - 6L20

21-32	Resistors
K201	Relay
201-223	Fuses
301-324	Terminals
400-404	24 V
451-474	0 V

4.2 Electrical Drawings

All electrical connections are documented and drawn in AutoCAD according to Wärtsilä standards. All cabinets, drawings, sensors and actuators are numbered with a unique number. The cabinet for 6L20 has the number 293P. All automation cabinets use the 200 series. Number 3 is for G3 (generator 3) and "P" stands for Panel.

4.2.1 AutoCAD Standards in Wärtsilä

To ensure that all drawings follow the same style, specific standards and rules of thumb are followed. One of the most notable ones is the snap function used in AutoCAD. All newer drawings use a snap of 2.5 mm, regardless of whether they are aligned as Portrait or Landscape. Objects, such as plints and terminals, are then 5 mm high. See figure 6 for reference. This ensures that the connected line always hits the middle of the object height. On older drawings a snap of 1 mm was used, and objects were 4 mm high. This is an old standard that only appears on older drawings. Using the snap function also ensures that no lines are flying around connected to nowhere, though they, to the eye, appear connected.

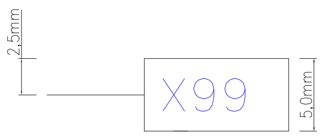


Figure 6. Using 2.5 mm snap in AutoCAD.

4.2.2 Making a New Template

To be able to make drawings, some sort of template was needed. Existing drawings in the laboratory were gone through and compared to the needs in this project. Quite quickly a version that suited our needs was found, though some minor changes had to be made. The developed template was aligned as portrait, which allowed many channels to be listed under each other on the left side. A maximum of six channels per page were agreed upon, as each channel requires quite a lot of vertical space, 40 mm to be exact. The channel height, on the other hand, gives plenty of room to draw other objects like converters, sensors, etc. next to each channel.

Everything unnecessary, like extra wires and unused pins are left out, in order to keep it simple and easy for the user. Multi wire-cables are drawn with one line and numbered in both ends. Only relevant information is drawn. If only the third pair is connected, only the third pair is drawn. Other pairs might appear on other drawings. See figure 7

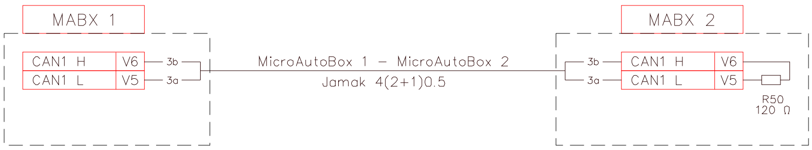
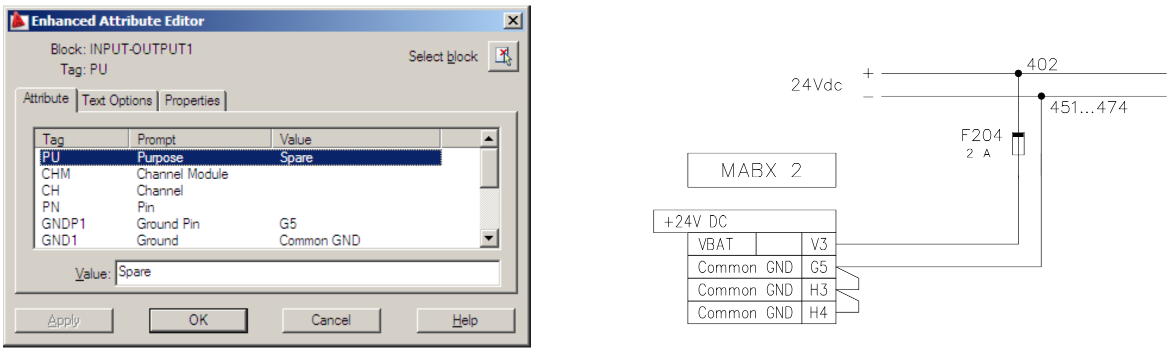


Figure 7. Jamak 4 pair cable with multiple wires.

Working with blocks in AutoCAD is very effective when you have to make lots of drawings. When blocks are used you can change the content of the text fields by double-clicking on it.



(a) Editing attributes (b) A similar block

Figure 8. Using blocks in AutoCAD.

4.2.3 Drawing Numbering

As mentioned in chapter 4.2, everything is numbered. This helps the user to know for example where a specific cable goes.

To be consistent when numbering drawings, Wärtsilä Lab has developed its own standard concerning all the specific numbers in a drawing number series. This helps users to separate drawings from each other and eases understanding of what kind of a drawing it is. An example of a drawing name made for the 6L20 Rapid Prototyping unit is found in Table 3. A complete collection of drawings is found in appendix 1.

Table 3. Complete drawing numbers of drawing 913911.dwg.

Additional Information					filename.dwg						
Building	Diesel Lab	Electrical Drawing	A3	Vaasa	Automation Systems	Circuit Diagram	Genset 3	Running Number	Digital In	Running Number	Revision Number
8 0	7	8	3	V	9	1	3	9	1	1	A

5 Application on SCE

During the autumn of 2011 it was planned for another laboratory engine, the Single Cylinder Engine (SCE) in Vaskiluoto, to be equipped with a similar system.

5.1 SCE Engine

The SCE, as you can tell by its name, has only one cylinder. This makes this engine perfect for testing purposes. When testing different engine parts and settings, there is only one cylinder to make changes to. Users have better access to engine parts when there are no other cylinders next to them, for example when installing special measurements and instruments. On the other hand, when there is only one cylinder, lots of vibrations start to occur. Therefore a mass balancing system is installed to compensate for first and second order mass forces.

The engine is also very flexible and well equipped with auxiliary systems such as multiple fuel lines, Liquefied Natural Gas (LNG) supply, charge air compressors, dryer, heating, cooling etc. The cylinder bore is variable from 260 mm to 400 mm. This engine is equipped with a UNIC and D2T Morphee2 testbed automation system, as well as a D2T Osiris real-time combustion-analysis system. Also, PLC systems from Modicon control auxiliary systems with the help of hundreds of sensors and actuators. More details can be found in figure 9.

SCE is a dedicated test engine for combustion performance development only. This gives more testing per time.

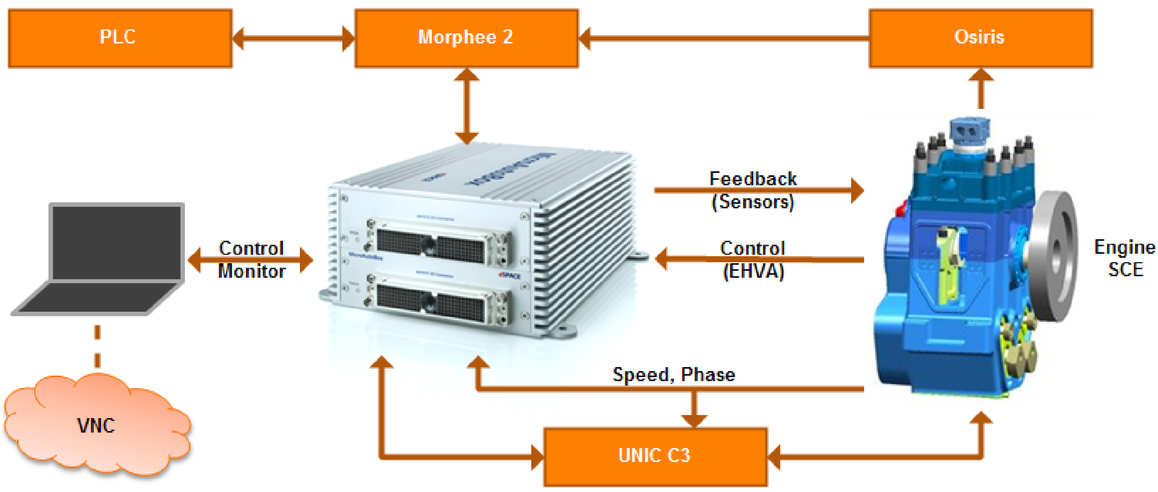


Figure 9. SCE automation system and auxiliary systems

The valves on SCE are the same type as the ones used on W32 engines. The force required to press down such a valve spring is a lot bigger than the force needed on 6L20. Instead of using one EHVA block to control both valves of the same type, a separate EHVA block is now needed for each valve. Though we have only one cylinder this gives us the need of four EHVA blocks.

5.2 Equipment

On 6L20, two identical MicroAutoBoxes were used as they were working together, controlling three cylinders each. Since then dSPACE has released their second generation MicroAutoBox. A MicroAutoBox II 1401/1511/1512 was chosen for SCE. See figure 10. This means that it has the DS1401 base board, and DS1511 and DS1512 I/O boards. MicroAutoBox II 1401/1511/1512 is the only model equipped with two I/O boards, which means it is practically the same as using two identical boxes connected to each other, but only one computer is needed and no communication has to be set up between these two boxes. A DS1552 multi-I/O module was mounted on the DS1512 I/O board for further I/O connectivity. See Table 4 for further technical specification.

Figure 10. dSPACE MicroAutoBox II 1401/1511/1512 - ©dSPACE GmbH

All equipment, including MicroAutoBox, BreakOutBox, terminals, power supply, converters etc, was mounted inside a cabinet from Rittal. The cabinet chosen measures 1200 mm × 800 mm × 200 mm (Height × Width × Depth), which is good enough for this purpose and this amount of equipment. Even in the future, this cabinet size should allow for further expansions.

Table 4. MicroAutoBox II - Technical Specifications

MicroAutoBox II		**1401/1511/1512**
Revision		22
CPU		900 MHz
RAM		16 MB
DS1511	Digital In	40
	Digital Out	40
	Analog In	16
	Analog Out	4
DS1512	Digital In	16
	Digital Out	16
	Analog In	24
	Analog Out	4

5.2.1 BreakOutBox

The BreakOutBox developed by dSPACE GmBH was originally intended to be used for analytical purposes, for example in the front seat of your car to make a quick measurement. This means it was delivered without any fasteners or anything to attach it to the cabinet. On the other hand, the box is quite high, and the space inside was high enough to fit a bolt and a nut. Four holes were drilled through the backplate of the BreakOutBox and two 290 mm long DIN rails were fitted underneath the 250 mm wide box. The DIN rail was perfect for this purpose since it has holes drilled at regular intervals. Thanks to its shape the bolt cap could be hidden underneath (figure 11).

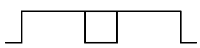


Figure 11. DIN-rail profile with bolt cap.

The BreakOutBox was attached to the cabinet backplate through the DIN-rails with regular M6 bolts. See figure 12.

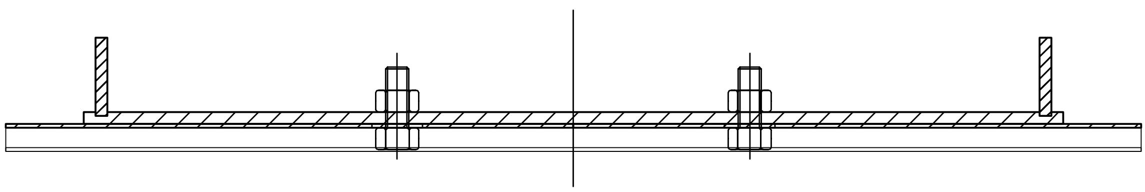


Figure 12. Fastener for MicroAutoBox BreakOutBox, made by a DIN rail.

5.2.2 Terminals

When the previous system on 6L20 was built, there was only one MicroAutoBox, which was wired straight to the BreakOutBox. From the BreakOutBox all required connections were wired to the corresponding connector, converter etc. Later when the system expanded into two identical boxes, the BreakOutBox was in use so all required connections (Note: Not all 156 pins on the MicroAutoBox, only the ones in use at the moment.) were wired with a few Jamak cables straight to the corresponding connector, converter etc.

Therefore this system was already from the beginning planned to have the MicroAutoBox's all 156 pins on both ZIF connectors wired straight out to terminals, so that connections are easily added and removed straight on the terminals. No need to cut up the cable and change anything in the connector side. Since each ZIF connector had 156 pins, and MicroAutoBox 1401/1511/1512 had two of them, this would take up a lot of space. A standard terminal is 5.2 mm wide which gives a total width of:

$$2\left(156 \cdot \frac{5.2\ mm}{1000\ mm/m}\right) = 1.62\ m \tag{1}$$

Even with two-story terminals (half width = 80 cm) this was a problem. The cabinet itself is only 80 cm wide. But with good quality three-story terminals from Phoenix Contact this was made possible.

$$2\left(\frac{156}{3} \cdot \frac{5.2\ mm}{10\ mm/cm}\right) = 54\ cm \tag{2}$$

A five meter long straight-through ZIF cable (with all 156 wires inside) from dSPACE was cut in half. The ZIF connector end was connected to MicroAutoBox and the open end was connected to the row of terminals. Each terminal was marked according to the same system as the MicroAutoBox. Table 5 and in figure 13 show more accurately how the terminals were marked. Characters 'I', 'O' and 'Q' are missing from the quantity, probably due to easy misinterpretations. This is also why small characters 'a'-'c' must be included. The same names are also used on the MicroAutoBox side.

Table 5. Marking of Phoenix terminals.

A1	A4	B1	...	Z4	a1	a4	b1	b4	c1	c4
A2	A5	B2	...	Z5	a2	a5	b2	b5	c2	c5
A3	A6	B3	...	Z6	a3	a6	b3	b6	c3	c6
1	2	3		150	151	152	153	154	155	156

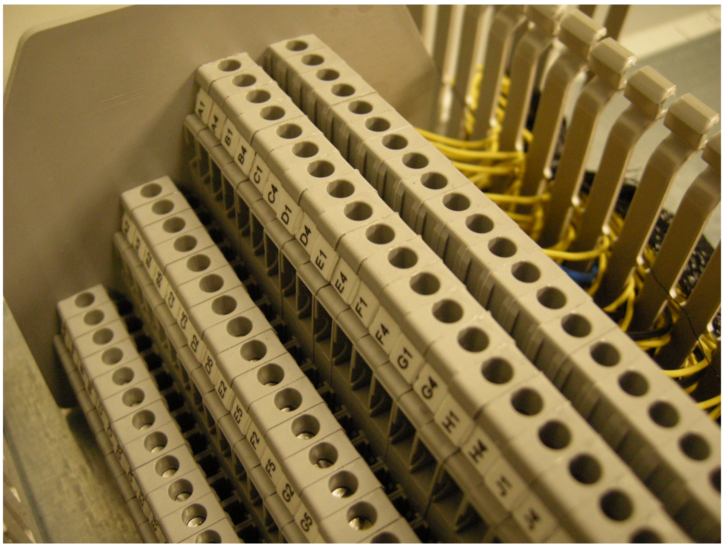
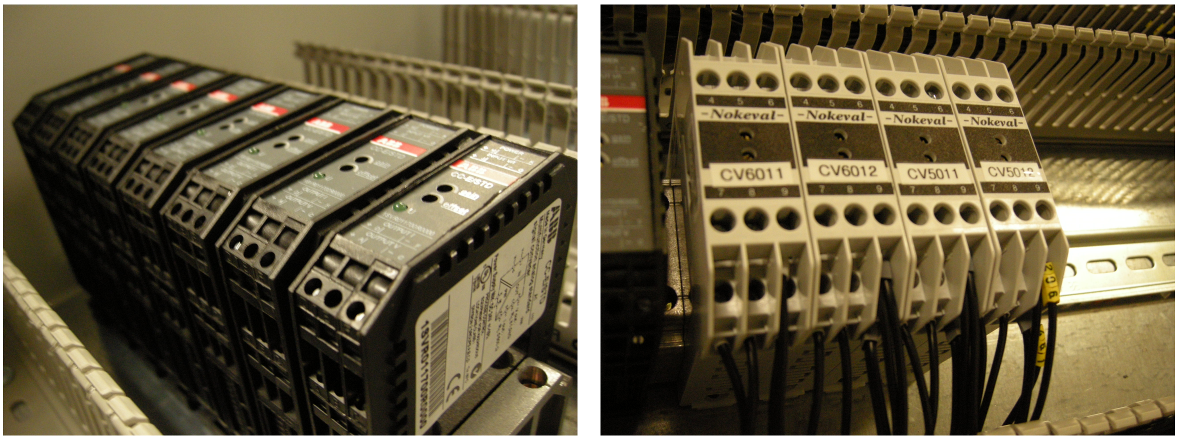


Figure 13. Terminals A1 to J4 connected and marked.

Note: The main idea of the BreakOutBox is only to remain unconnected in the cabinet, and for the MicroAutoBox to be connected straight to the terminals. Only when measurements or tests need to be made, the signals are quickly connected through the BreakOutBox. The ZIF connector from the MicroAutoBox will be moved to one end of the BreakOutBox, and a 50 cm long cable will be connected between the MicroAutoBox and the other end of the BreakOutBox.

5.2.3 Signal Converters

Signal converters are commonly used in the industry where a lot of different standards can be found. In a specific process, all kinds of different signals might be found and to get the systems to work together some signals might need to be converted. One end needs one type of signal and the other end needs another, so a signal converter is placed in between.



(a) ABB CC-E STD (b) Nokeval 641

Figure 14. Signal converters used in this project.

The analog-out signal of the MicroAutoBox is 0...5 V, and the DFplus control valve controlling the actuator requires 4...20 mA. The signal also needs to be very fast in order to keep up with the rest of the system. Signal converters from Nokeval are commonly used in the Laboratory, but for this purpose they were not fast enough. Faster signal converters manufactured by ABB were ordered (The same ones as the ones used on 6L20, ABB CC-E/STD).

From the DFplus control valve there is a feedback signal of -10...+10 V. MicroAutoBox requires on its analog-input channels a signal of 0...5 V. For this purpose the main intention was to use the same converters from ABB that were used on Analog out, but ±10 V was not supported by ABB CC-E/STD, so Nokeval 641 was used instead. Newer versions of 641 supported this directly without further modifications.

5.2.4 Precision Resistors

Another type of signal conversion occurs in the sensor signal that measures the position of the valve. Positek Linear Position Sensors are fed with 24 VDC. The returning signal is in the form of 4...20 mA. MicroAutoBox uses, as mentioned, 0...5 V on the Analog input. This is easily corrected with a 250 Ω resistor connected in parallel to the sensor. For maximum accuracy, precision resistors is to be used. According to Ohm's Law the following is true.

$$U = IR \tag{3}$$

Therefore

$$U_{4mA} = 4 \cdot 10^{-3}\ mA \cdot 250\ \Omega = 1\ V \tag{4}$$

$$U_{20mA} = 20 \cdot 10^{-3}\ mA \cdot 250\ \Omega = 5\ V \tag{5}$$

In software this is scaled so that the 1 V is interpreted as 0 %. The only drawback of this is that only 80 % of the measurable range is used. On the other hand, this is a very easy and accurate method for measurement. This is represented as R21...R26 in drawing 80783V913951 in appendix 1, and as R21...R24 in drawing WVCAD200025501 in appendix 2. For housing, the same three-story terminals from Phoenix Contact were used as in chapter 5.2.2.

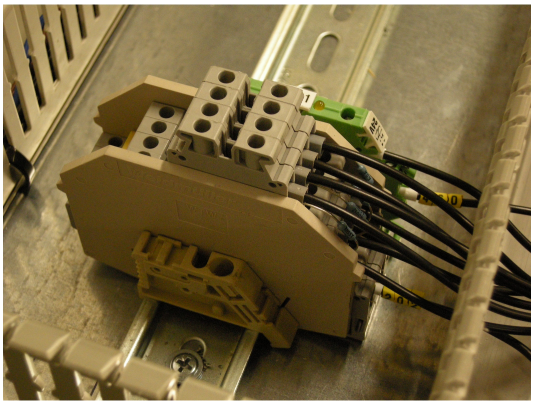


Figure 15. Precision resistors connected in parallel to sensor.

5.3 I/O Ports and Connections

In an earlier meeting between all people involved in this project, all required equipment had been agreed on. Then in another meeting with Mr. Glader and Mr. Hägglund, each port on the MicroAutoBox side was defined, and its purpose. Demands on equipment were compared to the specifications of the MicroAutoBox. A short list of notes was made with all involved inputs and outputs.

5.3.1 dspace_connections.xls

Since the 6L20 had the excel sheet with all I/Os, and many people have been using it for a quick look up of information, the natural instinct was to make one for SCE as well. The old one was used as a template, where all unnecessary connections were removed. The rest was compared to the notes made in the meeting where we agreed on what ports to use on the MicroAutoBox side. This template and also the old one were stored on the Wärtsilä intranet so that they could be easily accessed by the people who may need it.

With the excel sheet in hand the rest of the work was easy to organize. All drawing numbers, how to distribute all channels over the drawings, what to do and what not to do. This document worked as a "work distribution plan" for me.

5.3.2 Markings and Numbering

Roughly the same numbering system that was used on 6L20 in section 4.1.2 was also applied on SCE, with only minor changes. Most changes were due to fewer connections. For reference see table 6. Also here all cables, terminals, signal converters and relays were marked physically in the cabinet and also in drawings.

Table 6. Number series used for marking - SCE

21-24	Resistors
K201	Relay
201-214	Fuses
301-324	Terminals
400-409	24 V
451-474	0 V

5.4 Electrical Drawings

Also the SCE was equipped with drawings before the installation began on the engine. All drawings were distributed to the Laboratory intranet so that people involved could access them.

The numbering of drawings for the SCE was done in a slightly different way, since Waskiluoto Validation Center (WVC) is based on a Power Plant concept. Therefore the way of numbering drawings is done in a slightly different way. Table 7 illustrates the system. This way of numbering increases the total number of possible drawings dramatically.

Table 7. Complete drawing number of drawing 25201.dwg (Digital In).

Additional Info					filename.dwg				
Waskiluoto	Validation	Center	Cell 4	Engine Genset System	Running Number Related	to Cabinet Number	Digital Input	Running Number	Revision Number
W	V	C	AD	2000	2	5	2	01	A

6 Software and Functionality

As mentioned this system uses a model made in MATLAB®'s Simulink, with the help of dSPACE's own toolbox. The user may also choose to program in C. The model is downloaded into the MicroAutoBox, which communicates with the connected PC running ControlDesk®. For valve control based on engine measurements and hydraulic actuators, some sort of controller is needed in the Simulink model. It is known from earlier development stages in EHVA technology that traditional controllers have problems to perform well due to the dynamics of the hydraulic system. Adaptive learning controllers are therefore introduced into the system. The valve opening process in a diesel engine is such a periodic event that it is well suited for some sort of repetitive- or iterative learning controller. By measuring the detected tracking error between the signal and the target, the target signal might be modified in a way that compensates for delays and errors.[4]

Some sort of security is also needed. If a valve lift is delayed too much, a collision with the piston might occur. See chapter 6.2.6. Also the tuning of the controller is a very important part. Simulations have revealed growing reference signals if a too small controller gain was used. A saturation- or low-pass- filtering of the reference signal is also to be recommended.[4][3]

6.1 ControlDesk

ControlDesk® is a program developed by dSPACE GmbH for communication and control with MicroAutoBox, in real-time and in Simulink experiments. The program also features an integrated Simulink interface for offline model management. The same variables and blocks that are used in the Simulink model can also be used in ControlDesk®. The program might either be run in real-time or in simulation mode.

The user interface of ControlDesk® is built by the user and is very customizable. Lots of building blocks and tools to control and monitor variables of simulations are predefined in the program. Other features such as drag & drop functionality simplify user experience.

In the automation cabinet 293P, for the 6L20 EHVA system, there are two notebook computers running ControlDesk®. One for each MicroAutoBox. Both notebooks are connected to the laboratory network and controlled via VNC from the control room. A screenshot from ControlDesk® is found in appendix 3.

6.2 Simulink

The model that is built in Simulink is downloaded into the MicroAutoBox and stored in non-volatile memory. This means it requires no power to maintain the stored information. A power loss in MicroAutoBox is therefore not critical. Due to this, MicroAutoBox is allowed to start up autonomously after power-up, which increases startup time.

6.2.1 Measurements

Inputs to the model consist of measurements of speed and phase from the engine. The model needs to know in what phase the crankshaft and camshaft are to know in what position the piston is, and when to open and close valves. This is used as a "time axis" so to say. Also linear position sensors from Positek are mounted on top of the EHVA blocks. These sensors measure the lift of each valve.

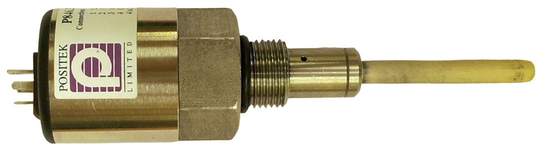


Figure 16. Linear Position Sensor

Note: It is common in the Laboratory to take measurements related to degrees of crank angle (CA), instead of time. Since the diesel engine is such a repetitive process, this is a better time unit. Every event is supposed to happen at the same degree every cycle with as few variations as possible. Often the concepts of Top Dead Center (TDC) and Bottom Dead Center (BDC) are also relevant. Measurements and control might be related in CA degrees to these. TDC is the phase when the piston is the closest to the cylinderhead, and BDC when it is the farthest away from.

6.2.2 Settings

The main idea of this system is its wide customization possibility. Therefore a lot of settings are available to the user in the ControlDesk® environment. The main parameters adjusted by the user are listed in table 8. The values are then sent forward to MicroAutoBox and the model.

Table 8. Different parameter settings for adjusting valve lift curves.

Short		Description
IVO	=	Inlet Valve Open (CA degrees)
IVC	=	Inlet Valve Close (CA degrees)
IN LIFT	=	Inlet Valve Lift (mm)
EVO	=	Exhaust Valve Open (CA degrees)
EVC	=	Exhaust Valve Close (CA degrees)
EX LIFT	=	Exhaust Valve Lift (mm)
EGR VO	=	Exhaust Gas Recirculation Valve Open
EGR DURATION	=	Exhaust Gas Recirculation Duration
VIO	=	Variable Inlet Opening

6.2.3 Valve Lift Profile Generator

Another handy tool implemented is the Valve Lift Generator. With the parameters defined in table 8, the model calculates a proper lift curve for the valves to follow. Since all these parameters are adjustable, it is possible to generate various curves. The generated curve works as a reference. The controller tries to follow the reference to its fullest, but delays always occur due to the dynamics of the hydraulic system. The reference has to be adjusted in a way that compensates for delays and errors. More information on this can be found in chapter 6.2.4 and 6.2.5.[4][3]

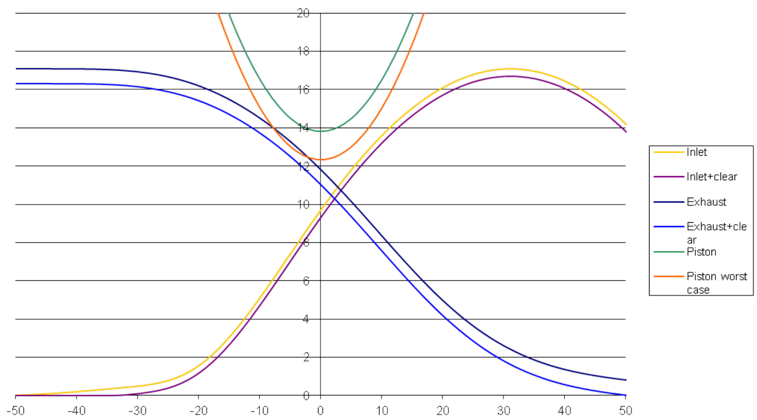
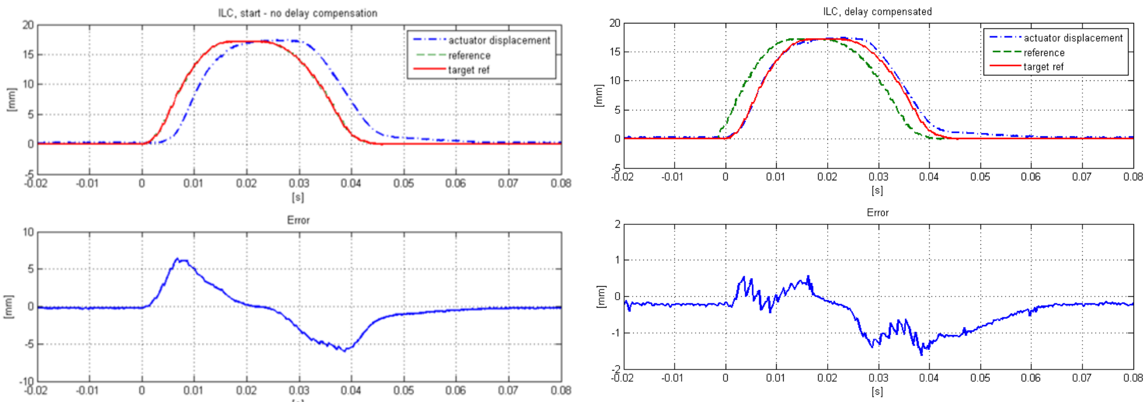


Figure 17. Liftprofiles, clearance and position of the piston

The user may change the parameters "on the fly", while the engine is running. The system waits until the valve is in closed position, and then changes the settings. For every change in parameter, the tracking error is delayed by one cycle.

6.2.4 Hydraulic Delay Measurement and Compensation

The dynamics of the hydraulic system cause the biggest tracking error in this case. Therefore the reference signal must be compensated to eliminate these delays. This is very helpful, especially during start and stop. The control system keeps track of the difference between reference and the actual position. It starts controlling the actuator 0.5 CA degrees earlier each cycle, until the delay is smaller than 1 CA degree. When a successful compensation has been done, the Iterative Learning Controller (ILC) is introduced. See chapter 6.2.5.[3]



(a) Before (b) After

Figure 18. Compensation of the hydraulic delay. © CIMAC 2010

6.2.5 Iterative Learning Controller

When the delay compensation is complete, the next step for the controller is to start to learn. ILC measures the error at every data point and saves it to memory. This is called memory-based learning. Figure 19 shows a schematic block diagram of the working principle of ILC. For every iteration of error measurement, the measured error turns into a curve shape, resembling the "system tracking error". This curve is added to the previous reference lift curve and also this is saved to memory. Over time this is gradually transformed into a shape resembling the minimum system tracking error. Due to simplicity, only a P-controller is used, while also other controllers might be used in case this is not effective enough. The simplest model of ILC is the one in the following equation.[4][3]

$$u_{i+1}(t) = u_i(t) + q\Delta y_i(t) \tag{6}$$

where u = control output, i=iteration index, q = constant learning gain and Δy = tracking error.

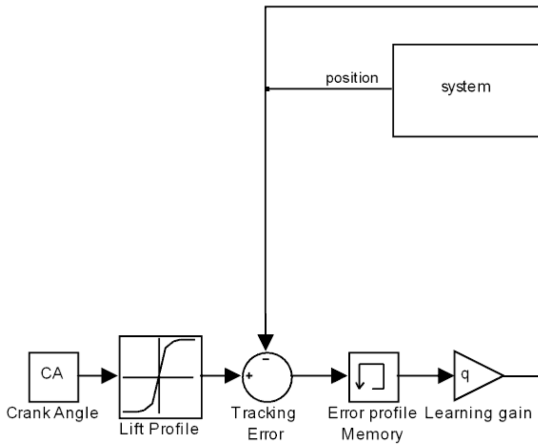


Figure 19. Block diagram of ILC.

By using the ILC, performance in lift profiles is increased a lot. As seen in figure 20, the delay between 'target reference' and 'actuator displacement' is almost completely eliminated. Also the reference signal is modified in a such way that the curves are almost identical. This is also notable in the error, which is now within ±0.5 mm, compared to ±6 mm before.[4][3]

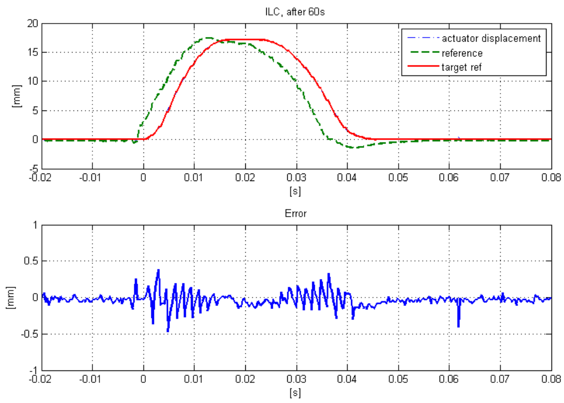


Figure 20. ILC after 60 s. © CIMAC 2010

At some point the error stops decreasing and starts to increase instead. If the ILC is left to continue its work, at some point it can no longer follow the increasing reference value. Therefore the ILC is stopped when the sum of absolute error is within a specified tolerance. Another good method is to divide the different phases of a profile into different learning phases (such as lift, dwell, close, dwell), all handled individually with individual compensation. Normally, this compensation and learning are reached within a few seconds (30 - 60 cycles).[4][3]

To ensure that valves follow a proper lift curve is very essential. If a new conceptual camshaft profile is tested with the help of EHVA, and it is of interest to start manufacturing that profile, it is of great importance that the testing is considered equivalent to the concept of the diesel engine. Also if the delay becomes too large, valves might also risk colliding with the piston.

6.2.6 Safety Systems

To avoid inconveniences such as collision between piston and valve, some sort of safety system is also needed. The measured position of the valve is compared to the position of the piston. Figure 17 shows how the piston could, in a worst case scenario, mechanically meet with the exhaust valve. If the tracking error mentioned in chapter 6.2.5 grows too large, it is better to revert back to start and start learning from the beginning. Simulations have shown that otherwise the error might continue to grow incredibly large. Also, sensor failures and external shutdowns from PLC and UNIC are treated as safety instructions.[4]

When something happens, the engine is stopped and the valves are moved to a safe position. In the ControlDesk® user interface, the reason is shown as a stop code.[3]

7 Results

As a result of this thesis, SCE was equipped with a working EHVA system controlled by dSPACE MicroAutoBox. The automation cabinet was properly planned taking into account inconveniences from earlier systems. The system and the automation cabinet were also constructed.

Also the documentation for both 6L20 and SCE is now in order. All required drawings for the systems are stored on the Wärtsilä intranet and can easily be accessed by the users of each system.

The development of the new AutoCAD template was also of great importance. All similar systems will from now on be using the new template in their documentation.

8 Conclusion

A lot has happened during the time I have been writing this thesis. The work has been interesting and I have learned a lot.

Now that the EHVA system on 6L20 has a complete documentation with drawings, it is a lot easier for anyone to work on this system. A printed copy of the drawings is stored inside the automation cabinet to provide easy access for the electrician.

I have happily witnessed this project on SCE become reality. The cabinet was built and connected by myself, and by the time I am writing this it has been sent to Tampere University of Technology (TUT) for further testing with the EHVA system. TUT has been involved in the development of the concept and the technology of the whole EHVA system from the beginning, and therefore they also want to take measurements on this system. Also, all the drawings for SCE that I have have been very beneficial, both for Wärtsilä and for TUT.

A Functional Description will also be written for 6L20. This along with the drawings should be a good basic introduction to the system. The functional description is not a part of this thesis, but roughly the same material will be used, only a shorter version.

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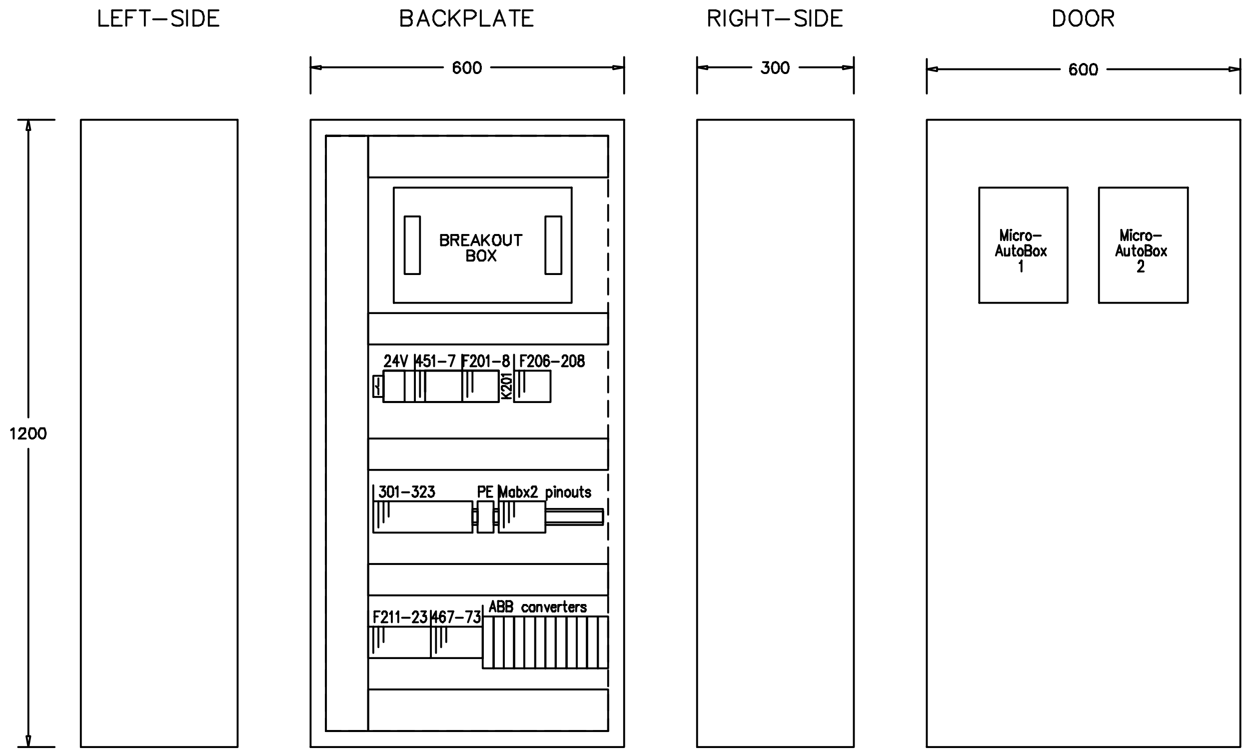
APPENDICES

1	Drawings for 6L20	17 pages
2	Drawings for SCE	10 pages
3	ControlDesk® Screenshot from 6L20	1 page

Appendix 1: Drawings for 6L20



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AVECON Työ nro	

Wärtsilä Finland Technology

Cell 3, 293P / G3_dSPACE
Cabinet Layout

Pos. 293P
Piir. no Dwg nr 8078 3V 9139 01
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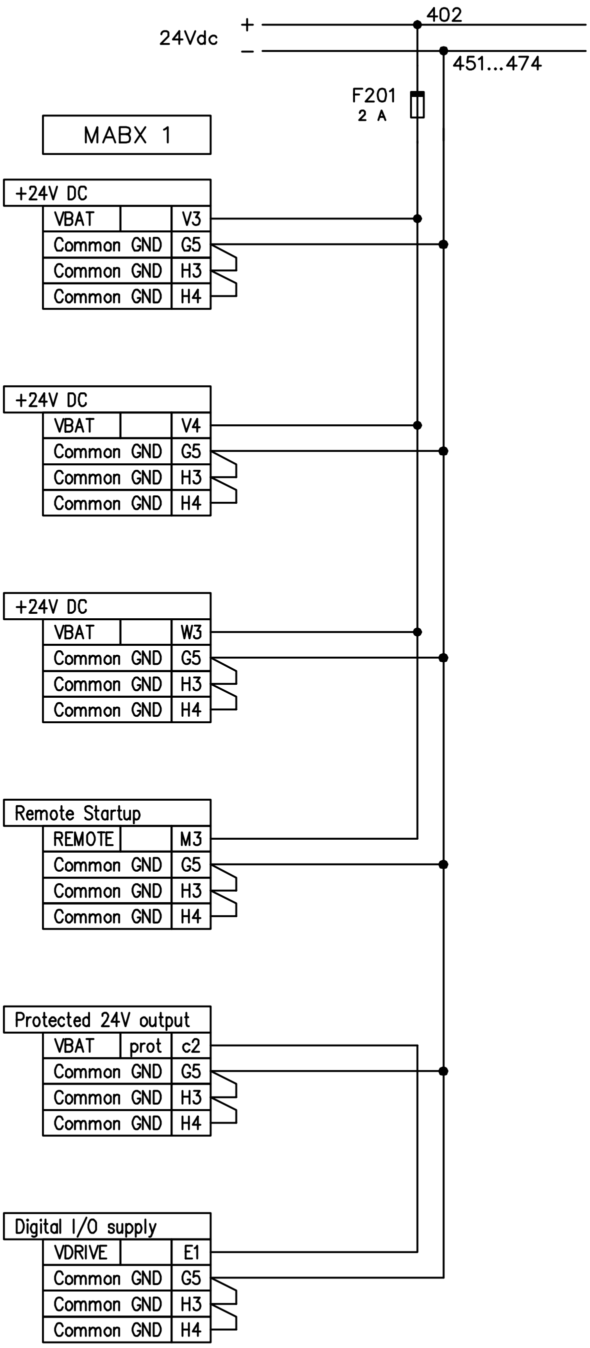

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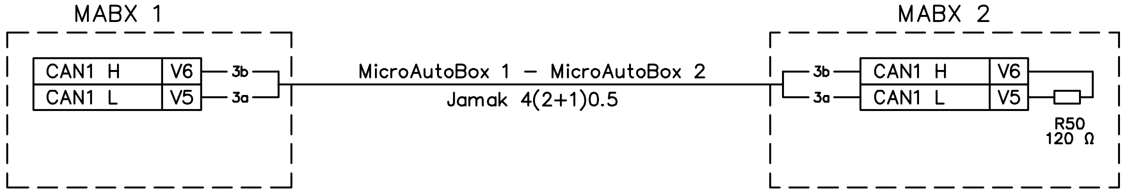

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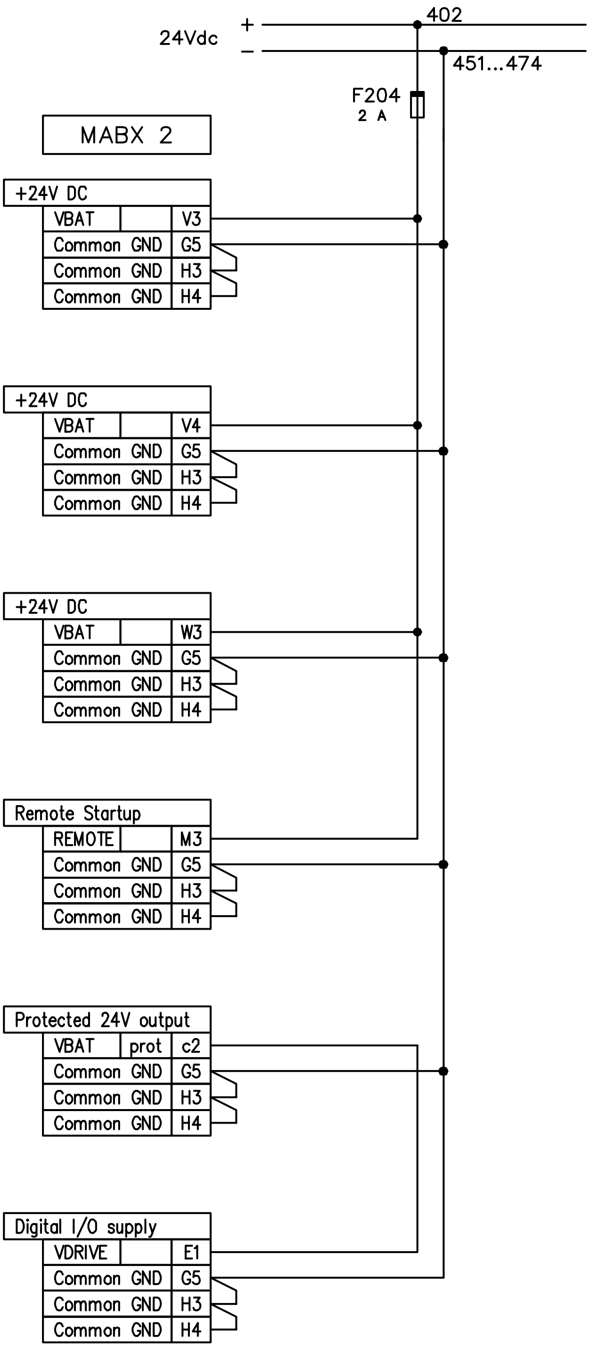

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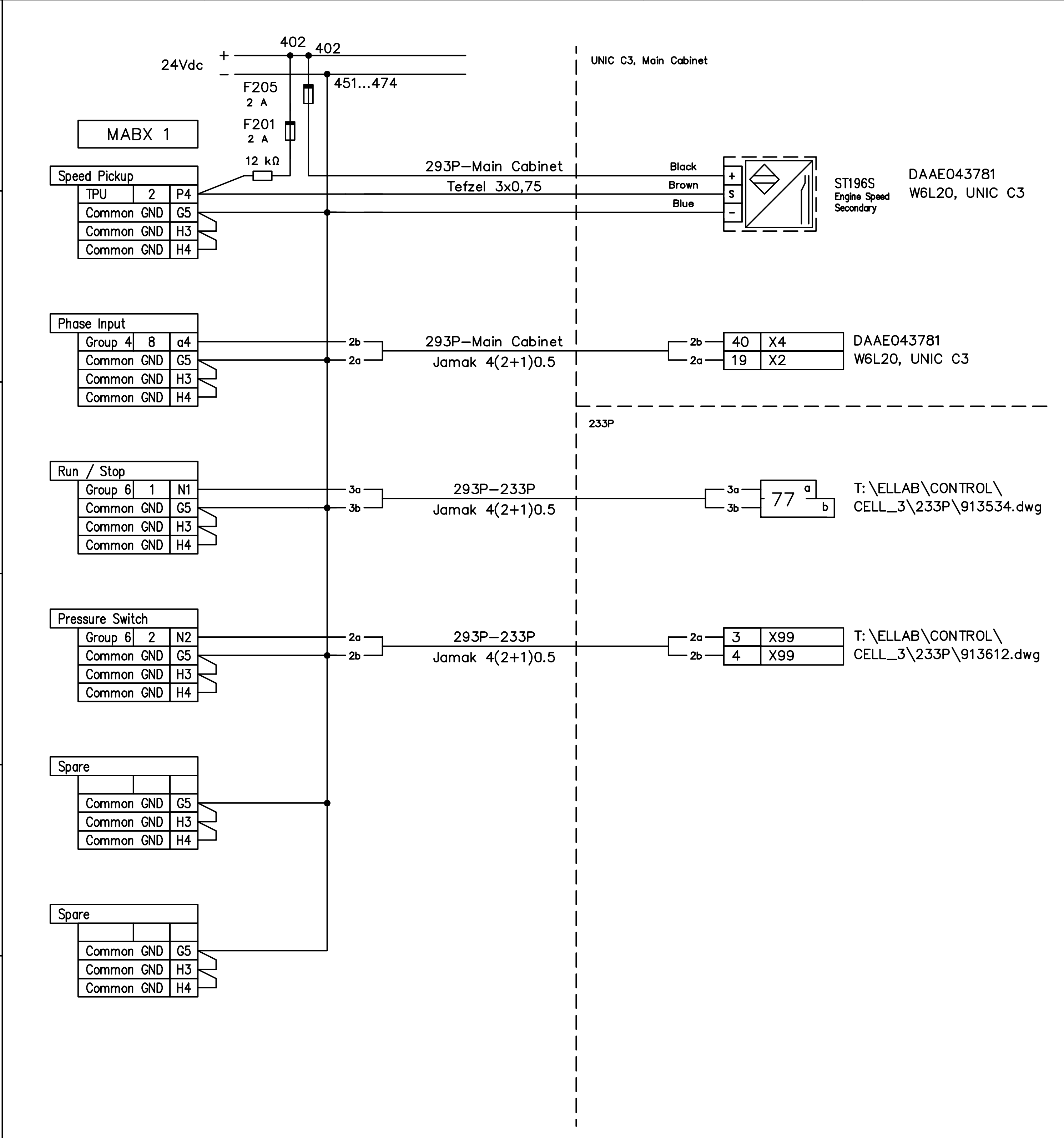

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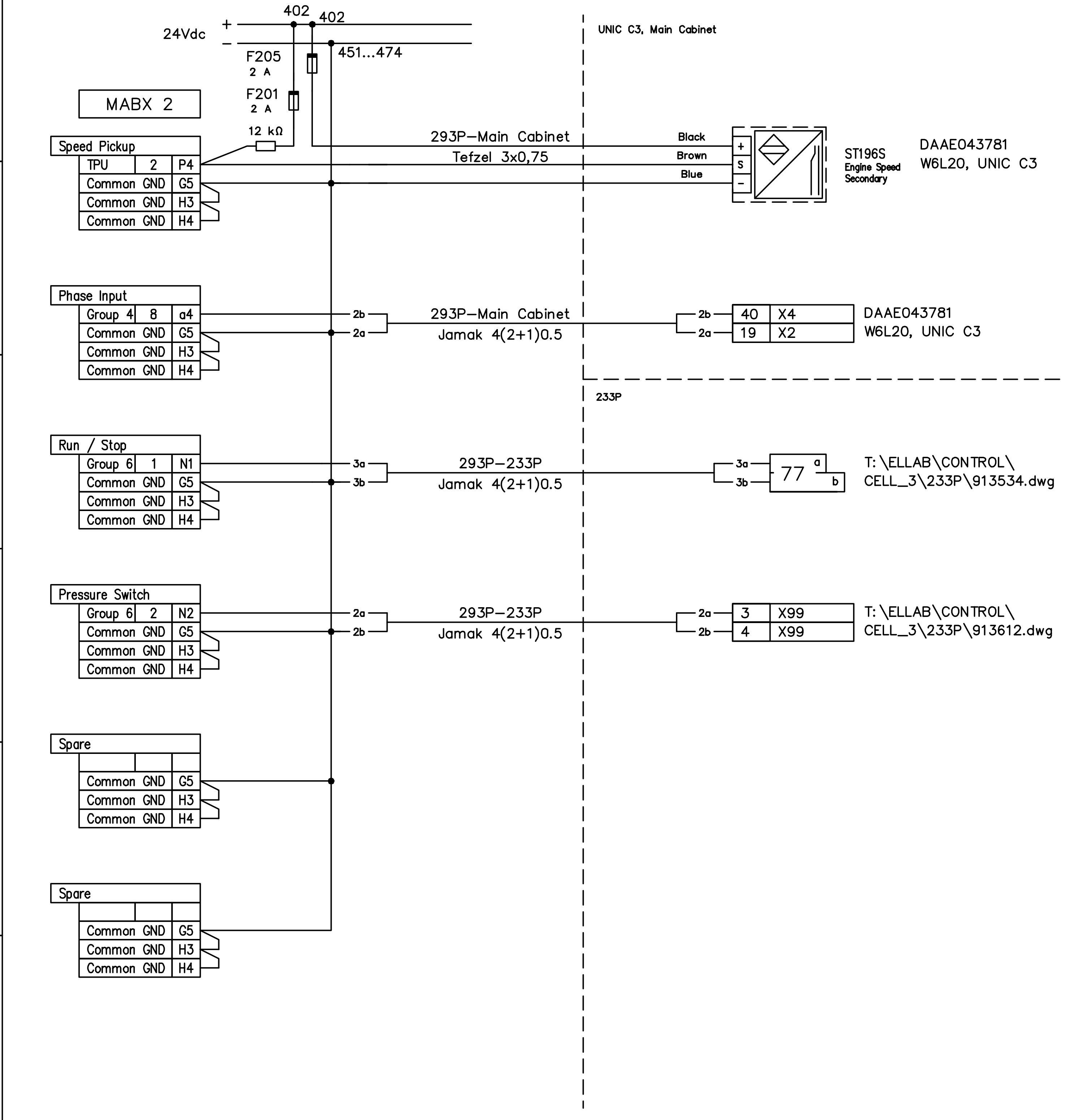

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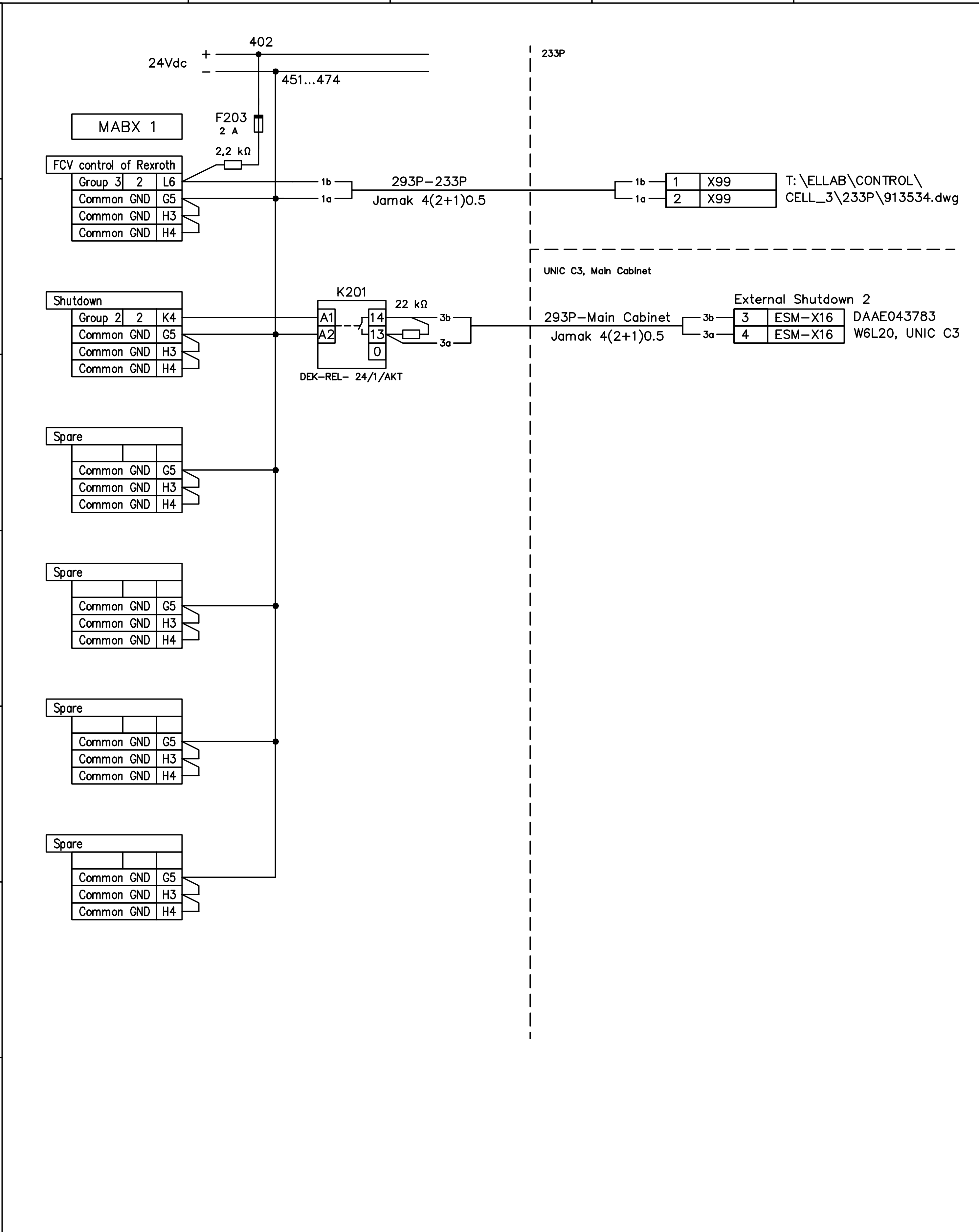

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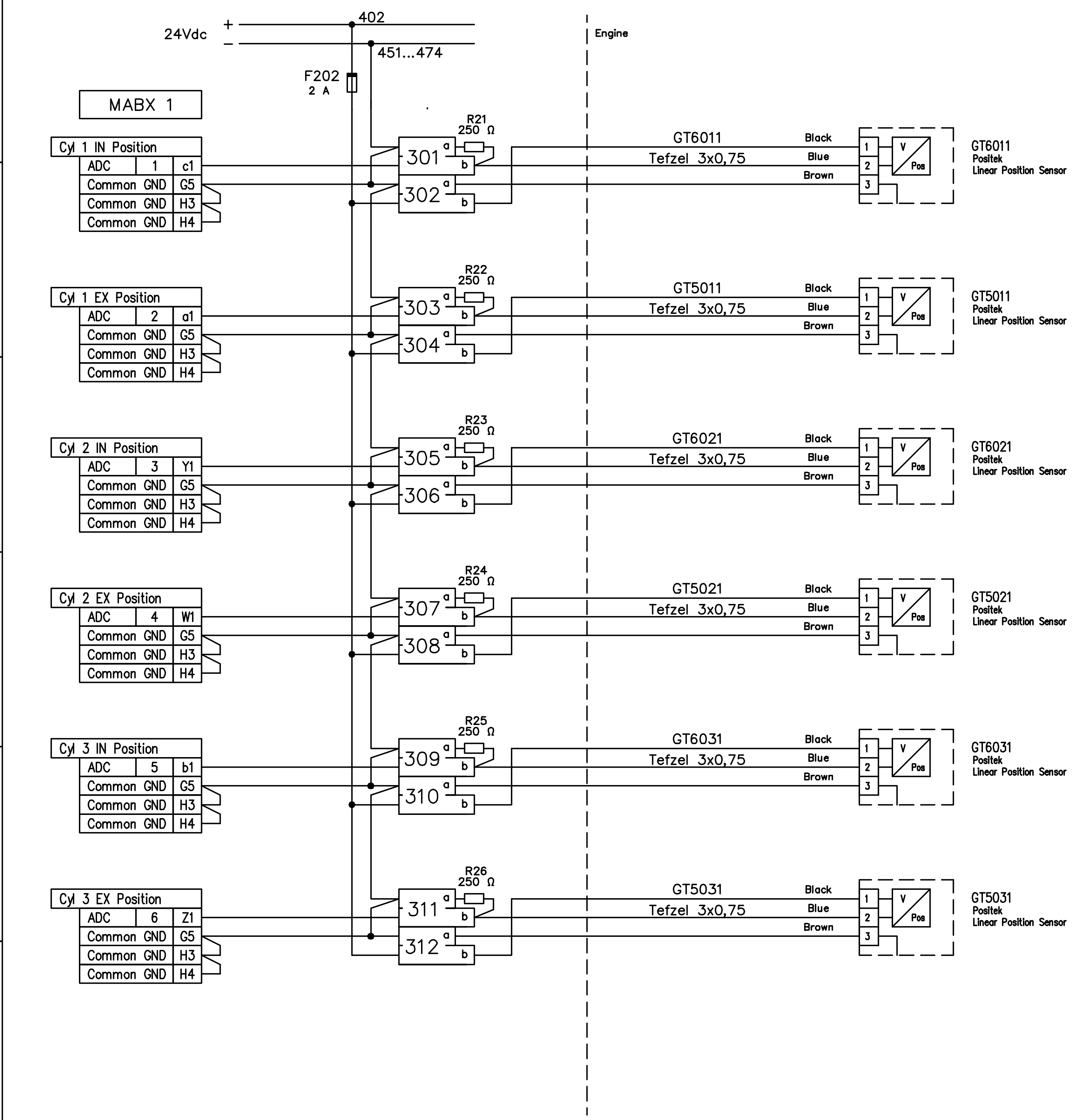

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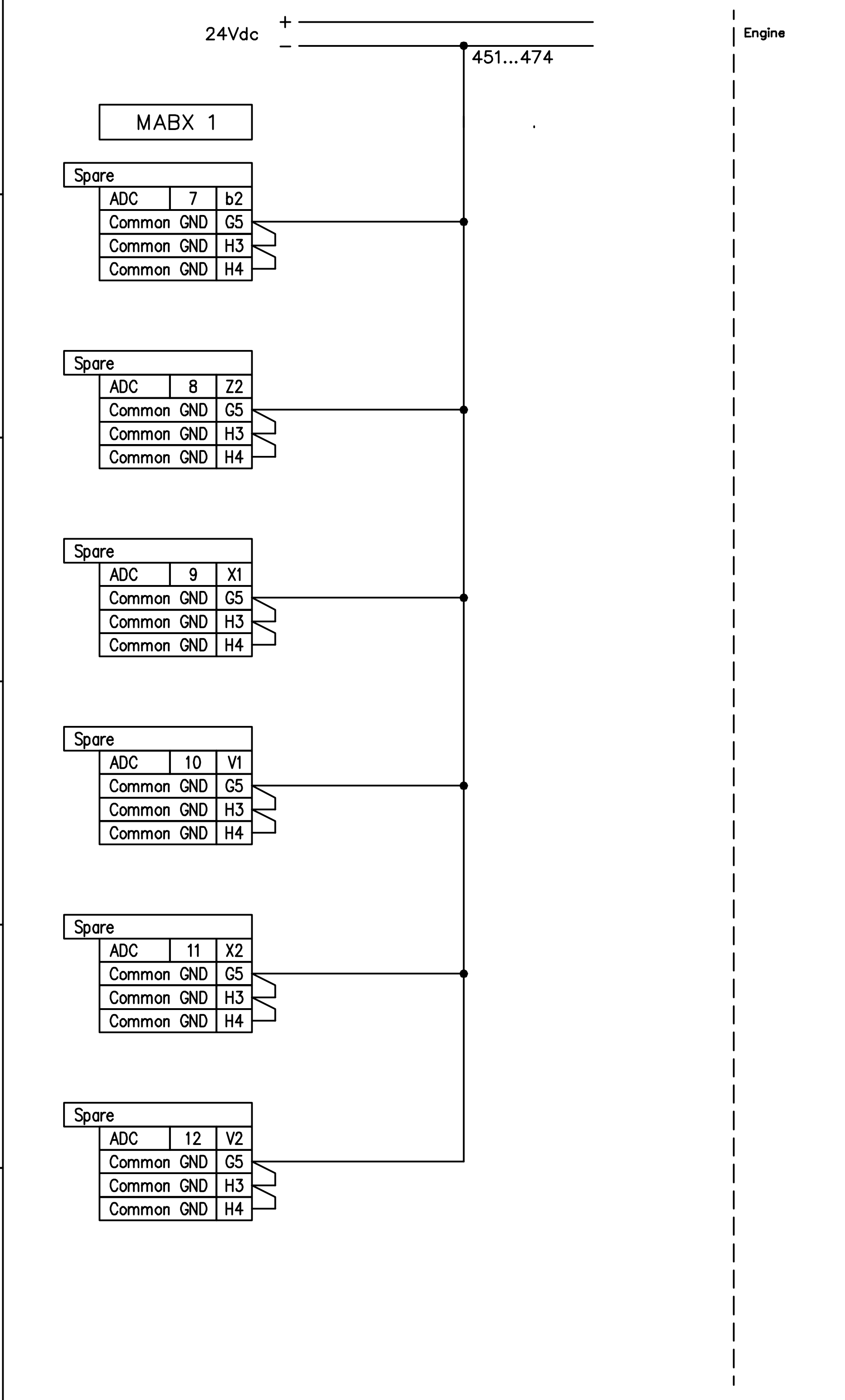

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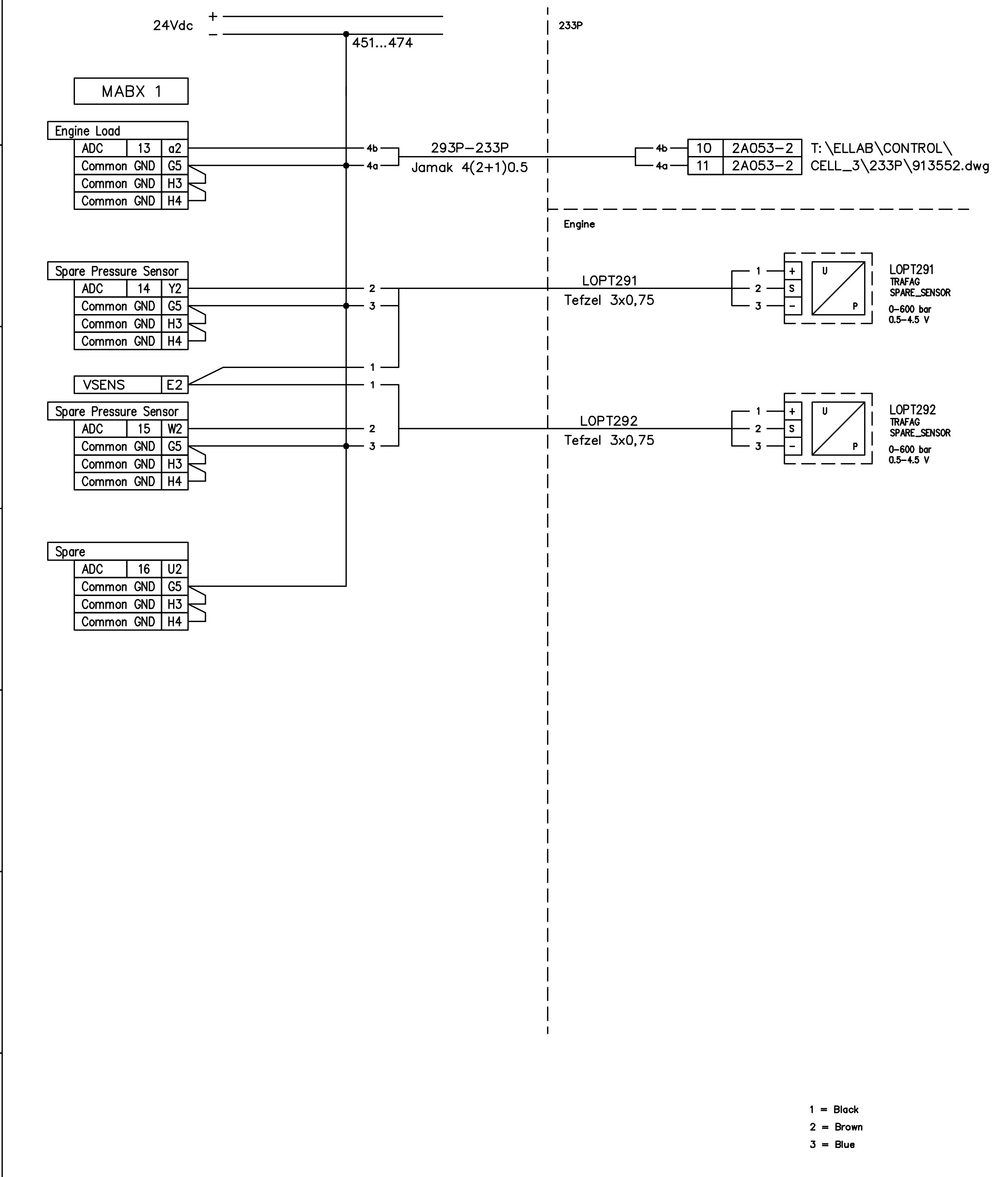

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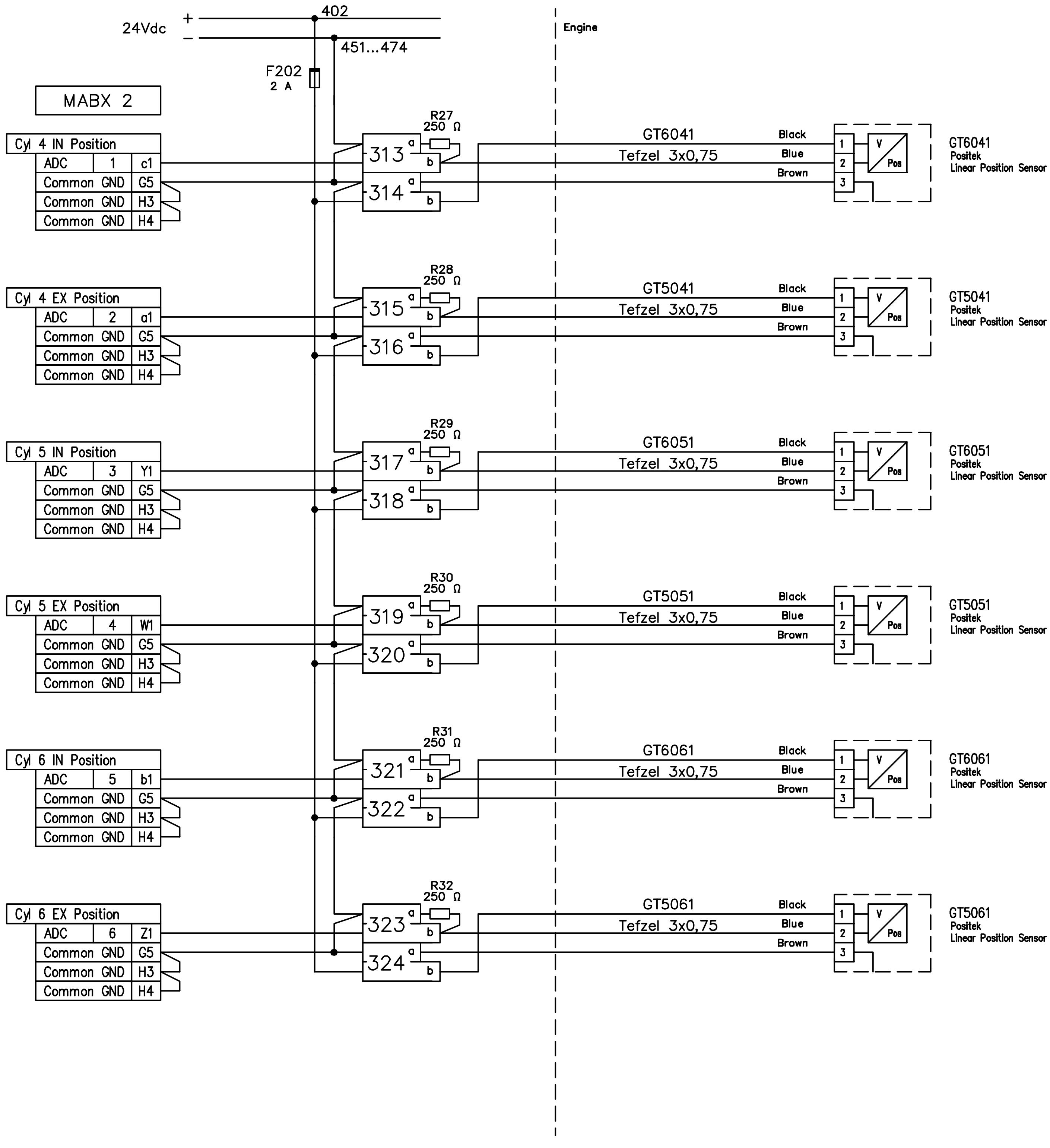

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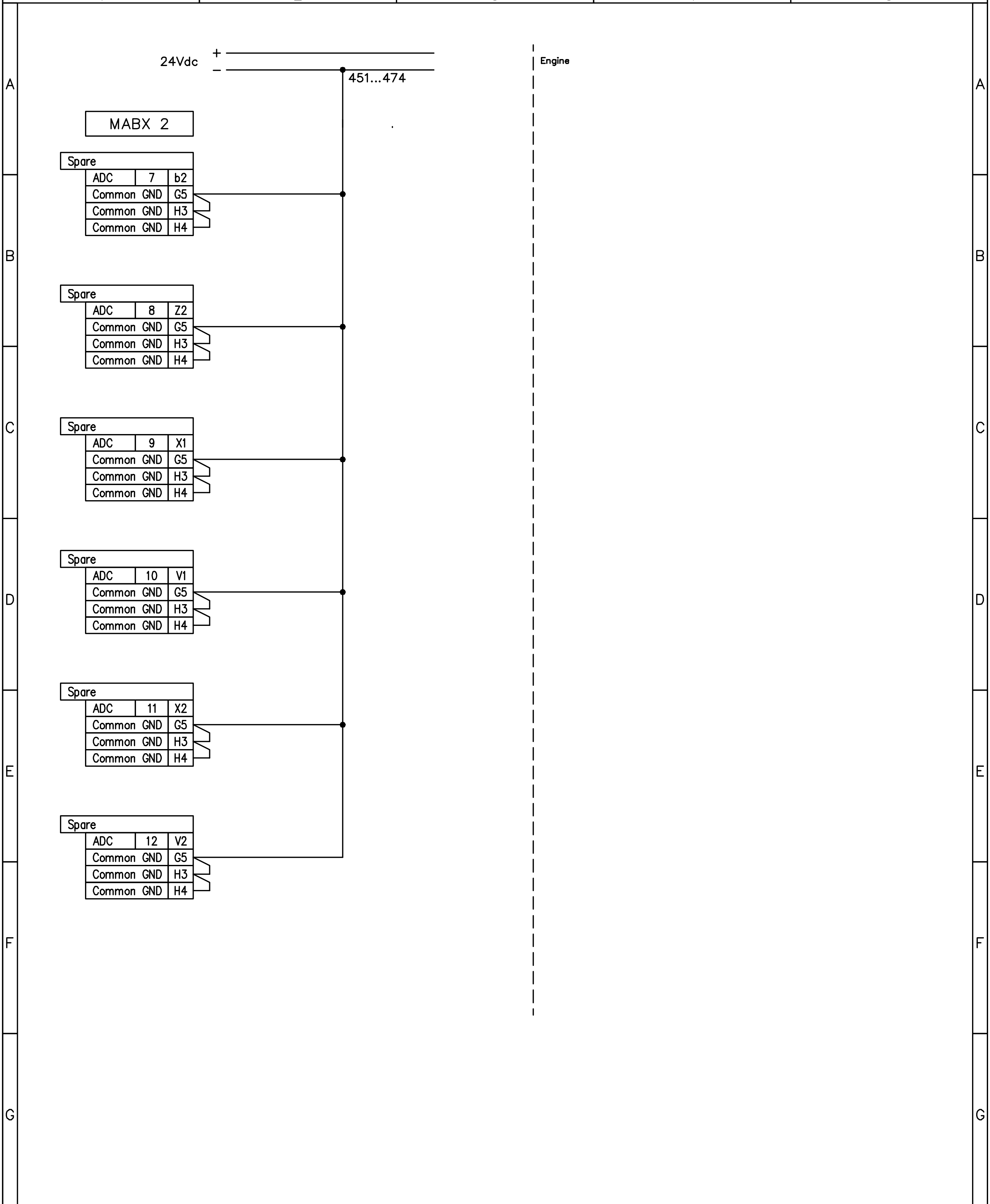

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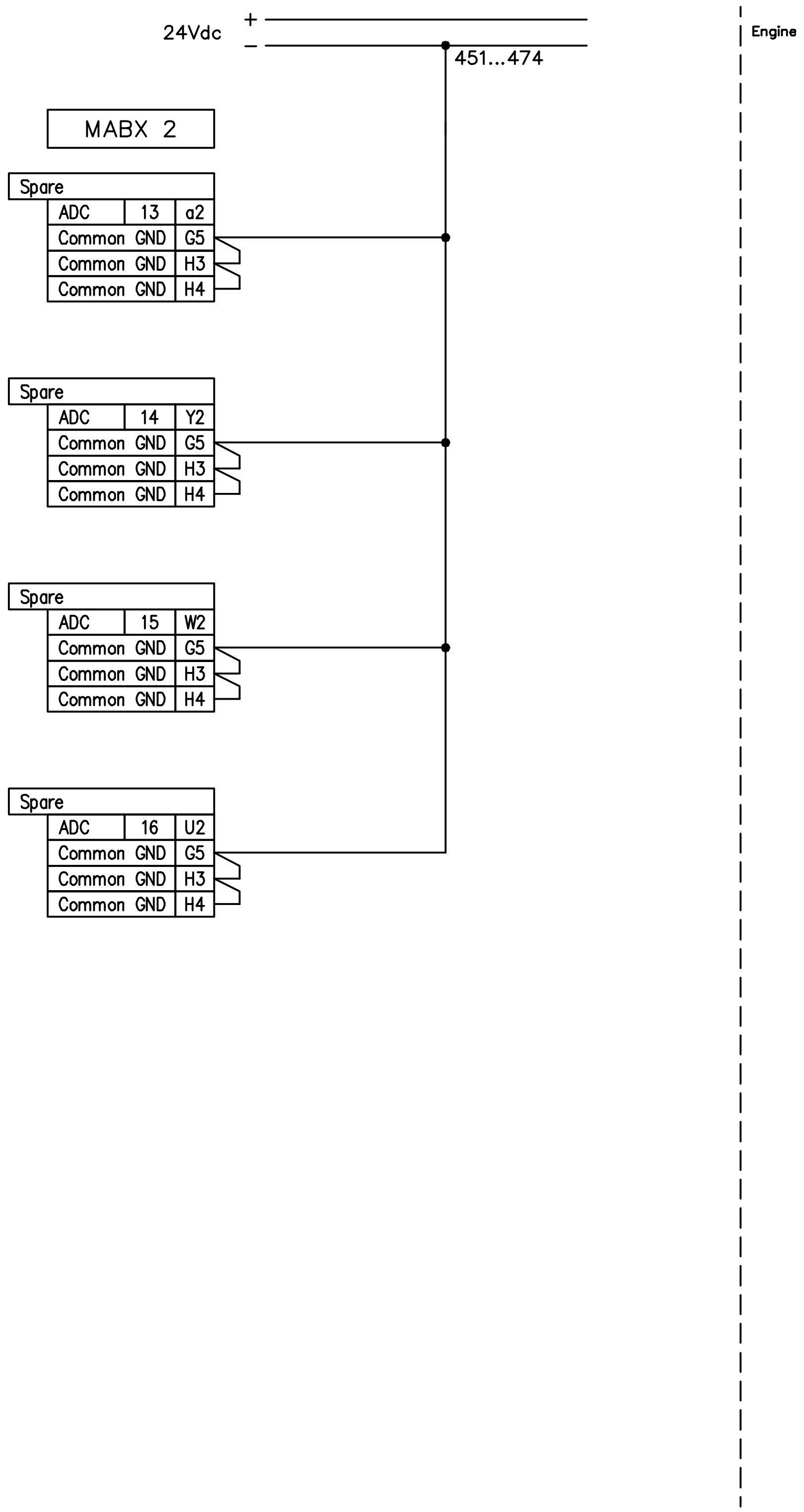

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MADE: –

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CHKD.

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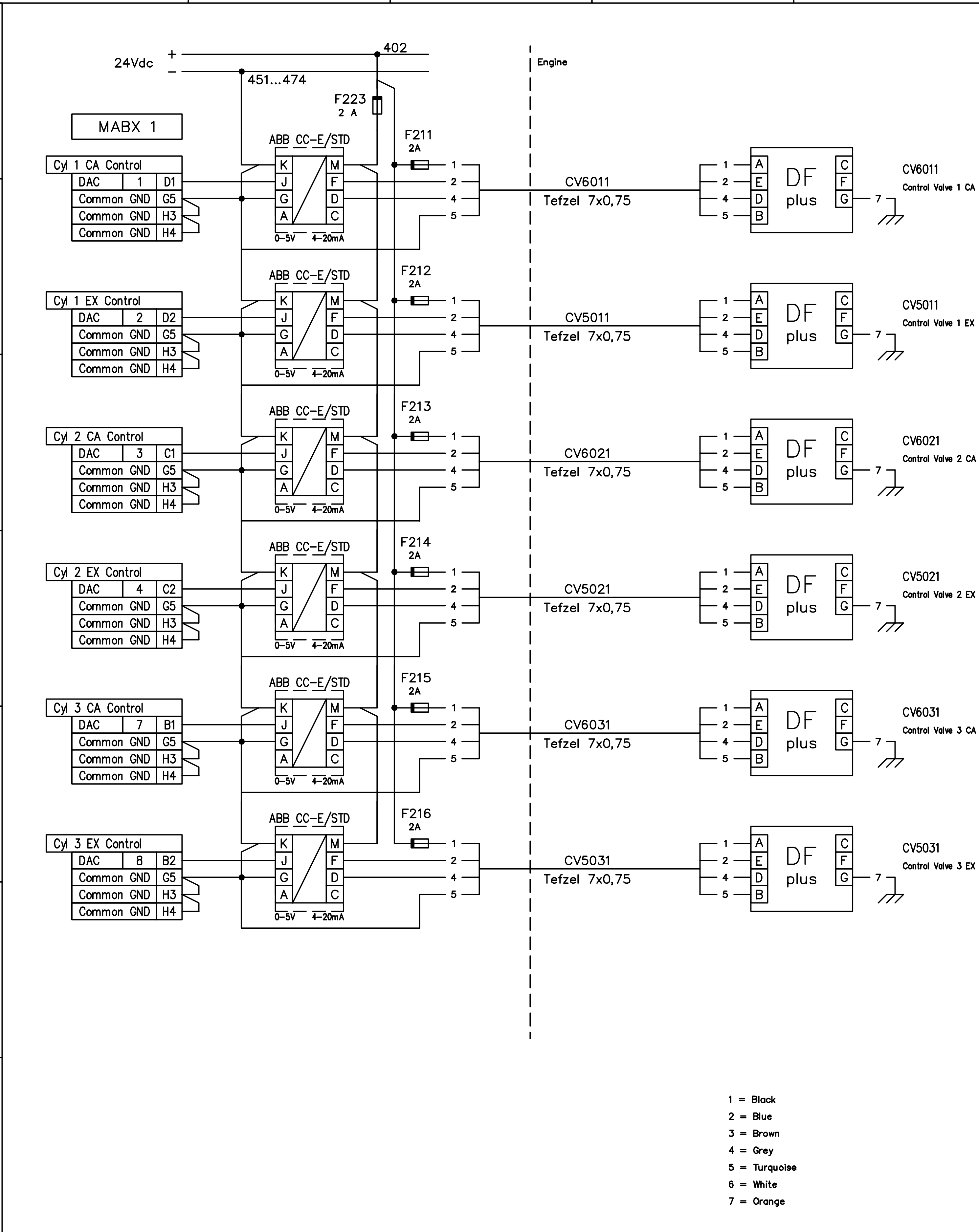

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BUILDING ACT: LAB

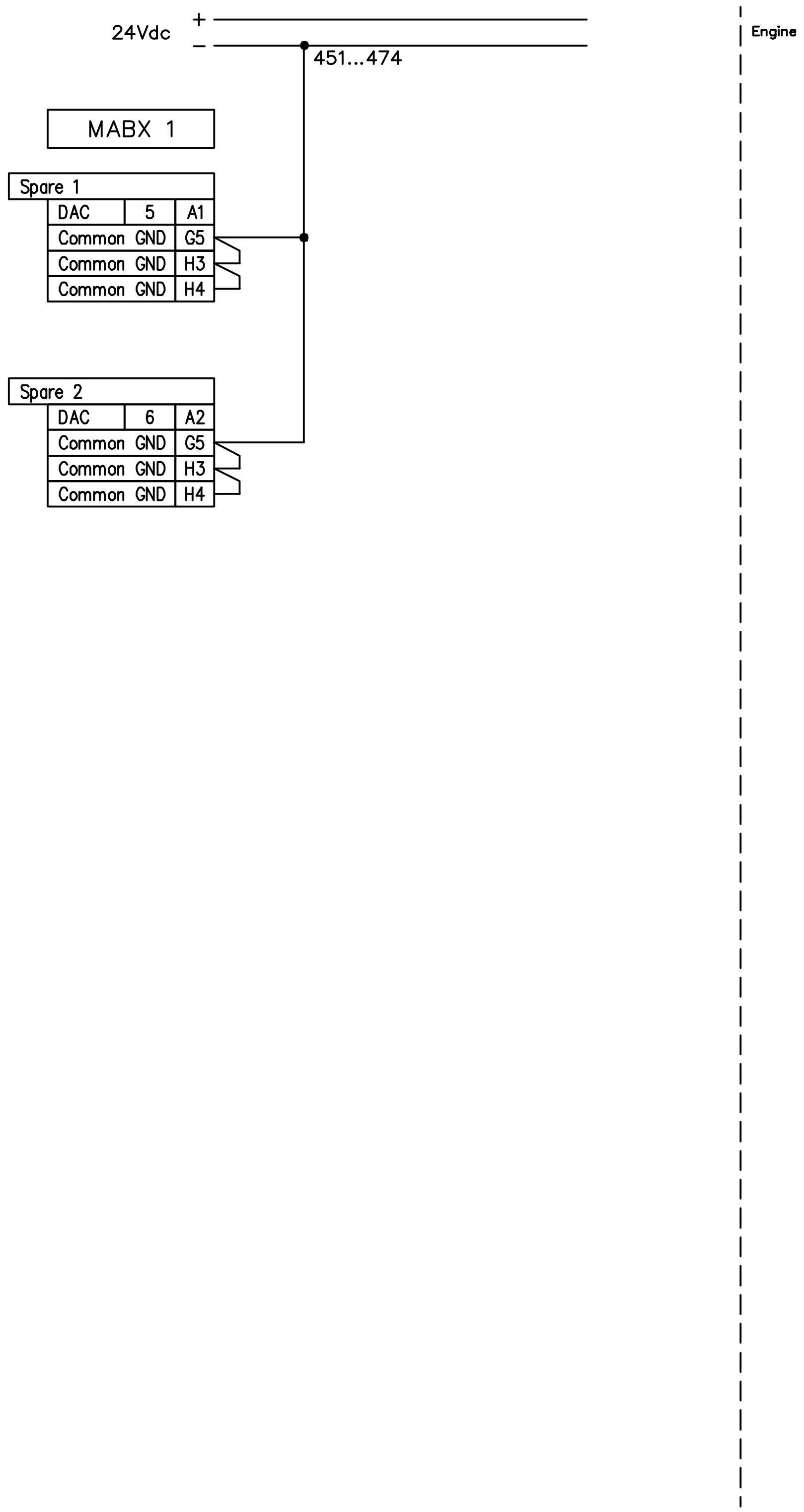
NAME AND ADDRESS: Wärtsilä Finland Technology

DRAWING ART: Wiring Diagram

CONTENT OF DRAWING: Cell 3, 293P / G3_dSPACE Analog Output (0−5 V)

DRAW. FILE	\CONTROL\CELL_3\293P\913971.DWG
DRAWER	TBi
MADE	–
DATE	13.10.2011
CHKD.	
DRAWING Nr.	8078 3V 9139 71
REVISION	

Revision (Name & Date)	Revision (Name & Date)
A	C
B	D



WÄRTSILÄ

BUILDING ACT: LAB

NAME AND ADDRESS: Wärtsilä, Finland, Technology

DRAWING ART: Wiring Diagram

CONTENT OF DRAWING: Cell 3, 293P / G3_dSPACE Analog Output (0–5 V)

DRAWER: TBi

MADE: –

DATE: 13.10.2011

CHKD.:

DRAW. FILE: \CONTROL\CELL_3\293P\913972.DWG

DRAWING Nr. 8078 3V 9139 72 REVISION

Revision (Name & Date)	Revision (Name & Date)
A	C
B	D

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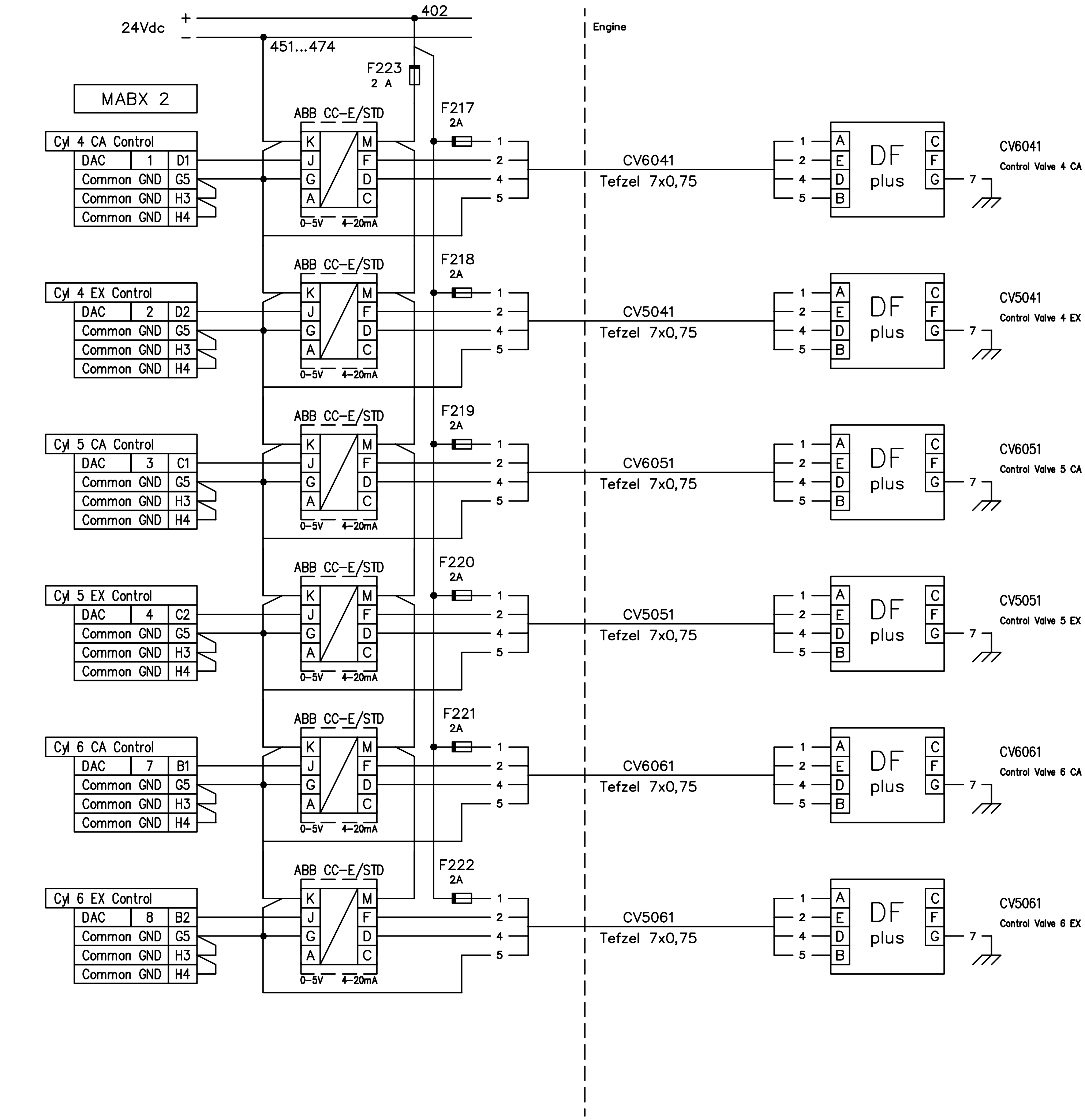


1 = Black
2 = Blue
3 = Brown
4 = Grey
5 = Turquoise
6 = White
7 = Orange

WÄRTSILÄ

BUILDING ACT: LAB

NAME AND ADDRESS: Wärtsilä Finland Technology

DRAWING ART: Wiring Diagram

CONTENT OF DRAWING: Cell 3, 293P / G3_dSPACE Analog Output (0–5 V)

DRAWER: TBi

MADE: –

DATE: 13.10.2011

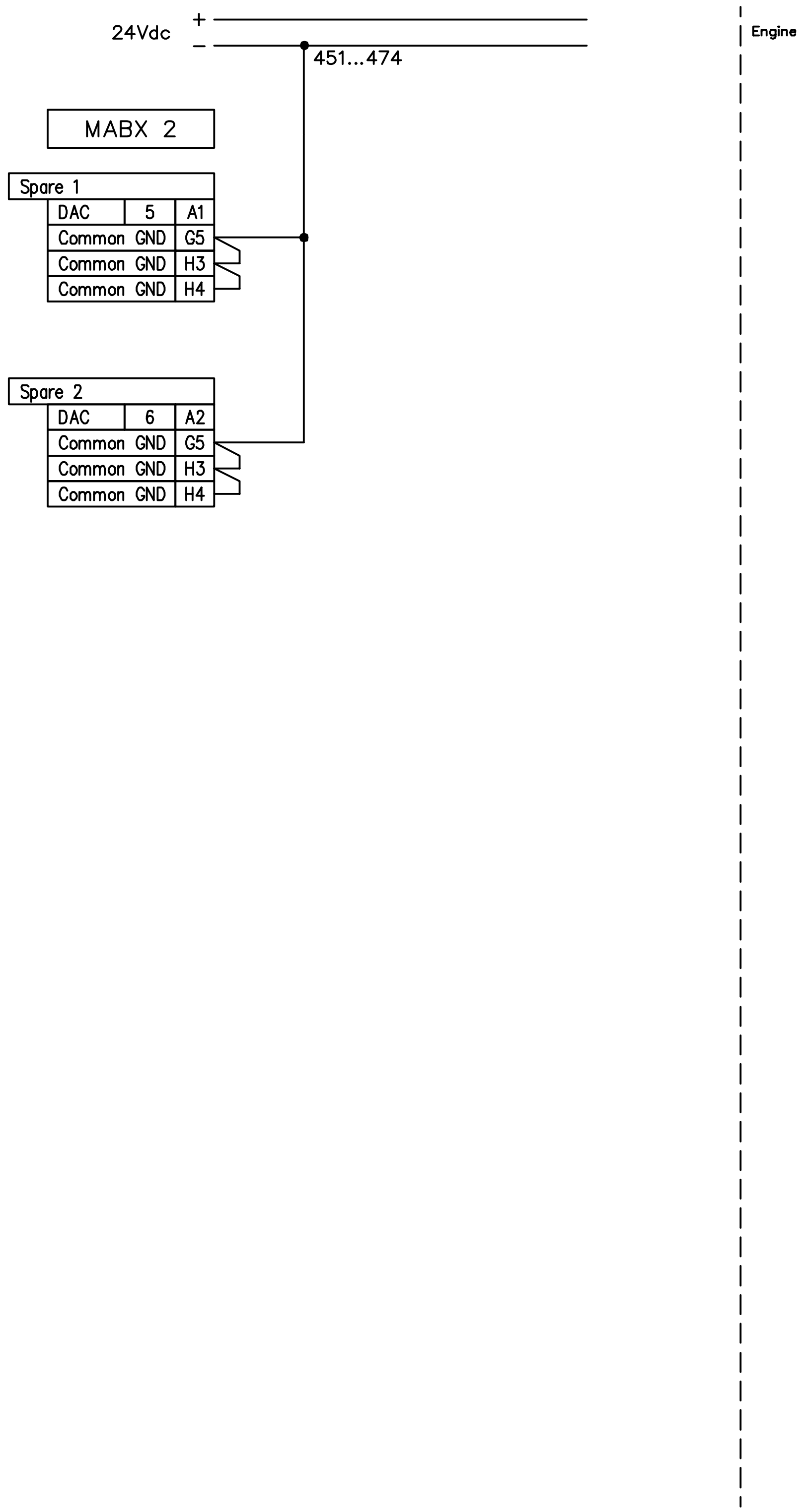
CHKD.

DRAWING Nr. 8078 3V 9139 73

REVISION

DRAW. FILE \CONTROL\CELL_3\293P\913973.DWG

Revision (Name & Date)	Revision (Name & Date)
A	C
B	D



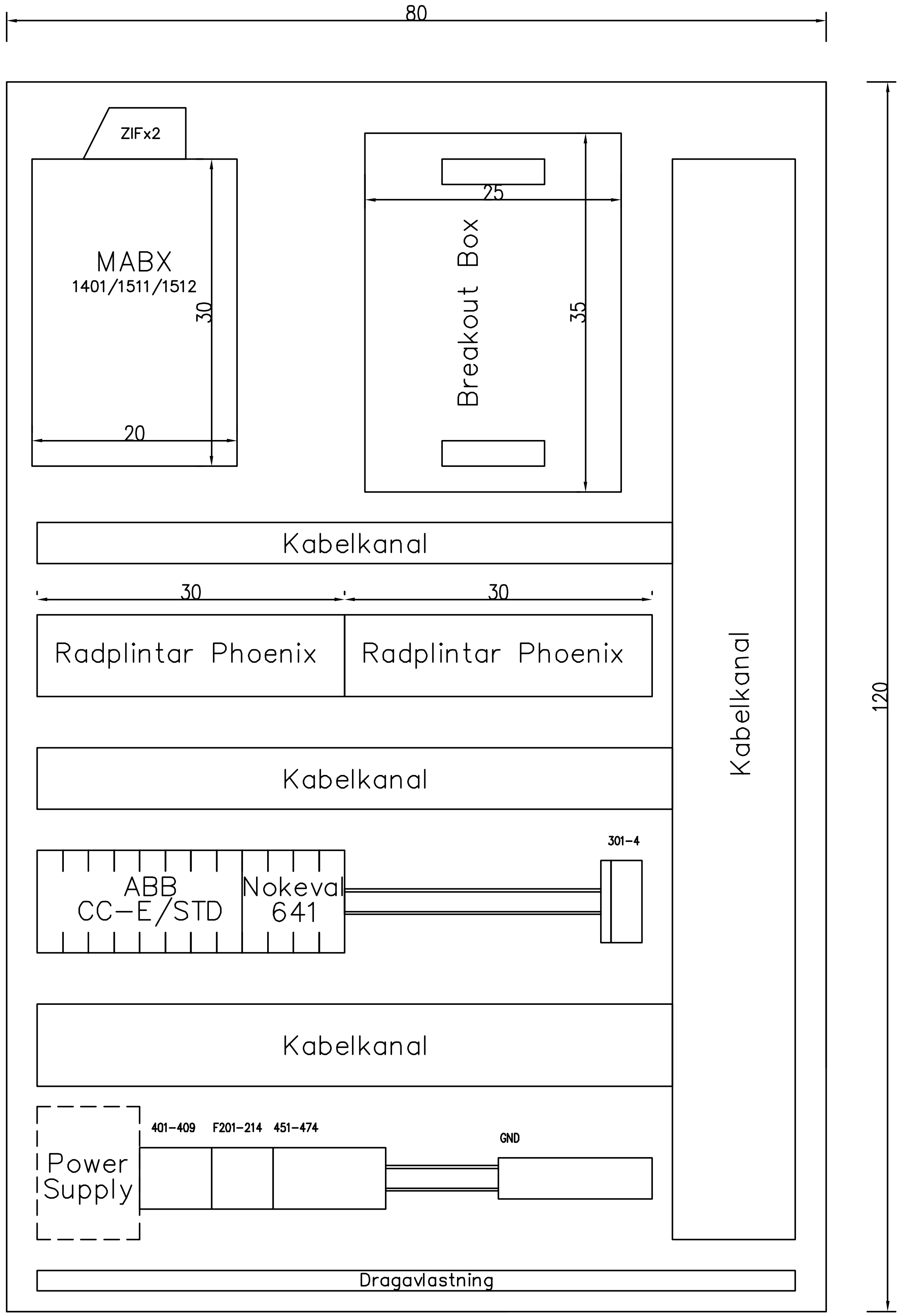
WÄRTSILÄ

BUILDING ACT LAB		DRAWING ART Wiring Diagram	
NAME AND ADDRESS Wärtsilä Finland Technology		CONTENT OF DRAWING Cell 3, 293P / G3_dSPACE Analog Output (0–5 V)	
DRAWER TBi	MADE –	DRAWING Nr. 8078 3V 9139 74	REVISION
DATE 13.10.2011	CHKD.		

DRAW. FILE \CONTROL\CELL_3\293P\913974.DWG

Appendix 2: Drawings for SCE

Revision (Name & Date)	Revision (Name & Date)
A	C
B	D



WÄRTSILÄ

BUILDING ACT: LAB

NAME AND ADDRESS: Wärtsilä Finland Technology

DRAWING ART: Wiring Diagram

CONTENT OF DRAWING: SCE, BAP045 / G4_dSPACE Cabinet Layout

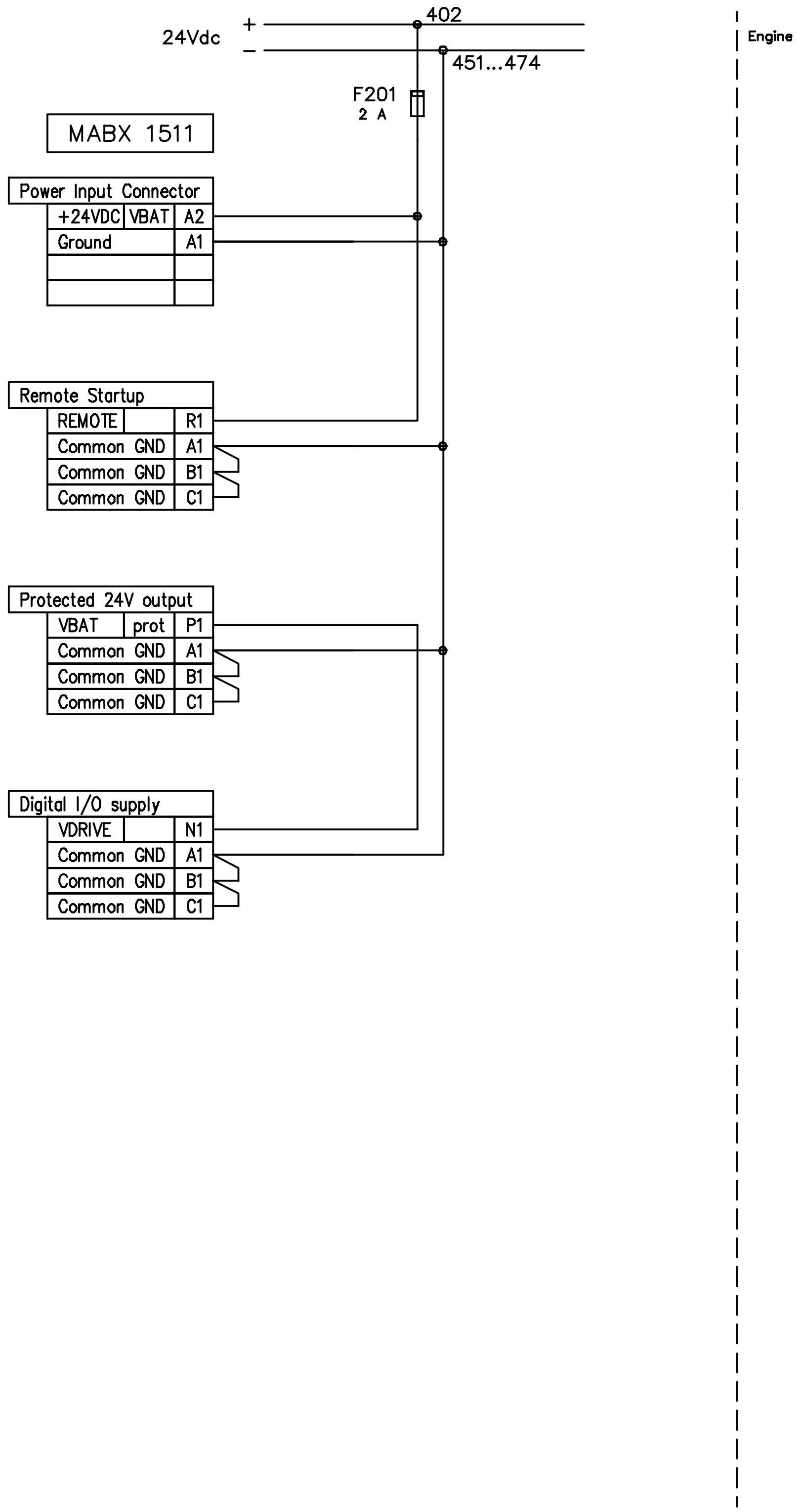
DRAWER: TBi | MADE: –

DATE: 3.2.2012 | CHKD.:

DRAW. FILE: \CONTROL\WVC\G41\DSPACE\25001.DWG

DRAWING Nr. WVCAD200025001 | REVISION

Revision (Name & Date)	Revision (Name & Date)
A	C
B	D



WÄRTSILÄ

BUILDING ACT: LAB

NAME AND ADDRESS: Wärtsilä Finland Technology

DRAWING ART: Wiring Diagram

CONTENT OF DRAWING: SCE, BAP045 / G4_dSPACE Power Supply

DRAWER: TBi

MADE: –

DATE: 7.11.2011

CHKD.:

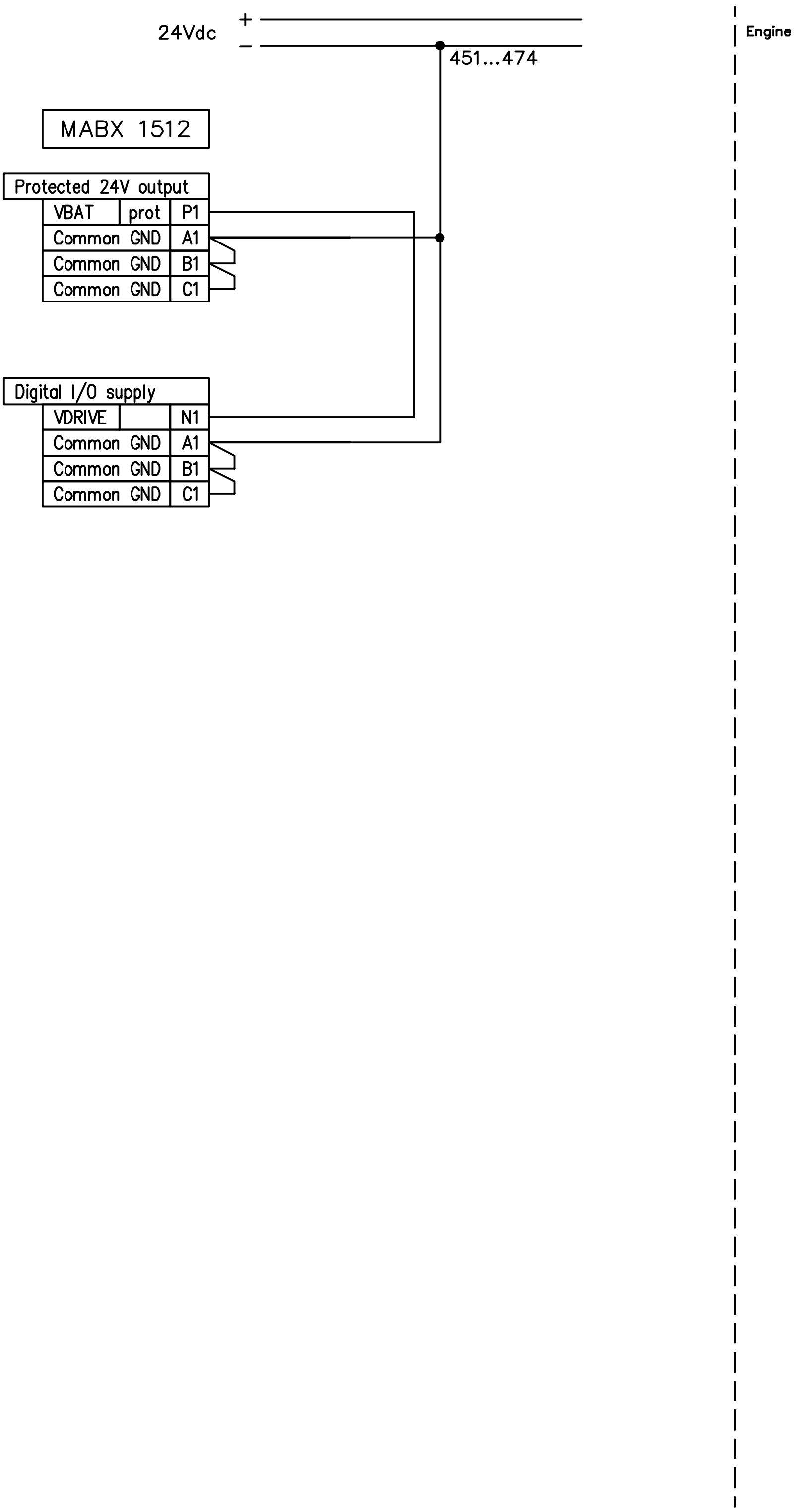
DRAW. FILE: \CONTROL\WVC\G41\DSPACE\25002.DWG

DRAWING Nr.: WVCAD200025002

REVISION:

Revision (Name & Date)
A
B

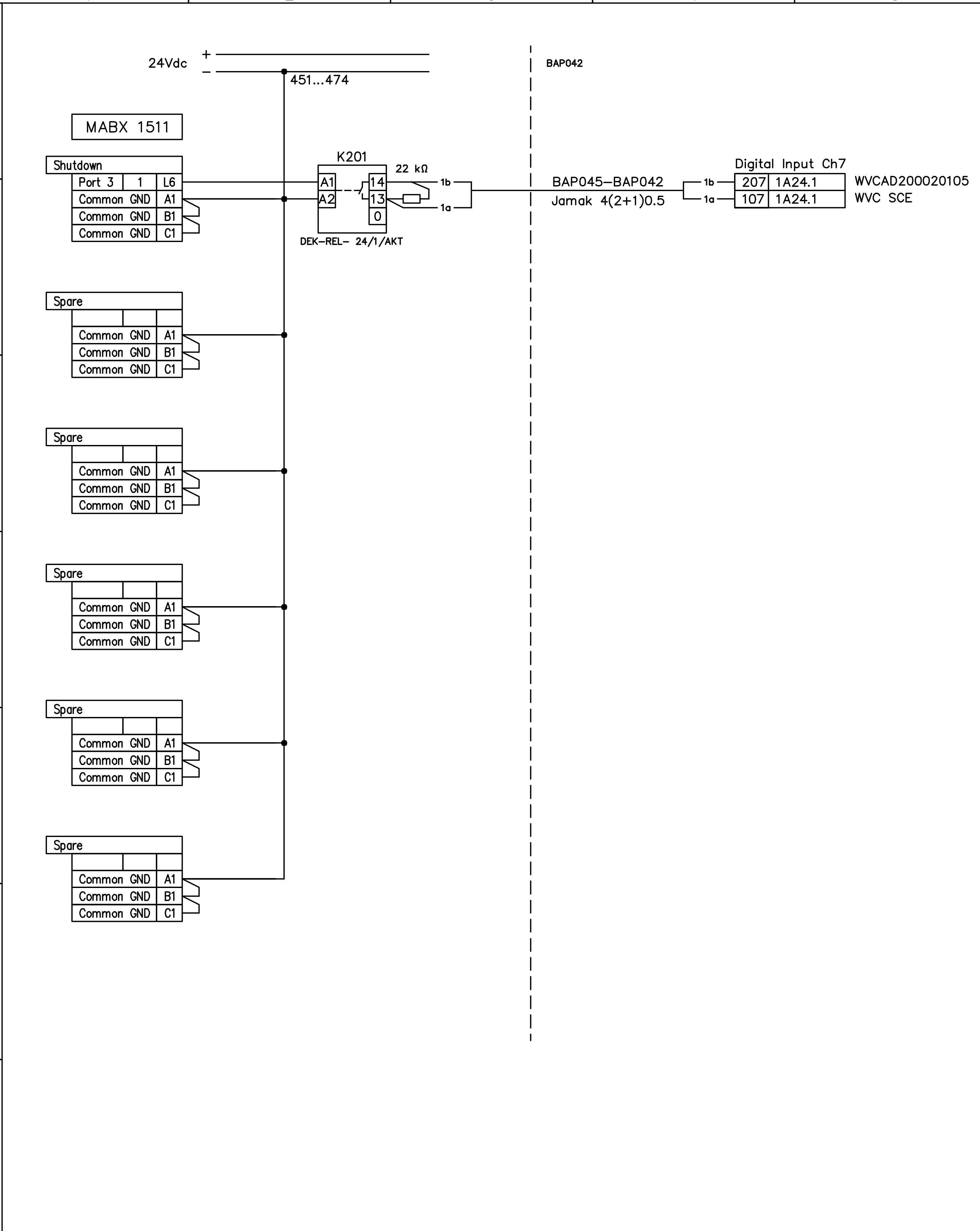
Revision (Name & Date)
C
D



BUILDING ACT	LAB
NAME AND ADDRESS	Wärtsilä Finland Technology
DRAWER	TBi
MADE	–
DATE	7.11.2011
CHKD.	
DRAWING ART	Wiring Diagram
CONTENT OF DRAWING	SCE, BAP045 / G4_dSPACE Power Supply
DRAWING Nr.	WVCAD200025003
REVISION	
DRAW. FILE	\CONTROL\WVC\G41\DSPACE\25003.DWG

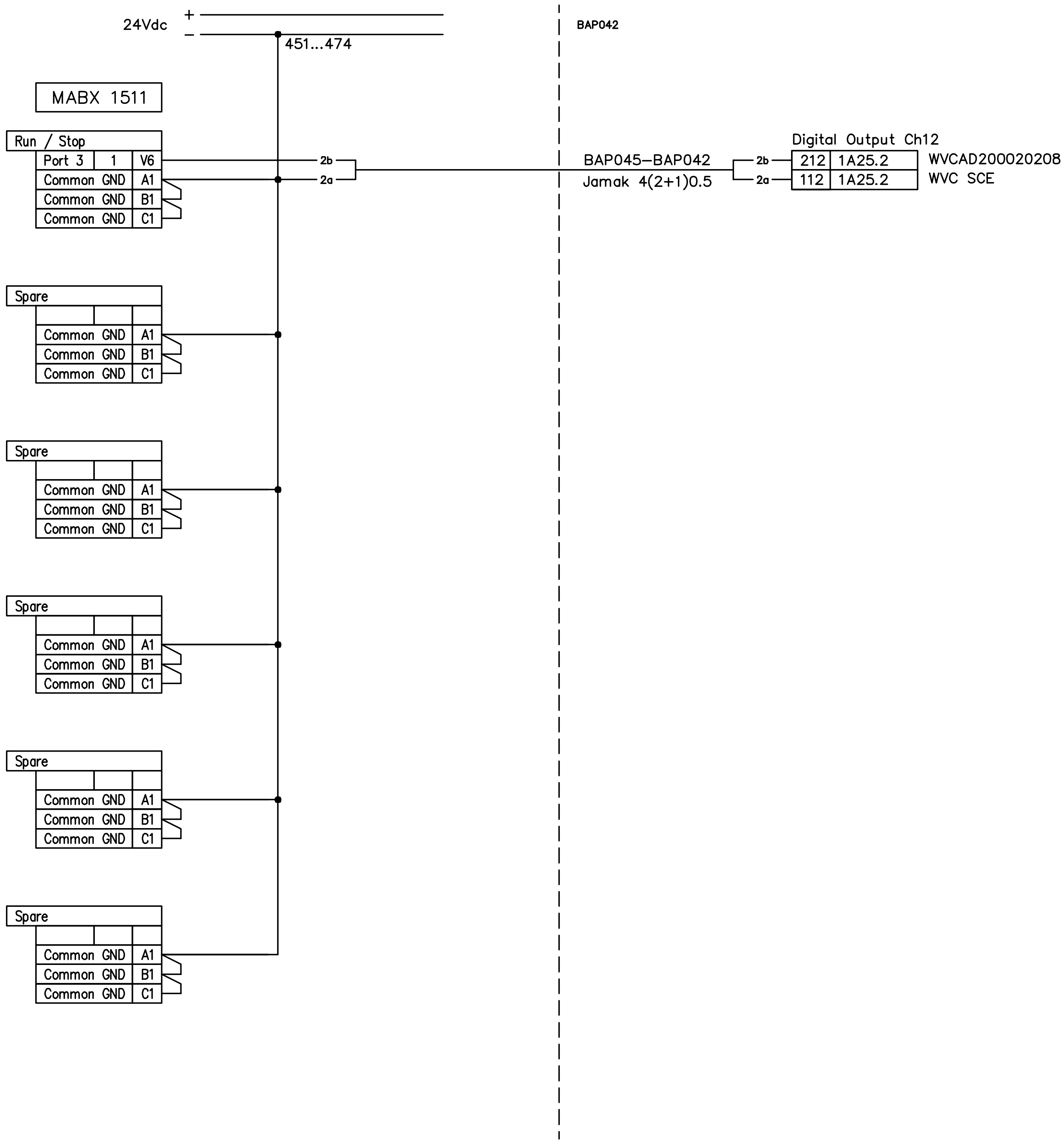
WÄRTSILÄ

Revision (Name & Date)	Revision (Name & Date)
A	C
B	D



WÄRTSILÄ	BUILDING ACT: LAB	DRAWING ART: Wiring Diagram
	NAME AND ADDRESS: Wärtsilä Finland Technology	CONTENT OF DRAWING: SCE, BAP045 / G4_dSPACE Digital Output (0–24V)
DRAW. FILE \CONTROL\WVC\G41\DSPACE\25101.DWG	DRAWER TBi / MADE – / DATE 7.11.2011 / CHKD.	DRAWING Nr. WVCAD200025101 REVISION

Revision (Name & Date)	Revision (Name & Date)
A	C
B	D



WÄRTSILÄ

BUILDING ACT: LAB

NAME AND ADDRESS: Wärtsilä Finland Technology

DRAWING ART: Wiring Diagram

CONTENT OF DRAWING: SCE, BAP045 / G4_dSPACE Digital Output (0–24V)

DRAW. FILE: \CONTROL\WVC\G41\DSPACE\25101.DWG

DRAWER: TBi

DATE: 14.11.2011

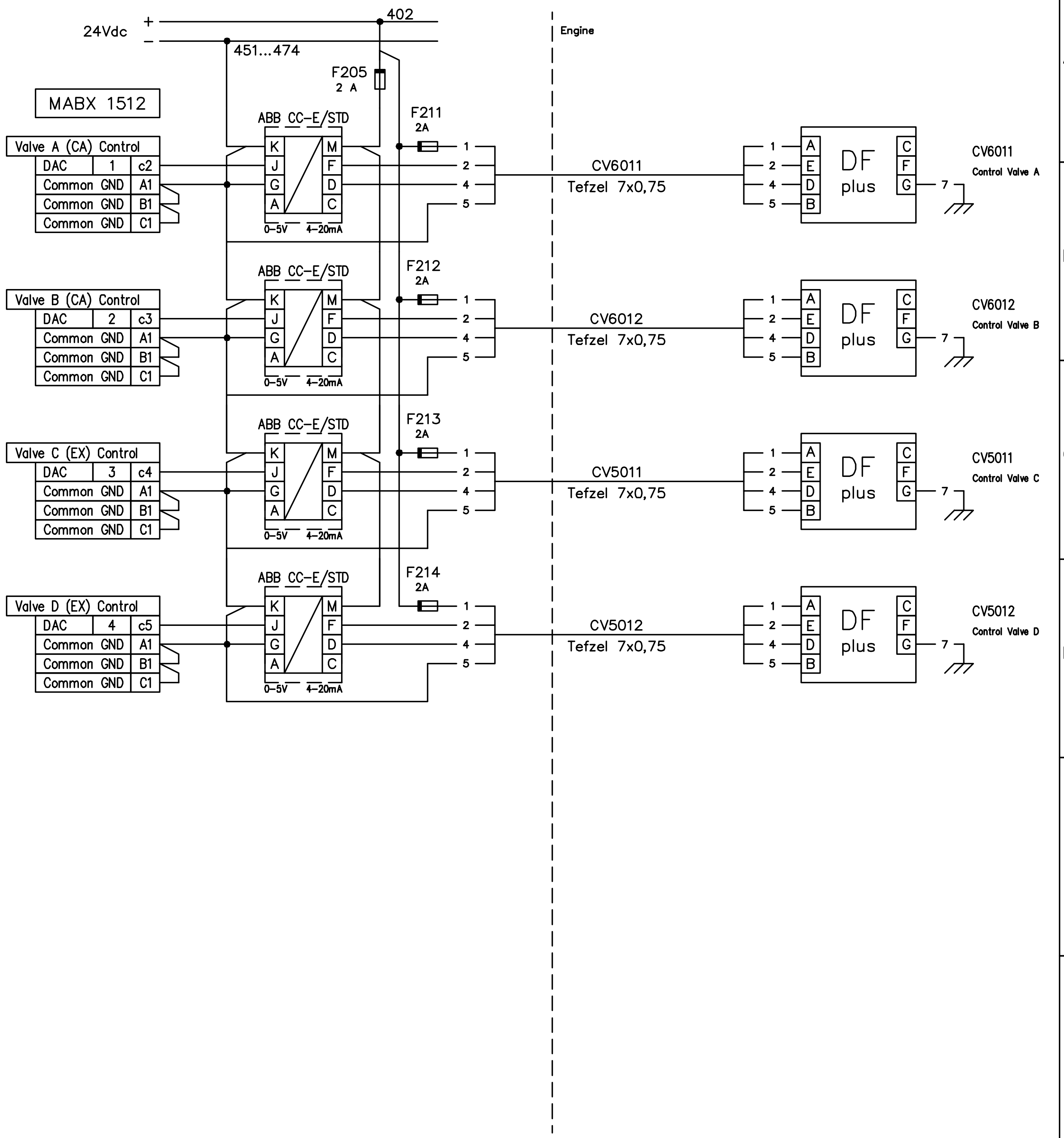
MADE: –

CHKD.

DRAWING Nr. WVCAD200025101

REVISION

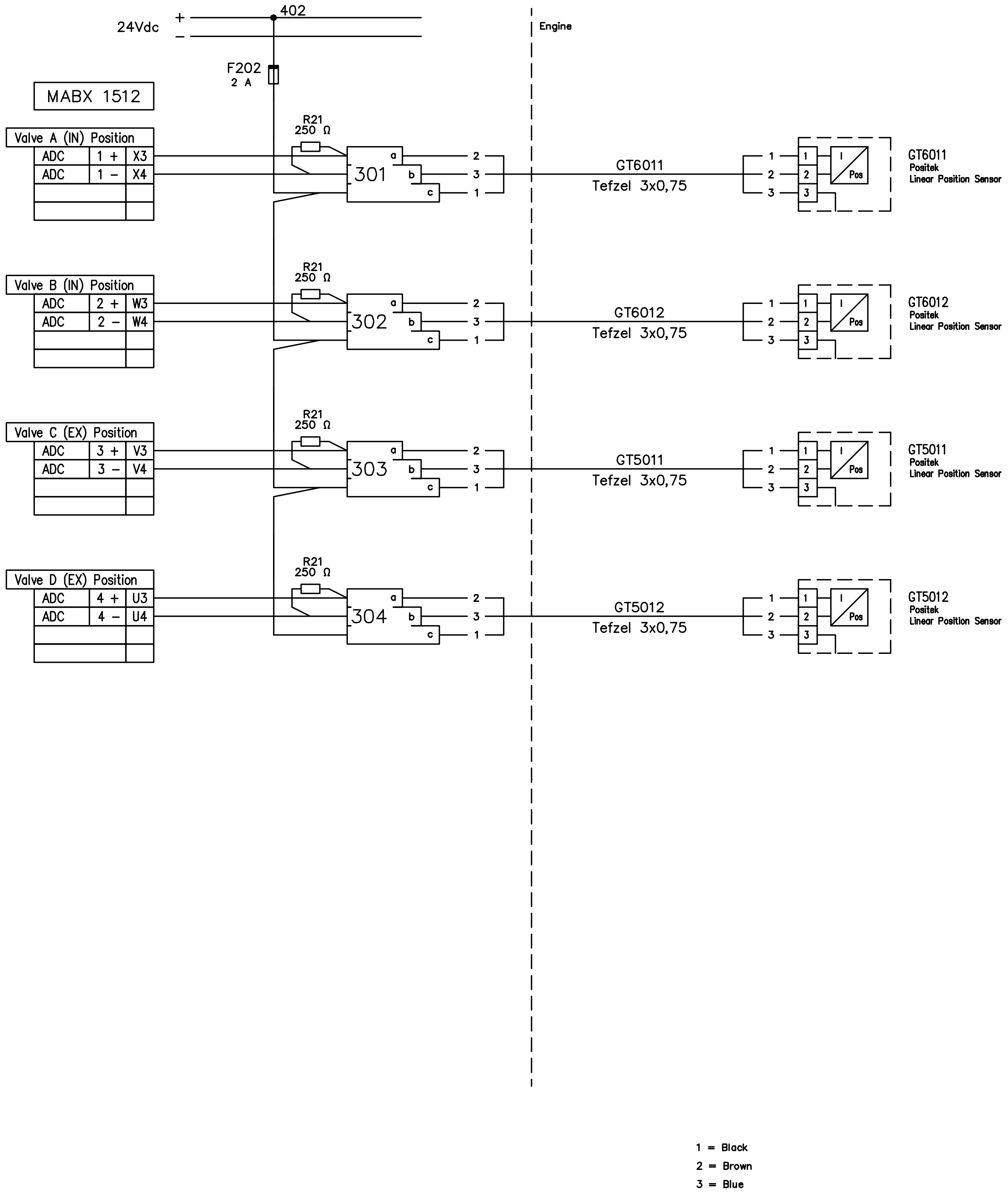
Revision (Name & Date)	Revision (Name & Date)
A	C
B	D



1 = Black
2 = Blue
3 = Brown
4 = Grey
5 = Turquoise
6 = White
7 = Orange

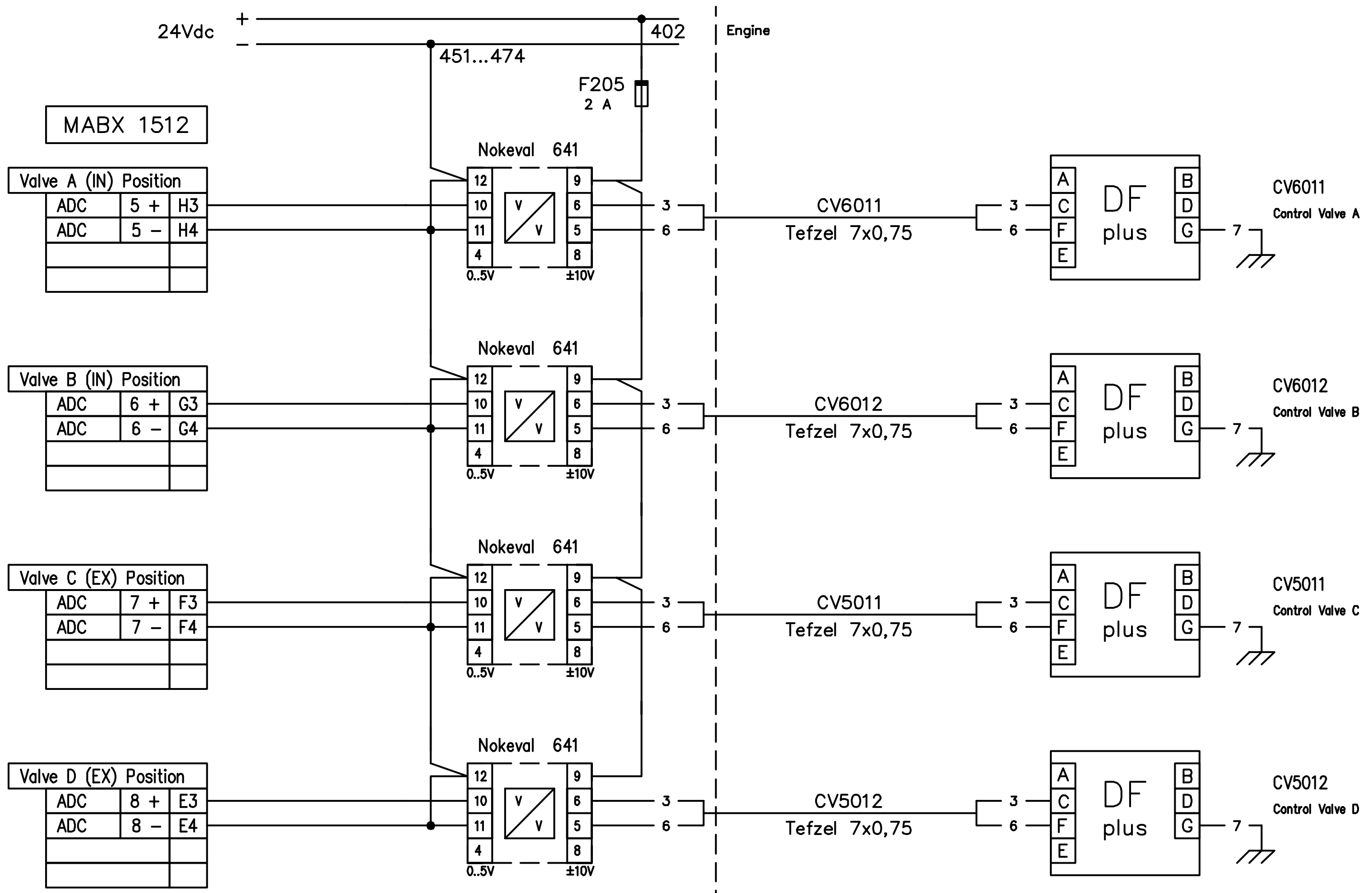
WÄRTSILÄ	BUILDING ACT: LAB	DRAWING ART: Wiring Diagram
	NAME AND ADDRESS: Wärtsilä Finland Technology	CONTENT OF DRAWING: SCE, BAP045 / G4_dSPACE Analog Output (0-5 V)
DRAW. FILE \CONTROL\WVC\G41\DSPACE\25301.DWG	DRAWER TBi · MADE – · DATE 4.11.2011 · CHKD.	DRAWING Nr. WVCAD200025301 · REVISION

Revision (Name & Date)	Revision (Name & Date)
A TBi 24.01.12	C
B	D



WÄRTSILÄ	BUILDING ACT: LAB	DRAWING ART: Wiring Diagram
	NAME AND ADDRESS: Wärtsilä Finland Technology	CONTENT OF DRAWING: SCE, BAP045 / G4_dSPACE Analog Input (0–5 V)
DRAW. FILE \CONTROL\WVC\G41\DSPACE\25501.DWG	DRAWER TBi; DATE 7.11.11; MADE –; CHKD.	DRAWING Nr. WVCAD200025501 REVISION A

Revision (Name & Date)	Revision (Name & Date)
A	C
B	D



1 = Black
2 = Blue
3 = Brown
4 = Grey
5 = Turquoise
6 = White
7 = Orange

WÄRTSILÄ

BUILDING ACT: LAB

NAME AND ADDRESS: Wärtsilä Finland Technology

DRAWING ART: Wiring Diagram

CONTENT OF DRAWING: SCE, BAP045 / G4_dSPACE Analog Input (0–5 V)

DRAWER: TBi

MADE: –

DATE: 7.11.2011

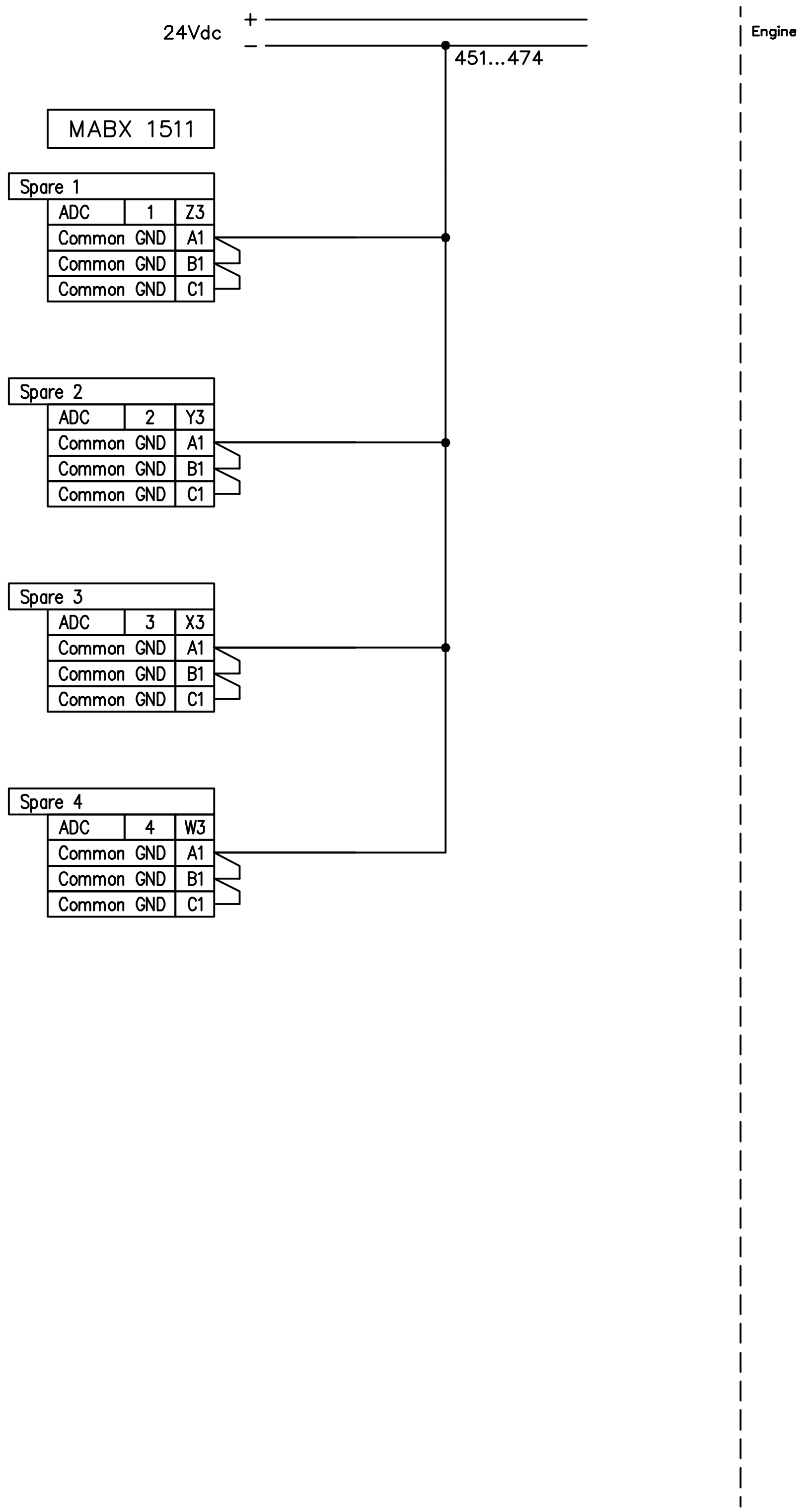
CHKD.

DRAW. FILE: \CONTROL\WVC\G41\DSPACE\25502.DWG

DRAWING Nr.: WVCAD200025502

REVISION

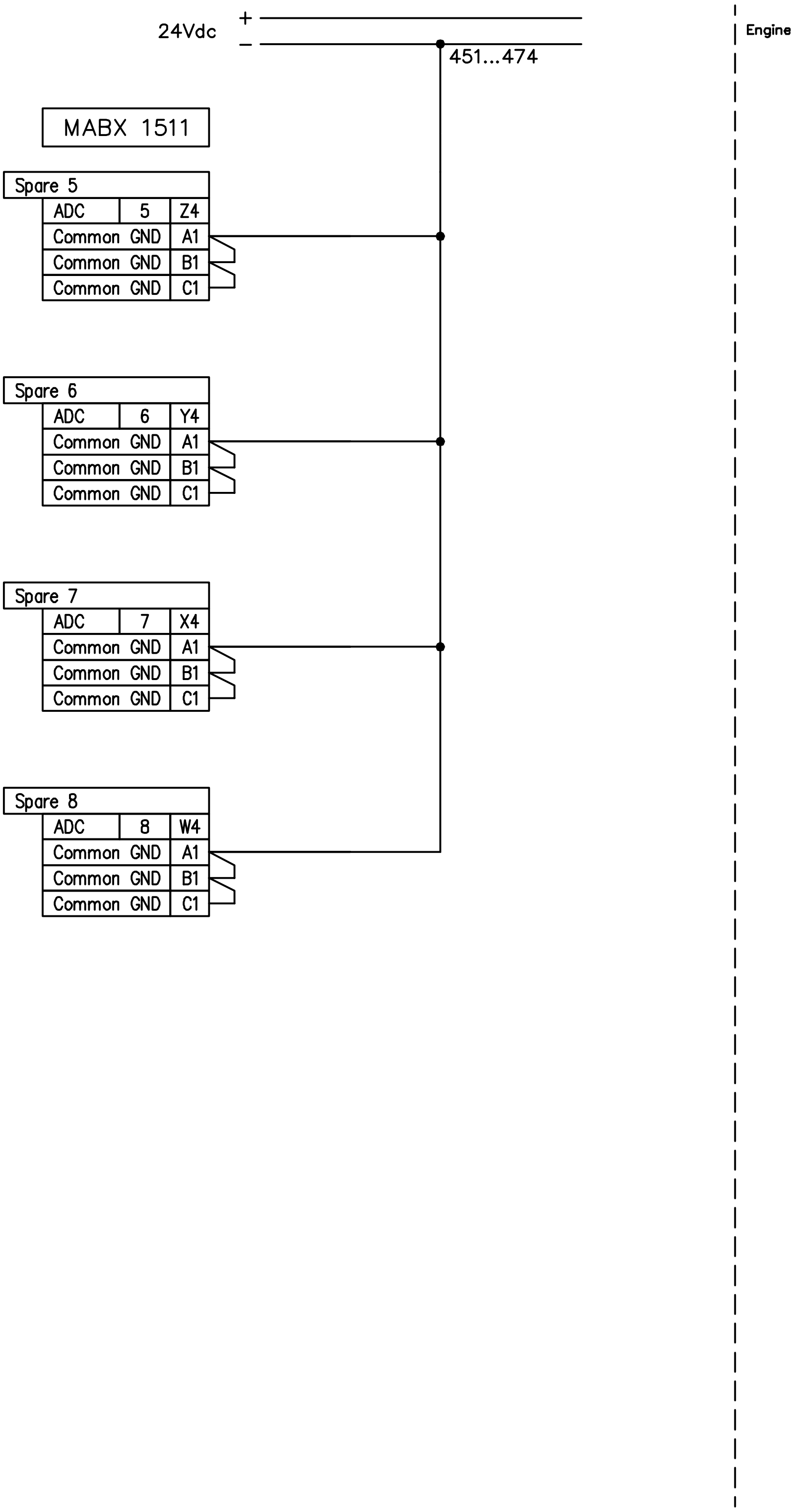
Revision (Name & Date)	Revision (Name & Date)
A	C
B	D



WÄRTSILÄ

BUILDING ACT	LAB
NAME AND ADDRESS	Wärtsilä Finland Technology
DRAWING ART	Wiring Diagram
CONTENT OF DRAWING	SCE, BAP045 / G4_dSPACE Analog Input (0–5 V)
DRAWER	TBi
MADE	–
DATE	7.11.2011
CHKD.	
DRAW. FILE	\CONTROL\WVC\G41\DSPACE\25503.DWG
DRAWING Nr.	WVCAD200025503
REVISION	

Revision (Name & Date)	Revision (Name & Date)
A	C
B	D



WÄRTSILÄ

BUILDING ACT: LAB

NAME AND ADDRESS: Wärtsilä Finland Technology

DRAWING ART: Wiring Diagram

CONTENT OF DRAWING: SCE, BAP045 / G4_dSPACE Analog Input (0–5 V)

DRAW. FILE: \CONTROL\WVC\G41\DSPACE\25504.DWG

DRAWER: TBi

MADE: –

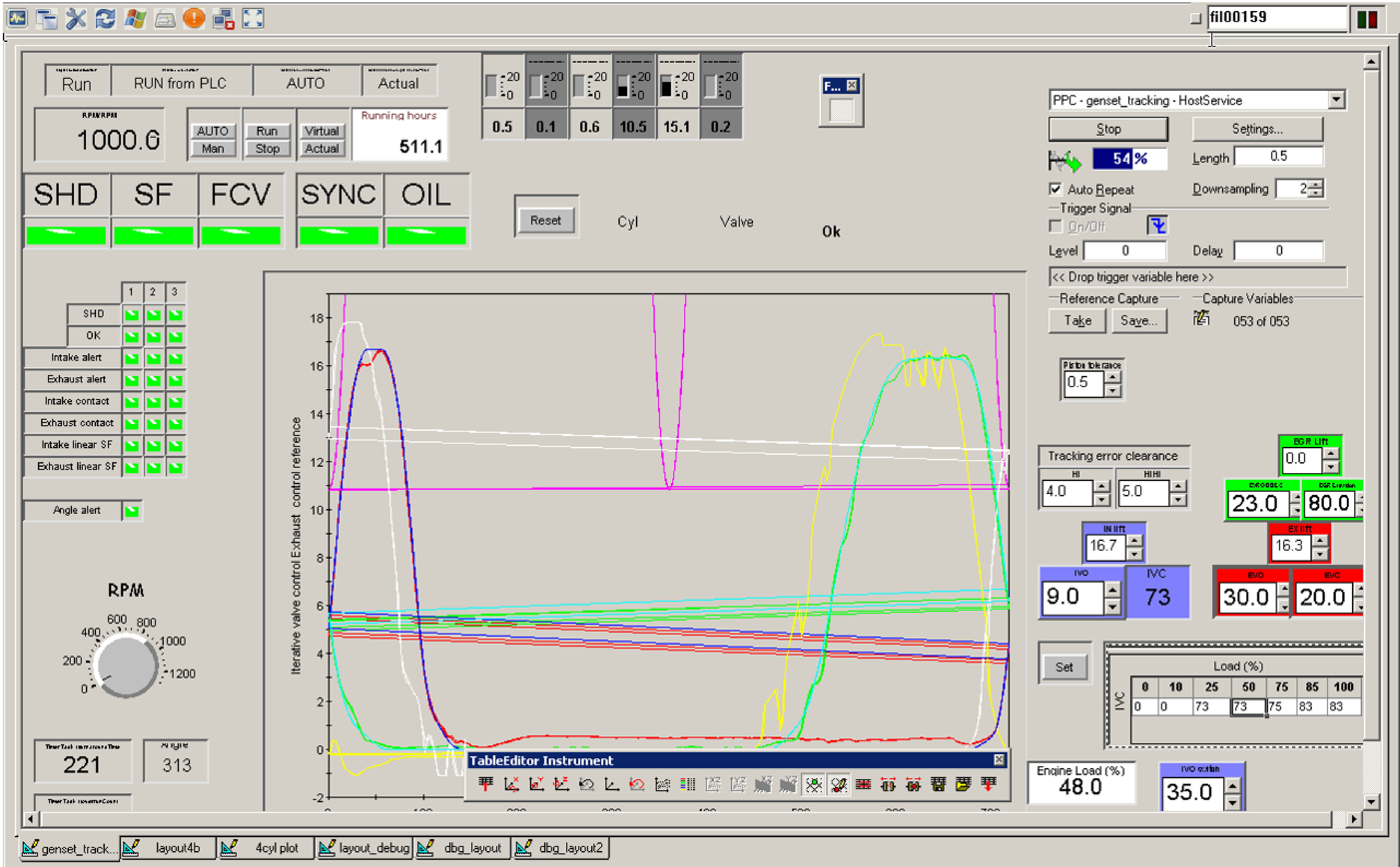
DATE: 7.11.2011

CHKD.:

DRAWING Nr.: WVCAD200025504

REVISION:

Appendix 3: ControlDesk®


fil00159
Run
RUN from PLC
AUTO
Actual
1000.6
AUTO
Man
Run
Stop
Virtual
Actual
Running hours
511.1
SHD
SF
FCV
SYNC
OIL
0.5
0.1
0.6
10.5
15.1
0.2
Reset
Cyl
Valve
Ok
SHD
OK
Intake alert
Exhaust alert
Intake contact
Exhaust contact
Intake linear SF
Exhaust linear SF
Angle alert
RPM
221
313
Iterative valve control Exhaust control reference
TableEditor Instrument
PPC - genset_tracking - HostService
Stop
Settings...
54 %
Length 0.5
Auto Repeat
Downsampling 2
Trigger Signal
On/Off
Level 0
Delay 0
<< Drop trigger variable here >>
Reference Capture
Take
Save...
Capture Variables
053 of 053
0.5
Tracking error clearance
HI 4.0
HIHI 5.0
EGR Lift 0.0
23.0
80.0
IN lift 16.7
EX lift 16.3
IVO 9.0
IVC 73
EVO 30.0
EVC 20.0
Set
Load (%)
IVC
Engine Load (%)
48.0
35.0
genset_track...
layout4b
4cyl plot
layout_debug
dbg_layout
dbg_layout2