

Evaluation of Insulation Monitoring Devices in an Isolated DC System

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BACHELOR'S THESIS

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Abstract

This Bachelor's thesis has been done on behalf of Wärtsilä Research & Development for the team Testing & Validation. The thesis's purpose was divided into two main objectives: evaluating a suitable Insulation Monitoring Device (IMD) candidate for the engine automation system and determining why Wärtsilä uses isolated (IT) systems on their marine applications.

Wärtsilä's engine automation system, a complex system built upon smaller IT subsystems monitored by so-called IMDs, has had issues with insulation faults and insulation resistance measuring errors during internal UNIC tests. It was decided to perform an extensive comparison test of three different DC capable IMDs. The comparison test was conducted on a running W31 engine at the engine Laboratory in Vaasa.

A question arose as to why Wärtsilä uses IT systems in their marine application. Therefore, based on recommendations from International Standards, the thesis's theoretical part consists of information regarding distribution systems, earthing principles, and electrical safety in vessels.

The thesis's result proposes a suitable IMD candidate for the engine automation system and determines why Wärtsilä uses IT systems on their marine applications.

Language: English Keywords: Insulation Monitoring Device, device evaluation, comparison test, IT system

EXAMENSARBETE

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Abstrakt

Detta examensarbete har gjorts på uppdrag av Wärtsilä Research & Development, för teamet Testing & Validation. Examensarbetets syfte var uppdelat i två huvudmål: att utvärdera en lämplig isolationsövervakningsenhet för motorautomationssystemet och fastställa varför Wärtsilä använder isolerade (IT) system i sina marina applikationer.

Wärtsiläs motorautomationssystem, ett komplext system uppbyggt av mindre IT-delsystem som övervakas av s.k. isolationsövervakningsenheter, har haft svårigheter med isolationsfel och mätfel av isolationsmotståndet under interna UNIC-tester. Det beslutades att utföra ett omfattande jämförelsetest av tre olika DC-kapabla isolationsövervakningsenheter. Jämförelsetestet genomfördes på en opererande W31-motor vid motorlaboratoriet i Vasa.

En fråga uppstod varför Wärtsilä använder IT-system i sina marina applikationer. Examensarbetets teoretiska del, som baserar sig på rekommendationer från internationella standarder, består därför av insamlad information angående distributionssystem, jordningsprinciper och elsäkerhet i fartyg.

Examensarbetets resultat föreslår en lämplig isolationsövervakningsenhet för motorautomationssystemet och fastställer varför Wärtsilä använder IT-system i sina marina applikationer.

Språk: engelska

Nyckelord: isolationsövervakningsenhet, apparatutvärdering, jämförelsetest, IT-system

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Tiivistelmä

Tämä opinnäytetyö on tehty Wärtsilä Research & Development, Testing & Validation -osastolle. Opinnäytetyön tarkoitus oli jaettu kahteen päätavoitteeseen: arvioida sopiva eristystason valvontalaite moottoriautomaatiojärjestelmälle ja selvittää, miksi Wärtsilä käyttää eristettyjä (IT) järjestelmiä merisovelluksissaan.

Wärtsilän moottoriautomaatiojärjestelmällä, monimutkainen järjestelmä, joka on rakennettu pienemmistä IT-osajärjestelmistä, joita valvotaan ns. eristystason valvontalaitteilla, on ollut vaikeuksia eristysvirheiden ja eristysvastuksen mittausvirheiden suhteen sisäisten UNIC-testien aikana. Kolmen erilaisen DC-yhteensopivan eristystä valvovan laitteen kesken päätettiin suorittaa laaja vertailutesti. Vertailutesti tehtiin käynnissä olevalla W31-moottorilla Vaasan moottorilaboratoriossa.

Kysymys nousi esiin, miksi Wärtsilä käyttää IT-järjestelmiä merisovelluksissaan. Opinnäytetyön teoriaosa, joka perustuu kansainvälisiin standardeihin, sisältää siksi kerättyä informaatiota alusten jakelujärjestelmistä, maadoitusperiaatteista ja sähköturvallisuudesta.

Opinnäytetyön tulos ehdottaa sopivan eristystason valvontalaitteen moottoriautomaatiojärjestelmälle ja määrittää, miksi Wärtsilä käyttää IT-järjestelmiä merisovelluksissaan.

Kieli: englanti

Avainsanat: eristystason valvontalaite, laitteen arviointi, vertailutesti, IT-järjestelmä

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Appendix 3 Conflicting measurements of direct insulation faults

Appendix 4 Conflicting measurements of 50 k Ω insulation faults

List of abbreviations

AC	Alternating Current
CR	Common Rail
DC	Direct Current
EDL	Enhanced Diagnostics Log
HV	High Voltage
IEC	International Electrotechnical Commission
I_m	The maximum current value that can flow between earth and the system, limited to the internal d.c. R_i
IMD	Insulation Monitoring Device
L-	Negative (neutral) conductor
L+	Positive conductor
LV	Low Voltage
PSA	Power Supply Actuators
PSD	Power Supply Driver
PSS	Power Supply System
R_a	Specific insulation resistance threshold value at which the device responds, adjustable or permanently set on the device
RCD	Residual Current Device
RCM	Residual Current Monitor
R_F	Insulation resistance in the system being monitored
R_i	The internal resistance of the IMD

SME	Single Main Engine
UNIC	Unified Controls
UNITool	Wärtsilä software configuration tool
Ω	Ohm

1 Introduction

Hardware testing is an essential part of ensuring that—by measuring, recording, and evaluating data acquired during controlled operation—a device or system functions according to a given specification requirement. This thesis evaluates three different DC capable Insulation Monitoring Devices (IMD) by collecting and analysing data acquired from performing comprehensive tests for each device.

IMDs are used in Wärtsilä's engine automation systems to protect against consequences from insulation faults by providing an alarm indication at an early stage if the insulation resistance decreases. The currently in-use devices have been selected based on their specifications, but an evaluation of their suitability in the engine automation system has not been done. Therefore, it was decided to perform a comprehensive comparison test between three different IMDs to evaluate a suitable candidate for the system and see if a different combination of devices would ultimately protect the system

This thesis is written on behalf of the Testing & Validation team at Wärtsilä Research and Development. The thesis clears up information regarding earthing principles and electrical safety in vessel's and why Wärtsilä uses isolated (IT) systems in their marine applications. The thesis framework is built upon IEC International Standards.

1.1 Wärtsilä

Wärtsilä is a worldwide innovator in smart technology and complete lifecycle solutions that focuses on the marine and energy markets. Wärtsilä maximises vessels and power plants' environmental and economic performance by underscoring maintainable innovation, absolute efficiency, and data analytics. As of 2020, Wärtsilä had approximately 18 000 employees and operations in more than 80 countries worldwide. (Wärtsilä, 2021)

1.2 Background

Since October 2018, I have been working as a UNIC Testing Trainee at the department Testing & Validation within the marine business. My primary duties have been hardware testing and documentation of hardware components for the Wärtsilä UNIC engine automation system.

Insulation faults and insulation resistance measuring errors have been an underlying issue in the engine automation system when simulating insulation faults during internal UNIC tests; some faults have not been detected by the system nor the devices and caused unexpected system behaviour. As the engine automation system is complex, satisfactory detection of insulation faults and insulation resistance measuring errors is challenging to fulfil. An insulation fault can be a very critical problem if it is not detected and cleared immediately. Therefore, it is vital to have an appropriate device to enable sufficient and time-effortless detection of these faults as the fault could potentially lead to system failure and worst-case scenario engine shutdown.

The Bachelor's thesis originated from this issue. It also raised the question of why Wärtsilä uses IT systems in their marine applications.

1.3 Objectives and scope

The purpose of this thesis can be divided into two main objectives. First, a comparison test between three different IMDs (ABB CM-IWS.1S, Bender isoUG425, and DOLD IL5881.12/100) will be performed on a W8V31CR lab engine to evaluate a suiting candidate for the engine automation system. Both the ABB and Bender types are currently in use within the engine automation system but have so far not been compared in a full-scale test on an engine. DOLD IL5881.12/100 is a new candidate to be tested. Secondly, a determination is needed on why Wärtsilä uses IT systems on their marine applications by performing research regarding the subject and investigating internally.

This thesis follows the requirements set by the International Electrotechnical Commission (IEC) standards. For this thesis, IEC 60092-201 and IEC 61557-8 were utilised. IEC 60092-201 contains recommendations for system design of electrical installations in vessels, while IEC 61557-8 covers Insulation Monitoring Devices for low voltage IT distribution systems up to 1000 VAC and 1500 VDC.

2 Marine power systems

In marine applications, the engine is the most valuable key component in terms of electrical power generation and marine propulsion, enabling the distribution of power and the vessel's progress in the water. Wärtsilä specialises in combustion engines which are mainly used for these types of components. Power generation is done by converting the energy of the engine's fuel into mechanical energy, which in this case are rotations. The engine's shaft rotates and transfers the mechanical energy to an electric generator which then creates power. The same rotation also spins a propeller which creates propulsion.

The safety in electrical installations and systems can be verified by implementing various protective measures, such as system earthing. (Dictionary, 2021; Wärtsilä, n.d.)

2.1 Wärtsilä 31

The Wärtsilä 31 (W31) is a 4-stroke medium speed engine with high overall performance and efficiency. The engine is designed to be applicable in a wide range of vessel types and marine applications, both as main propulsion and auxiliary engine. The W31 can be optimised either as a constant speed engine or as a variable speed engine, which follows a propeller curve. The engine's power output is 4.2-9.8 MW at 720-750 rpm, depending on the number of cylinders, which can be 8-16 (Wärtsilä, 2015)

For the comparison test, the W8V31CR lab engine with SME configuration was utilised. This specific 8-cylinder (8V) lab engine uses two-stage turbocharging and has a common rail fuel injection system. As the name indicates, the system is common for every cylinder of the engine. Every cylinder is connected to a rail, and a high-pressure injection system provides the fuel pressure with adjustable valve actuation. (Connolly, 2017)

The term SME (Single Main Engine) is naming for a situation where propulsion is necessary to be guaranteed by one engine. As this thesis is mainly electrically oriented, the SME configuration's relevant matters are that both the power and UNIC systems differ. (Wärtsilä, 2018)

2.2 Power distribution

A vessel's power system's function is to safely distribute electrical power to different AC and DC subsystems and equipment connected to it. The main switchboard is the most noticeable feature of the system: the main switchboard powers distribution boards, section boards, and motor starter groups. Transformers interconnect the High Voltage (HV) and Low Voltage (LV) distribution sections. The main switchboard is located in the engine control room, and the electrical power generation and distribution are monitored and controlled from there. If over-current occurs in the system, fuses and circuit breakers are critical components, as they automatically disconnect a faulty circuit.

AC distribution is much more common in marine applications than DC distribution, as it follows shore practice. LV DC systems are often powered via galvanically isolated AC/DC power supplies fed from an LV AC distribution board. E.g. Wärtsilä UNIC is fed by an extensive DC system built upon smaller isolated DC systems powered by AC/DC supplies. (Maes, 2014, p. 7).

According to the international standard IEC 60092-201 (2019), two types of DC distribution systems are considered standard for electrical installations in marine applications: Two- and three-wire systems. The Two-wire DC system is a unipolar DC system consisting of only two conductors (L+ and L-), between which the supply is connected (Figure 1). The Three-wire DC system is basically two unipolar systems connected in series, also called a bipolar DC system consisting of two conductors (L+ and L-) and a middle wire (M) (Figure 2). The supply is taken from the two outer conductors or the middle wire and either outer conductor; the middle wire carries the difference-current. (IEC 60092-201, 2019, p. 18; Kaipia, et al., 2006; EEGGUIDE, 2014)

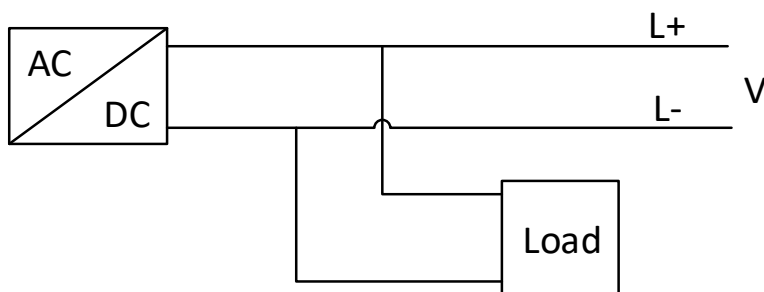


Figure 1. Two-wire DC system.

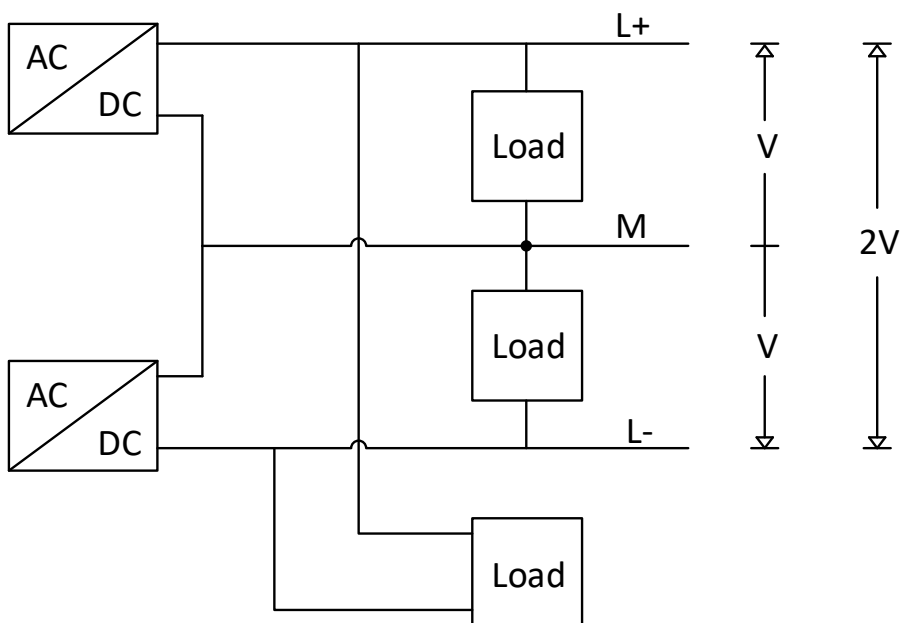


Figure 2. Three-wire DC system.

Protection of the systems and system equipment is done by implementing various protective measures defined by standards based on the system's needs. According to (IEC 60092-201, 2019), IT and TN-S earthing types are considered standard as a system's protective measures. (BENDER Group, 2009, p. 2)

As this thesis mainly focuses on LV DC systems, only earthing examples in the DC environment will be showcased. However, the earthing principles explained in chapter 2.4 can be applied to LV AC systems as well.

2.3 UNIC

The Unified Controls (UNIC) automation system is an embedded engine control system designed by Wärtsilä. UNIC is responsible for control and monitoring as well as engine safety. UNIC is designed to withstand the extreme environments on engines; therefore, much attention has been spent on temperature and vibration endurance. This allows the system to have a compact design, as it can be mounted straight on the engine, reducing the cabling on and around the engine.

The system's architecture is based on so-called UNIC modules, which are distributed around the engine for flexible controls and measurements where locally needed. Communication between the modules is done via a robust communication bus.

The main parts of the UNIC system are distributed on-engine modules, the main cabinet, and a Local Control Panel (LDU). (Wärtsilä, 2019b)

The W8V31CR lab engine uses the 2nd generation UNIC 6-series system.

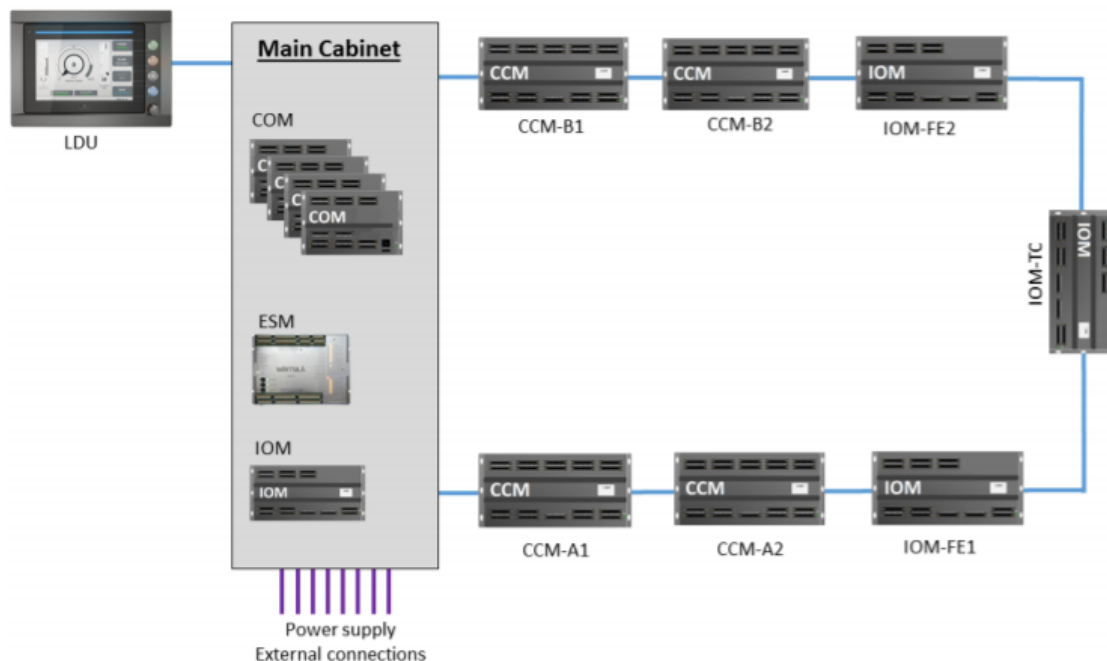


Figure 3. UNIC system overview - W31CR. (Wärtsilä, 2019b)

2.3.1 Main cabinet

The main cabinet is the main link between all engine automation. The engine's external systems are connected via the main cabinet. Furthermore, the distribution of power for engine components and actuators takes place in the main cabinet. The main cabinet consists of Communication Modules (COM), an Engine Safety Module (ESM) and an Input / Output Module (IOM).

Modules inside the main cabinet:

Communication Module (COM)

The COM is the key module for communication in the UNIC system. It handles several control functions, measures the engine speed and position, and is responsible for software and configuration update management. The module supports multiple interfaces such as OPC, Modbus, and hardwired I/O's. In addition, external systems are connected to the COM if needed.

Engine Safety Module (ESM)

The ESM module takes care of the most crucial engine safety functions and can shut down the engine without relying on any other system functions. The ESM monitors engine over-speed protection, lube oil pressure, cooling water temperature, and external systems connected to binary inputs.

Input / Output Module (IOM)

When the IOM module is placed inside the main cabinet, its main task is to extend the number of I/O channels for the on-engine measurements in UNIC. The module is also used for data gathering of analogue, binary, and frequency signals. (Wärtsilä, 2019b)

2.3.2 Distributed on-engine modules

Distributed on-engine modules are mounted around the engine in WTB terminal boxes, close to monitored and controlled sensors and actuators. They consist of Cylinder Control Modules (CCM) and Input / Output modules (IOM). They communicate with the COM modules inside the main cabinet through a High-availability Seamless Redundancy (HSR) communication bus.

Cylinder Control Module (CCM)

The CCM module's primary responsibility is to control and monitor the cylinder and its related functions. E.g. fuel injection, cylinder inlet valve timing control, combustion monitoring of pressure and knock are handled by the CCM.

Input / Output Module (IOM)

The IOM is placed close to sensors and actuators when distributed on the engine. The IOM's primary functions are to measure pressure, turbo speed and temperature. All measurement data is sent to the COM modules in the main cabinet for machinery protection evaluation or further distribution to external systems or the LDU. The module can also control actuators and solenoids needed for various process controls on the engine.

(Wärtsilä, 2019b)

2.3.3 Local control panel

The local control panel consists of a local display unit and an emergency stop button.

Local Display Unit (LDU)

The LDU consists of a touch display for local reading of important engine parameters and push buttons for local engine controls. The pushbuttons are mainly used for engine start, stop, shutdown reset, and selection of local/remote control

Emergency stop button

The emergency stop button is a normally closed push button and is placed near the LDU with the function to shut down the engine when pushed. Activation/deactivation of the button can be read from the LDU.

(Wärtsilä, 2019b)

2.3.4 Channels

Each module contains a specific amount of I/O channels, and each channel has a definite amount of signals ranging between 2 and 4. The following table presents the necessary channels used in this thesis.

Table 1. The modules' I/O channels.

Channel	Description	Modules containing the channels			
ADI	Analogue / Digital Input	COM			
ADIO	Analogue / Digital Input / Output			IOM	
ADO	Analogue / Digital Output	COM			
AI	Analogue Input	COM	CCM	IOM	ESM
AO	Analogue Output	COM			
DI	Digital Input	COM			
DO	Digital Output	COM			ESM
DRV	Driver Output		CCM		
FDI	Fast Digital Input	COM	CCM	IOM	ESM
FDO	Fast Digital Output	COM			
HSD	High Side Drive Output			IOM	
PSD	Power Supply Driver		CCM		
PSS	Power Supply System	COM	CCM	IOM	ESM
Temp	Temperature Sensor Input		CCM		

2.3.5 UNITool

UNITool is a maintenance and monitoring software tool developed by Wärtsilä. The tool is used for engine troubleshooting, tuning of engine parameters, and recording and monitoring the UNIC system. Furthermore, the download and configuration of software to the UNIC system is done via UNITool. (Wärtsilä, 2019b)

For this thesis, UNITool was mainly used for retrieving system diagnostics and recording and monitoring ISO codes by using UNITool's Enhanced Diagnostics Log (EDL) and Trending function. ISO codes contain process values and are linked to module channel inputs, outputs and symbols within the UNIC system.

The EDL collects and reports all types of diagnostic information in real-time from a system (Figure 4). The EDL automatically starts when UNITool is in online mode and connected to a system in operation. The Trending function is used for recording and collecting data from specific ISO code values (Figure 5). ISO code values need to be added manually to a trend window from the "Process values and I/O" tree-structured list (Figure 6) in order to record and collect data from them.

Enhanced Diagnostics Log (History)				
PC Time	Module	Type	Message	Parameter Data
2021-02-18 07:29:59.778	COM-10 1	Event	Engine mode: Start	
2021-02-18 07:29:59.778	COM-10 1	Event	Start command	
2021-02-18 07:29:59.783	COM-10 2	Event	Engine mode: Start	
2021-02-18 07:29:59.783	COM-10 2	Event	Start command	
2021-02-18 07:30:01.143	COM-10 2	General	Start state, Injection on speed reached	
2021-02-18 07:30:01.149	COM-10 1	General	Start state, Injection on speed reached	
2021-02-18 07:30:02.955	COM-10 2	DC	DC value written is below minimum li...	-2, GT519 - Exh WG valve position
2021-02-18 07:30:03.173	COM-10 2	General	Start state, Rail pressure reached	

Figure 4. Enhanced Diagnostics Log (EDL).



Figure 5. UNITool Trending.

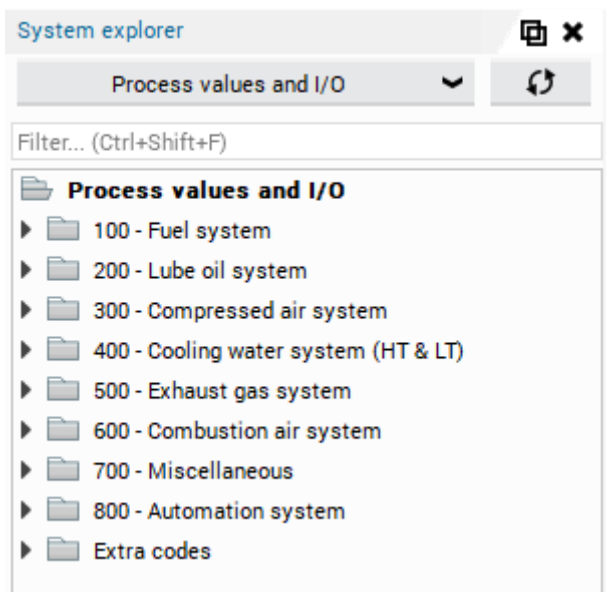


Figure 6. Process values and I/O tree-structured list.

2.3.6 UNIC power supply system

The power supply system is an extensive system built upon redundant DC-subsystems that powers the UNIC system's different domains. The subsystems use galvanically isolated redundant AC/DC power supplies powered from an LV distribution board of 230 VAC. These subsystems are isolated, meaning that the 0 V of the systems are separated from earth (IT system) and have no direct connection to any point of the engine's primary power system, except earth.

Both two- and three-wire subsystems are utilised in the system, with the exception of omitting the middle wire in the three-wire modification. Two-wire subsystems are used in 24 VDC and 48 VDC configurations (Figure 7), while three-wire subsystems are used in 110 VDC configurations (Figure 8).

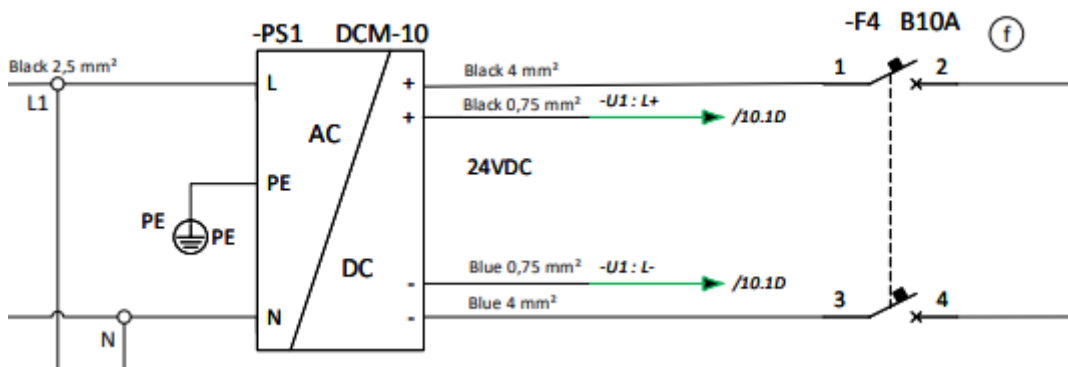


Figure 7. 24 V two-wire DC subsystem example from UNIC power supply system. (Wärtsilä, 2019a)

The W8V31CR lab engine is configured as a single main engine (SME). In addition to the standard power supply system, the SME's PSS and PSD power domains branches to two backup CCM modules, where the PSD power branch is separately fused. Fusing the PSD power branch; is to limit the power disruption in case of internal failure in the CCM DRV circuitry.

Each subsystem has its dedicated circuit breaker installed directly after the supply's output. The circuit breakers are double-poled, meaning they protect both the positive and negative wires. The power cables are directed to the engine's main cabinet, where the supplies are separated according to the engine automation system's needs. The maximum length and cable size are arranged to withstand enough short-circuit current, but the cabling cost is still optimised. (Wärtsilä, 2018; Wärtsilä, 2019b)

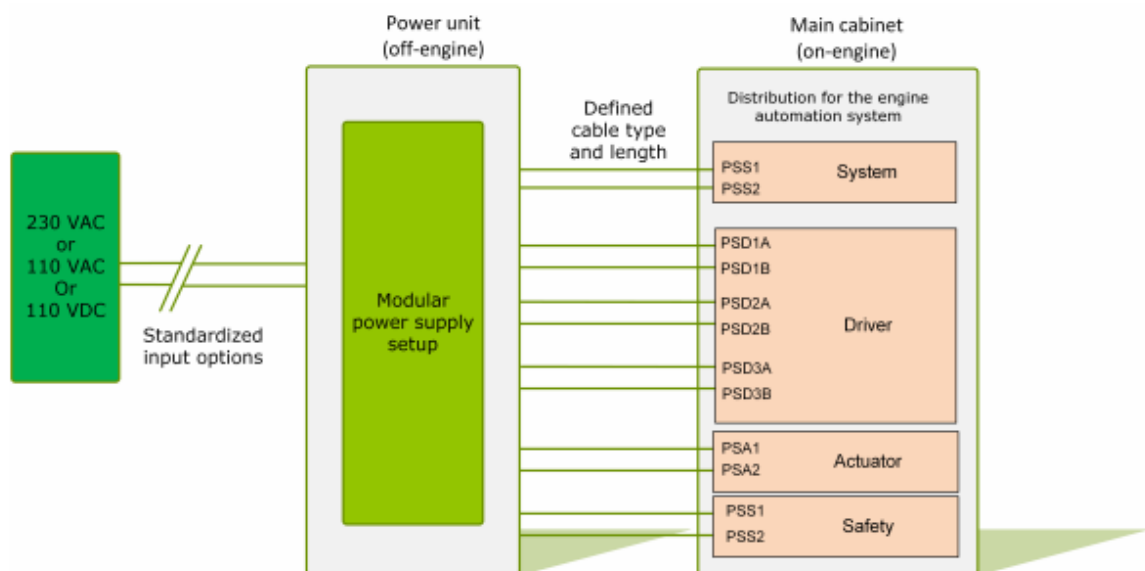


Figure 9. Overview of the power supply system. (Wärtsilä, 2019b)

2.3.6.1 DCM-10 and DCM-20 power supplies

Two types of modular AC/DC power supply units are used to generate 24 VDC, 48 VDC, and 110 VDC power domains. DCM-10 and DCM-20 both have the same standardised input options, 110 VAC, 230 VAC or 110 VDC. The difference between the two power supply units is the output voltage and current capacity. DCM-10 has a nominal voltage output of 24 V with 20 A current capacity, whereas the DCM-20 has a nominal voltage output of 48 V with 10 A current capacity.

The supplies can either be used as stand-alone devices or connected in parallel or series:

- Stand-alone use: Normal use with nominal output capacity
- Parallel use: Current capacity is double with the same voltage
- Series use: The voltage is double with the same current capacity

(Wärtsilä, 2018)

2.3.6.2 Insulation monitoring

In the power supply system, insulation monitoring is done so that for each pair of redundant subsystems, an Insulation Monitoring Device (IMD) is implemented. Five IMDs are connected in the power supply system (U1, U2, U3, U4 and U5), whereas only four of them are in use, as seen in Figure 10. U4 is a spare IMD that does not monitor any system.

The IMDs are configured to detect deterioration of the insulation resistance as soon as possible. In practice, this means that the insulation resistance threshold (R_a) value is set to the highest available. Detection of an insulation fault is monitored in UNITool via an output relay NO-contact from the IMD (Figure 11). When the fault appears, the contact closes, and a signal is outputted and registered to the ISO code NS7799_1. The ISO code is linked to the COM-10-2 module.

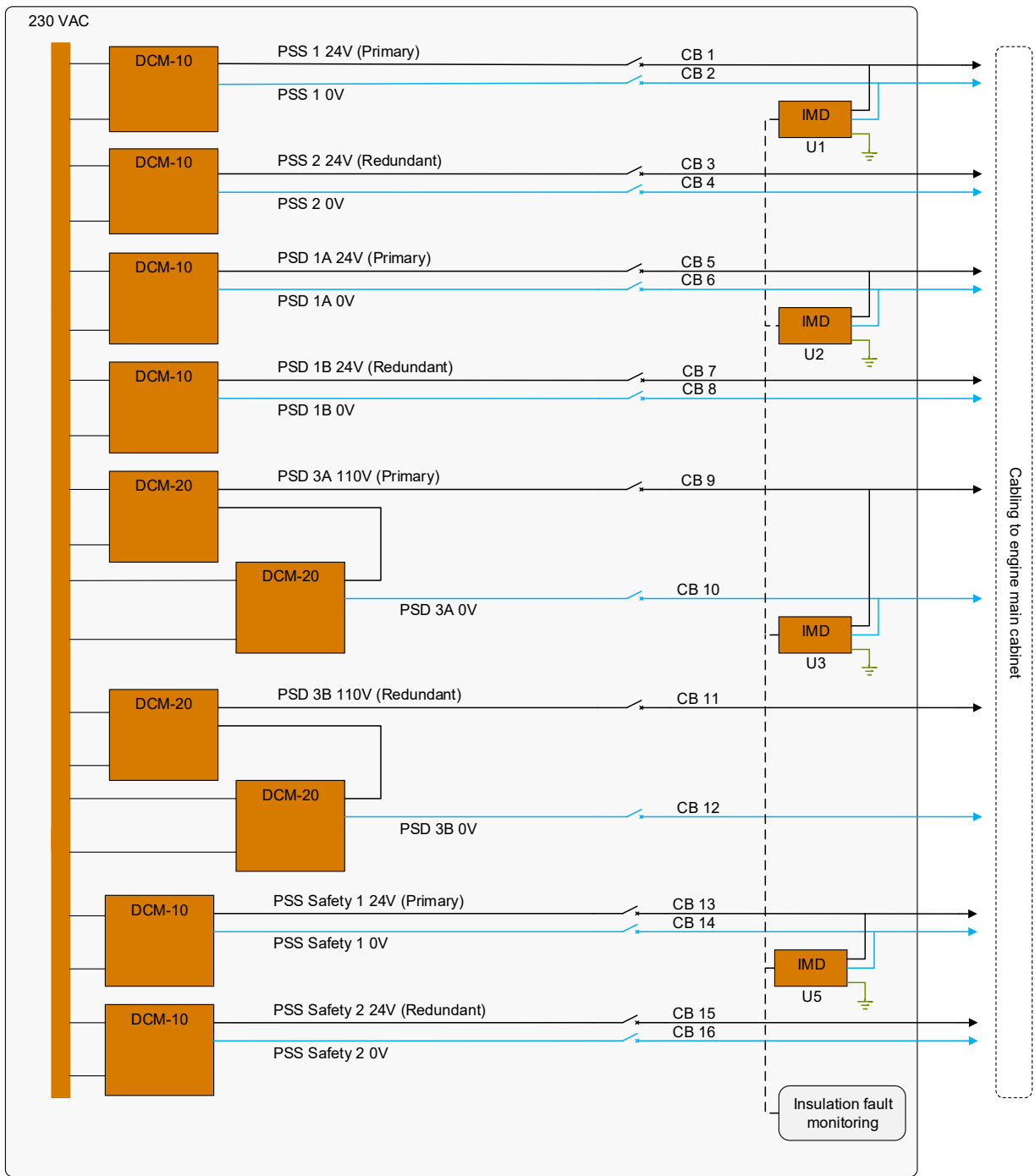


Figure 10. Insulation monitoring in the UNIC power supply system on the W8V31CR lab engine.

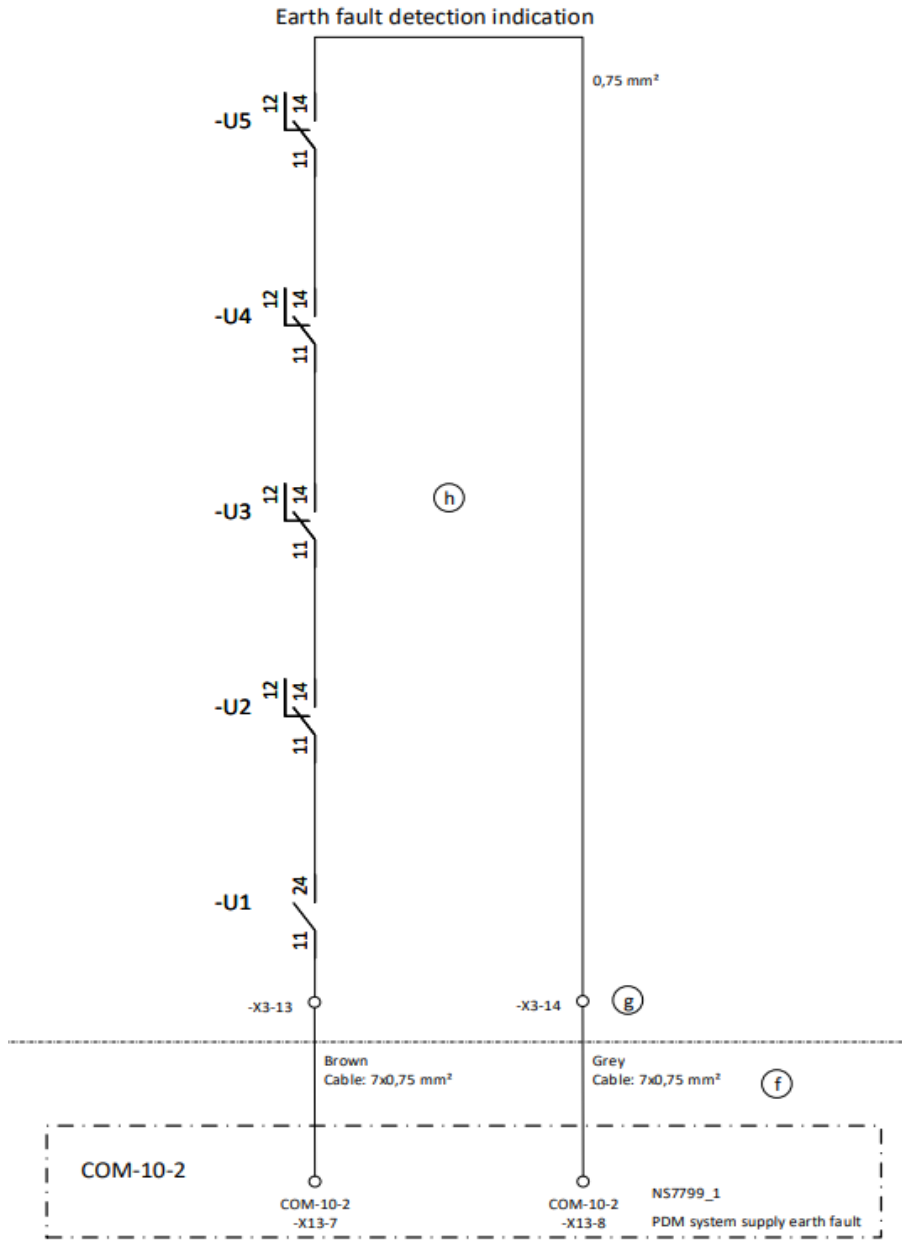


Figure 11. Remote insulation fault detection. (Wärtsilä, 2019a)

2.4 System earthing

The main reason for earthing the metal structure of electrical equipment within a system is to improve protection to the public and property in general. An earthing system should be designed so that, if a fault occurs on any appliance, the risk of exposed conductive equipment touched by an individual should not reach a fatal level.

IEC 60092-201 (2019) considers IT and TN-S earthing as standard for distribution systems in marine applications. The system earthing must be carefully chosen, as it determines the system's behaviour and characteristics. More precisely, keeping the system's voltage within predictable boundaries and maintaining a current flow, allowing detection of undesirable connection between earth and the system's conductors. The system earthing is also a contributing factor related to supply reliability, system outlay, maintenance and Electromagnetic compatibility (EMC). The type of system earthing can be identified with a two-letter code; the first letter describes the correlation between the power system and earth. The second letter describes the correlation between any exposed conductive equipment of the electrical installation and earth. (Lakervi & Holmes, 1996, pp. 40-44; Calves & Lacroix, 2004, p. 4; BENDER Group, 2009, p. 2; IEC 60092-201, 2019, p. 24)

2.4.1 IT system

The neutral conductor (L-) is isolated from earth or earthed via an impedance in the IT system, and exposed conductive parts have a direct connection to earth (Figure 12). The IT system is also otherwise known as an "isolated" or "unearthed" system. Despite not being intentionally connected to earth, the system is capacitively earthed by the conductors' capacitance to earth alongside any interference suppression capacitors throughout the system. (Lakervi & Holmes, 1996, pp. 43-45; IEC 60092-201, 2019, p. 25)

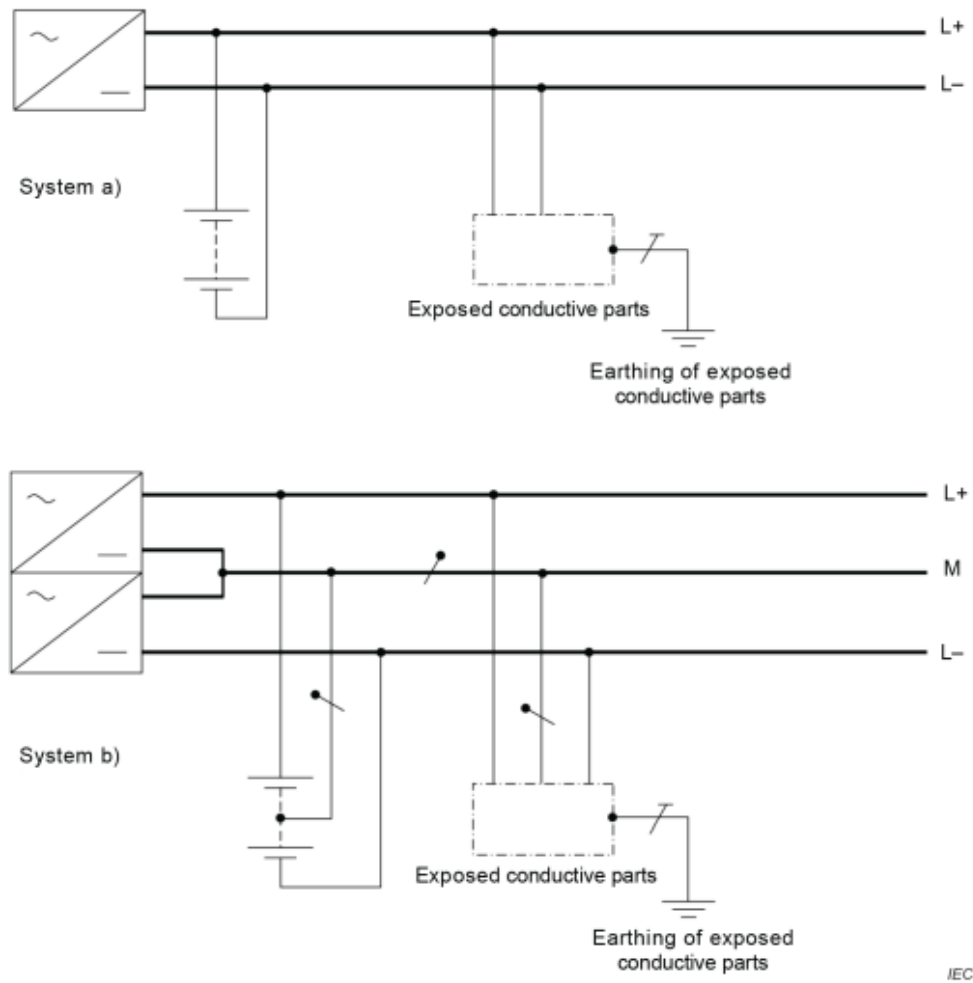


Figure 12. IT earthing implemented in two- and three-wire DC systems. (IEC 60092-201, 2019)

Requirements

In practice, the IT system requires specific measures to be implemented for satisfactory functioning. IEC 60092-201 (2019, p. 24) points out that an IMD must be used in the IT system to monitor the insulation resistance permanently. In accordance with IEC 61557-8 (2014, pp. 14-15), the IMD is also required to send out an alarm to a staffed control room.

An appropriate circuit breaker must be used to protect the system from the fault current (Lakervi & Holmes, 1996, p. 116). A first insulation fault will not cause the circuit breaker to trip because the fault current flows in an open circuit due to the isolation between the neutral conductor and earth. Instead, the IMD will trigger and signal deterioration in the insulation resistance value. The insulation fault must be cleared immediately as the risk of a second insulation fault may occur on a separate live conductor, and that would cause a system failure. It can be said that the IT system acts as a TN system directly after the

occurrence of the first insulation fault. IEC 60092-201 (2019, p. 24) refers to IEC 61557-9, which states that it is highly recommended to use insulation fault location systems, as it would speed up the process of locating the first insulation fault. (Electrical Equipment, 2011; Electrical Installation wiki, 2019; BENDER Group, 2009, p. 3)

2.4.2 TN-S system

In the TN system, also known as an earthed system, the neutral conductor (L-) is directly connected to earth. Exposed conductive parts are earthed to the same point via a protective earth conductor (PE) (Figure 13). The TN system can be divided into three types, with the distinction of different arrangement of the neutral and protective conductors: TN-S, TN-C, TN-C-S. IEC 60092-201 (2019) only refers to TN-S systems as standard. The “S” in TN-S refers to; the system having separate protective earth and neutral conductors throughout the whole system. (Lakervi & Holmes, 1996, pp. 43-45).

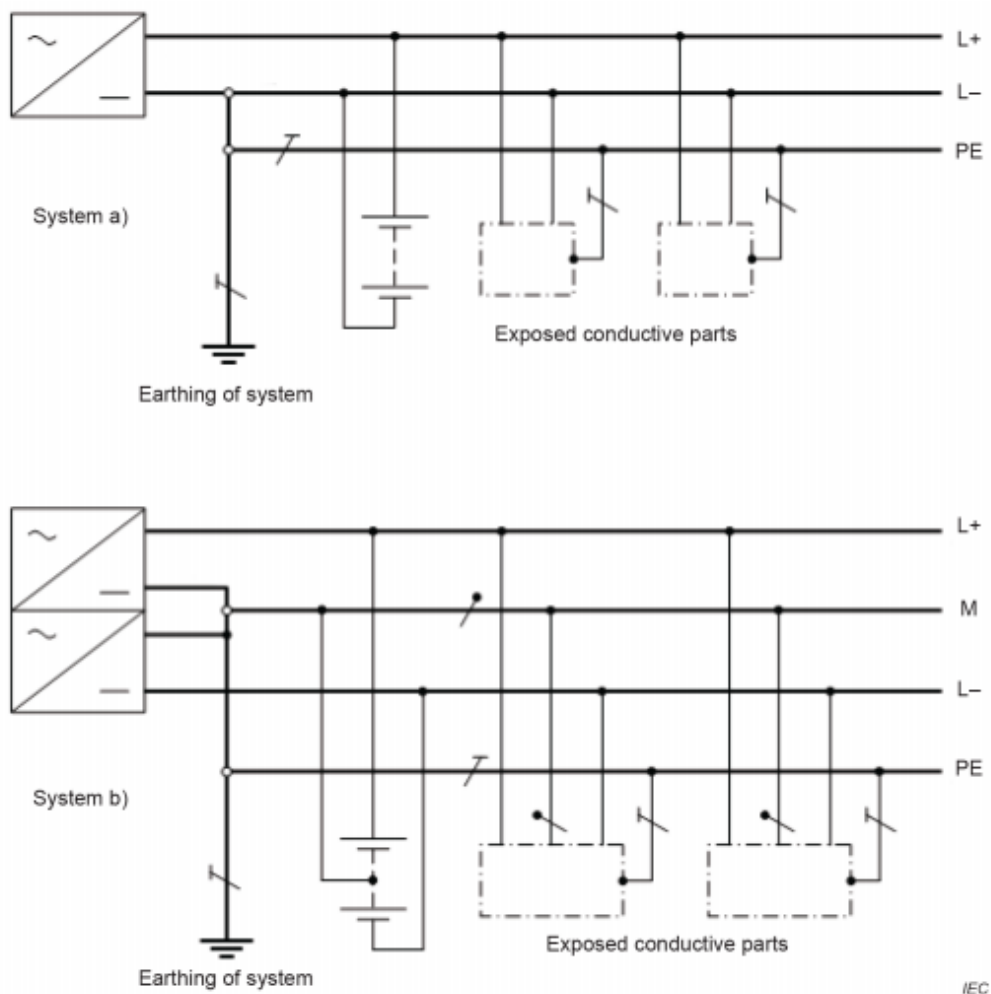


Figure 13. TN-S earthing implemented in two- and three-wire DC systems. (IEC 60092-201, 2019)

Requirements

When an insulation fault occurs in the TN system, the fault current flows through a path of only conductors, meaning that any insulation fault will create a short-circuit to earth and cause a system failure. A fault loop impedance limits the resulting fault current. The impedance comprises a series of impedance combinations, such as the transformer impedance, service cable impedance and the impedance of the PE (protective earth) conductor. Overcurrent protection can be used in cases where high current faults occur. However, implementing overcurrent protection will increase touch voltage during the short disconnection time between phase to neutral. (Joffe & Lock, 2010, p. 388; Electrical Installation wiki, 2019)

Suppose a circuit breaker is used to establish a TN-S system's protection. In that case, it must be verified that the fault current consistently exceeds the specified current-setting of the tripping device. The use of RCDs (Residual Current Device) may be needed and must be added in combination with the circuit breaker if:

- the loop impedance cannot be determined (e.g. cable length estimation difficulties, presence of ferromagnetic material close to wiring)
- the fault current is so low that the circuit breaker will not disconnect in time.

The selection of RCDs shall be made to limit the risk of unwanted tripping, e.g. resulting from high leakage capacitance. However, implementing a Residual Current Monitor (RCM) in the TN-S system would completely prevent unwanted tripping, as the RCM indicates when a fault current is present and prevents the RCD from tripping. (IEC 60092-201, 2019, p. 24; Electrical Installation wiki, 2019)

2.5 Comparison of system earthing types

The IT system has many advantages over the TN-S system, as seen in Table 2. However, the most significant difference is that nothing happens if an individual touches a live unisolated conductor or exposed conductive part in a fully intact IT system. Why? As mentioned in chapter 2.2.1, the neutral conductor is isolated from earth in the IT system, forming an open circuit when a first insulation fault occurs; a current cannot flow in an open circuit, making the IT system more secure. It is the other way around in the TN-S system; if not, circuit breakers and RCDs are implemented.

Secondly, the systems handle the first insulation fault differently. The IT system will continue its operation during a first fault, and the TN-S system will shut down directly if an RCM is not implemented. HOWEVER, the RCM is restricted to only energised systems and can only detect asymmetrical insulation faults carrying a fault current in the single-digit mA range – but no further (types of insulation faults will be brought up in chapter 3.1). In the IT system, it is possible to monitor insulation resistance in the M Ω range, meaning that the deterioration of the insulation can be noticed very early. (BENDER Group, 2009, p. 5; Pieler, 2019, pp. 2-3)

Table 2. Comparison between the IT and TN-S system.

Type of system	Advantages	Disadvantages
IT system	<ul style="list-style-type: none"> • Inherently safe • EMC-compliant • First insulation fault does not cause a system failure • Deterioration of the insulation resistance can be monitored in the megohm range • Low current leakage in smaller systems • The effect on nearby installation is minimised, which makes earthing effortless • Installation of cables and conductors requires little technical effort • Use of appropriate devices aids in the detection of insulation faults (IMDs) 	<ul style="list-style-type: none"> • Potential system failure on the 2nd insulation fault • Overcurrent protection is required for N conductor • All equipment has to be isolated for the voltage between external conductors
TN-S system	<ul style="list-style-type: none"> • EMC-compliant • RCM insulation fault monitoring 	<ul style="list-style-type: none"> • Any insulation fault will cause a direct system failure • Risk of earthings going undetected • Voltage rise in phase conductors during disconnection

(BENDER Group, 2009, p. 5; Pieler, 2019, pp. 2-3)

2.6 Wärtsilä marine system requirements

Continuous vibration originates from the engines, propellers, loading/unloading of a vessel, and the vessel's progress in the water. It is, therefore, not uncommon to get insulation faults when the conductor's insulation is chafed; wires break or come loose. When insulation resistance monitoring is implemented, insulation faults are alarmed instead of shutting down the system, and the deterioration of insulation resistance can be noticed in time. This functionality is, however, only possible with the implementation of IT systems.

Wärtsilä applies IT systems, with two- and three-wire configurations in the UNIC power supply system. The IT system is ideal for their demands, which are the protection of insulation faults and the possibility of enabling steady operation even if an insulation fault is present. This is especially important for so-called "essential systems" to which, among other things, the engines belong, as they are the key component to keeping the vessel alive.

Wärtsilä also isolates different systems from each other to avoid that an earth fault in one system creates some unwanted behaviour in another system, e.g. the UNIC system is fed via its own AC /DC power supplies. (Remsu, 2021)

3 The definition of insulation resistance

Insulation resistance can be characterised as the resistance to current leakage through and over the surface of the insulation surrounding a conductor. (SparkyFacts, n.d.).

In electrical safety, insulating a conductor reduces the risk of short circuits occurring as it prevents the conductive part of conductors from coming in contact with each other. Insulation is also a critical factor in preventing electrical leakage. The theory behind good insulation can be derived from Ohm's law: the more voltage, the more current will be generated and penetrated through the insulation if the resistance is constant. Therefore, it is vital to have a high resistance to obtain sufficient insulation. As seen in figure 14, the insulation of the wire is insufficient; in practice, this leads to an increased amount of electrical leakage, which lowers the insulation resistance and might lead to an insulation fault. (Megger, 2006, pp. 3-4)

Furthermore, insulation resistance is the defining variable in terms of an individual's safety and equipment's protection in electrical systems and electrical appliances. E.g. if the insulation resistance is inadequate: protection against indirect and direct contact cannot be established, defects in electrical appliances can put individuals in danger, and earth faults can cause fire hazard and, at worst, explosions. The insulation resistance on newly installed systems is often relatively good. However, the system's operation creates an unavoidable reduction of insulation resistance over time, increasing the risk of insulation faults. (BENDER Group, 2009, p. 2)

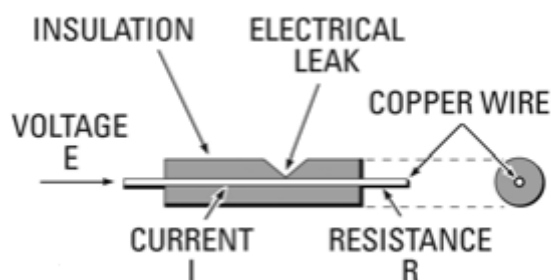


Figure 14. A visual explanation of the insulation resistance. (Megger, 2006)

3.1 Insulation faults

According to IEC 61557-8 (2014, p. 11), an insulation fault, also called an “earth fault”, can be characterised as a defect in the insulation of an electrical system or equipment that create a resistant route to earth. The insulation fault can occur as an asymmetrical fault on a single line conductor or as a symmetrical fault on all line conductors. In the asymmetrical insulation fault, the resistance between the phase conductors and earth are different. In a symmetrical insulation fault, the resistance between all phase conductors and earth is approximately the same. The probability of an asymmetrical fault occurring is the same in both AC and DC systems. Symmetrical insulation faults are more common in DC systems compared to 3-phase AC systems due to the probability being higher in DC systems as they only compromise two line conductors. (IEC 61557-8, 2014, pp. 11-12; BENDER Group, 2009, p. 6)

Most insulation faults occur in electrical equipment due to an insulation breakdown or a loose wire, enhancing the risk of a live conductor coming in contact with earth. The metal casing and other metal parts of the system’s appurtenant equipment shall be earthed to establish protection of an individual or electrical system from insulation faults. The earthing ensures that the voltage in reference to earth of the metal casing/parts of the equipment is kept at zero. Furthermore, to enable the detection of an insulation fault, an IMD can be implemented. (Maes, 2014, pp. 9-10)

3.2 Insulation Monitoring Device

An Insulation Monitoring Device (IMD) is a device that monitors the insulation resistance to earth of AC IT systems, AC IT systems with galvanically connected DC circuits up to 1000 VAC, and DC IT systems up to 1500 VDC. (IEC 61557-8, 2014, p. 11)

As the comparison test was be executed in a DC environment, the thesis mainly focuses on IMDs capable of monitoring DC systems’ insulation resistance.

The IMD is a crucial component for IT power supply systems to establish detection of a first fault between a conductive part and earth. (BENDER Group, 2009, p. 6)

The IMD must detect both symmetrical and asymmetrical insulation faults in the IT system (Figure 15 & 16). Devices that only can detect asymmetrical insulation faults are so-called earth fault relays (EFR); these devices are not classed as an IMD, according to IEC 61557. (IEC 61557-8, 2014, pp. 13-14)

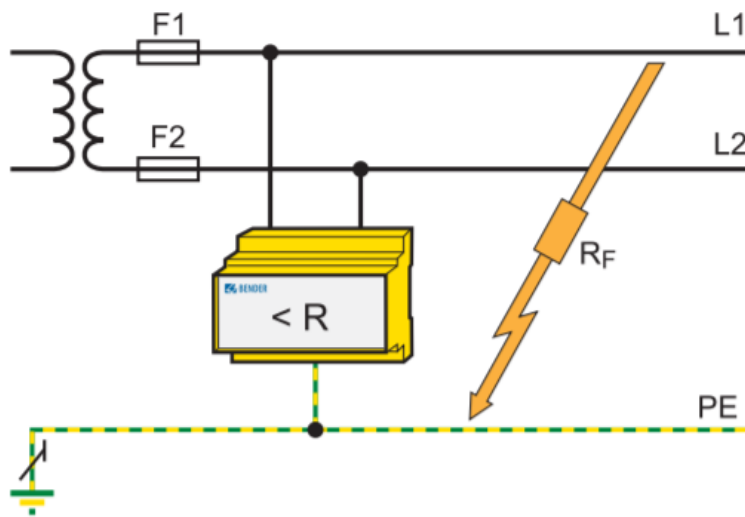


Figure 15. Asymmetrical insulation fault. (BENDER Group, 2009)

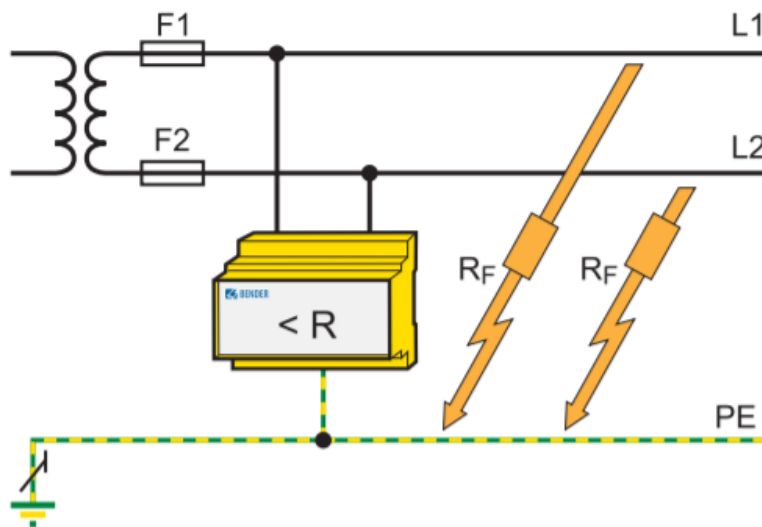


Figure 16. Symmetrical insulation fault. (BENDER Group, 2009)

3.2.1 General operating principle

The IMD is connected between the live conductors and earth in the IT system. The IMD is activated with a constant or pulsating measuring voltage U_m (depending on the type of device) and a specific insulation resistance threshold value (R_a). As a result of an insulation fault R_f occurring, the measurement circuit between the system and earth closes, generating a measuring current I_m (Figure 17, red line), which is equal to the insulation fault. According to Ohm's law, a corresponding voltage drop U is caused at the measuring resistance R_m to the measuring current I_m , being generated, using the following formula:

$$U = R_m \times I_m \quad (1)$$

Suppose the voltage drop U overshoots in correlation with the insulation resistance R_f between any live conductor and the reference point (earth) falling below the specific threshold value R_a . In that case, a signal is outputted, and the IMD sends out an alarm. This alarm can be defined as the first fault. The system can function normally with the presence of the first fault. However, if a second fault appears, and the first fault has not been cleared yet, there are two possible scenarios:

- The second fault appears on the same conductor as the first fault, nothing happens, and the system can continue to operate normally
- The second fault appears on a different conductor to the first fault. This double fault creates a short circuit via earth connections, which leads to a system shutdown in the worst-case scenario.

(IEC 61557-8, 2014, pp. 13-14; Calves & Lacroix, 2004, p. 12; Wikipedia, 2020)

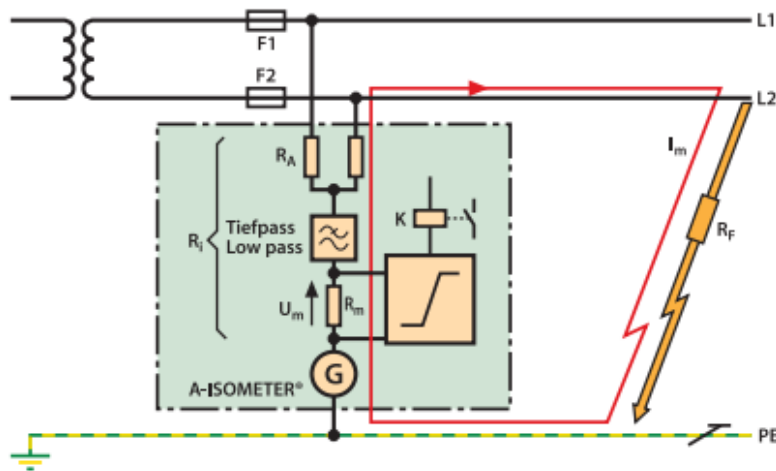


Figure 17. The IMD's operating principle. (BENDER Group, 2009)

3.2.2 ABB CM-IWS.1S

The CM-IWS.1S is capable of monitoring the insulation resistance under IEC 61557-8 requirements as it can detect both asymmetrical and symmetrical insulation faults. It can monitor systems with voltages up to 300 VDC but shall be supplied with 24 to 240 VDC. The IMD has an adjustable R_a value between 1 and 100 k Ω .

ABB's CM-IWS.1S uses a pulsating measuring principle, where the insulation resistance is calculated by feeding a pulsating measuring signal from the IMD to the system. The signal is automatically adjusted depending on the system's leakage capacitance and insulation resistance. The adjustment in the signal then forecasts the alternation in the insulation resistance. Using this type of measuring principle enables the detection of insulation faults causing both asymmetry and symmetry in a system.

Suppose the forecasted insulation resistance is equal to the next measurement cycle's calculated insulation resistance and is smaller than the specific threshold value R_a . In that case, the IMD output is de-energised and causes an alarm. The alarm is connected to a red indication LED (F). If the IMD is configured on automatic reset (S2 and S3 are left unconnected), the output automatically energises again when the insulation resistance is higher than R_a . If S2 and S3 are connected, manual reset is enabled. Manual reset of the IMD is done by pushing the test/reset button on the IMD or by using a remote reset (S2-S3 terminals). An insulation fault can be simulated by pushing the test/reset button on the IMD or by using a remote test button (S1-S3 terminals). (ABB, 2016)



Figure 18. ABB CM-IWS.1S. (ABB, 2016)

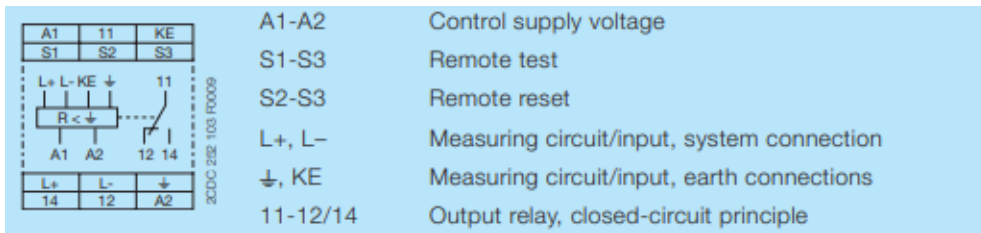


Figure 19. ABB CM-IWS.1S connection diagram. (ABB, 2016)

3.2.3 BENDER isoUG425

The isoUG425 is only capable of measuring the asymmetrical insulation resistance R_f ; therefore, it is not classed as an IMD according to IEC 61557-8. The IMD can monitor systems between 12 and 120 VDC but shall be supplied with 24 to 240 VDC. It has two R_a values (R_{a1} and R_{a2}) that can be adjusted between 1 and 100 k Ω . R_{a1} has to be set higher than R_{a2} .

An alarm will be produced when the insulation resistance R_f either reaches or drops below R_1 or R_2 . The alarm will be automatically cleared when R_f exceeds R_1 or R_2 . It is possible to assign the alarms to two output relays (K1 and K2) and two indication LEDs (AL1 and AL2). An insulation fault can be simulated by pushing the test button “T” on the device or by using a remote button test/reset button (T/R terminal).

The measuring principle for the isoUG425 is a type of passive measurement where the measured offset voltage is superimposed in the occurrence of an insulation fault on a live conductor. This measuring principle makes the isoUG425 only able to detect insulation faults that cause an asymmetry between the system and earth (asymmetrical insulation faults).

Compared to the other IMDs, BENDER isoUG425 is the only IMD equipped with a monochrome display. The display shows the measured values of the system. Configuration of the IMD is done via the buttons linked to the display. (Bender GmbH & Co. KG, 2018)



Figure 20. BENDER isoUG425. (Bender GmbH & Co. KG, 2018)

Terminal	Connectors
A1, A2	Connection to the supply voltage U_s via fuse (line protection). If being supplied from an IT system, both lines have to be protected by a fuse.*
E, KE	Connect each terminal separately to PE: The same wire cross section as for "A1", "A2" is to be used
L+, L-	Connection to the DC system to be monitored
T/R	Connection for the external combined test and reset button
11, 14	Connection to alarm relay "K1"
11, 24	Connection to alarm relay "K2"
A, B	RS-485 communication interface with connectable terminating resistor Example: Connection of a BMS Ethernet gateway COM460IP

Figure 21. BENDER isoUG425 connection diagram. (Bender GmbH & Co. KG, 2018)

3.2.4 DOLD IL 5881.12/100

The IL 5881.12/100 is only capable of measuring the asymmetrical insulation resistance, and therefore not classed as an IMD according to IEC 61557-8. The IMD has an adjustable R_a value between 5 and 200 k Ω and can monitor systems between 12 and 280 VDC. This specific model does not have separate supply connections (A1 and A2); the supply is taken from the monitored system (L+ and L-).

When R_f falls below the thresh-hold value R_a , the output relay gets de-energised, and a corresponding red indication LED lights up. If the IMD is configured on automatic reset (wire connection between LT and X1 terminals) and R_f is higher than R_a , the output automatically energises again, and the LED goes out. If LT and X1 are left unconnected, the

IMD must be manually reset by pushing the external or internal reset button. An insulation fault can be simulated to test the function of the device by pushing the tests button on the IMD or by using a remote test button (PT-X1 terminals)

The measuring principle of the DOLD IL 5881.12/100 is a type of asymmetry measurement method using a resistor bridge. Therefore, the IL5881.12/100 can only detect asymmetry in the monitored system. (E. DOLD & SÖHNE KG, 2019)



Figure 22. DOLD IL 5881.12/100. (E. DOLD & SÖHNE KG, 2019)

Terminal designation	Signal description
A1	L / +
A2	N / -
L+, L-	Connection for monitored IT-systems
PE	Connection for protective conductor
PT, X1	Connection for external test button
LT, X1	Connections for external reset or manual and auto reset: LT/X1 bridged: hysteresis function LT/X1 not bridged: manual reset
11, 12, 14 21, 22, 24	Changeover contact (insulation failure)

Figure 23. DOLD IL 5881.12/100 connection diagram. (E. DOLD & SÖHNE KG, 2019)

4 Comparison test

The comparison test consisted of a four-part test, comprehending one test without IMDs and three tests with different connected IMD types. The following IMDs were tested: ABB CM-IWS.1S, BENDER isoUG425 and DOLD IL 5881.12/100. The test without IMDs was executed to determine what type of errors occurs in the system when precluding the IMDs. The tests were performed on a running W8V31CR engine in the Laboratory.

The purpose of the tests was to collect enough data to then be able to evaluate a suitable candidate for the different subsystems within the engine automation system. Data was collected by simulating insulation faults on different module channels and distinguishing what faults the IMD detects. UNITool EDL and Trending function were used to monitor and record data from the specific ISO codes linked to the channels to see how they behave depending on which IMD was tested.

Two types of asymmetrical insulation faults were performed with different resistances: a direct insulation fault with almost no resistance and a 50 k Ω insulation fault where a 50 k Ω resistor was connected between the tested channel and earth.

4.1 Test planning

An Excel test sheet was constructed to keep track of gathered data. The test sheet was based on the engine's wiring diagram and power supply concept drawing together with a draft partitioning & device database file. Only unique active channels were tested, meaning only channels with a different connection of electrical equipment, to create different types of failure situations for the IMD to detect.

The test sheet was produced on the following criteria:

- Great overview experience enabling fast localising within the test sheet
- Time-efficient input of test data

4.1.1 Test sheet

The Excel test sheet was divided vertically into two parts: the first part shows essential information about the tested channels, and the second part shows the test results. Furthermore, the test sheet was divided into eight sections horizontally, containing one module's tested channels per section. The test sheet contains the following labels: channel

connection, channel isolation, ISO code, ISO code description, Monitored supply, signal, 50 k Ω insulation fault, Direct insulation fault, IMD, UNITool, and TTP.

A description list was created to clarify the purpose of the labels.

Table 3. Description of the Excel test sheet labels.

Label	Description
Module	The tested module
Channel	The tested channel
Channel Connection	Equipment connected to the tested channel
Channel Isolation	If the tested channel is isolated or non-isolated
ISO-code	Refers to the specific channel ISO-code in UNITool
ISO-code description	A description of the ISO-code
Monitored supply	Refers to the system of which the IMDs monitors
Signal	Declares the signals of the tested channel
50 kΩ insulation fault	insulation fault created on the tested channel with a 50 k Ω resistance between the channel and earth
Direct insulation fault	insulation fault created on the tested channel with minimal resistance between the channel and earth
IMD disconnected	insulation fault created on the tested channel with the IMD disconnected.
IMD	If the IMD triggered on the simulated Insulation fault
UNITool	If UNITool reported an error from the system caused by the simulated insulation fault
TTP	Trend Test Point. Defines the test point in UNITool trending function

4.2 Test preparations

For each module tested, a trending window was created with the appurtenant tested channels. The trending windows were saved as a TRENDDESKTOP File to be able to open them before the test.

Appropriate test cables, with a crocodile clip in one end and a test probe in the other, were constructed, and a 50 k Ω resistor was located. The 50 k Ω resistor and the cables were resistance measured to verify that they were fully functional.



Figure 24. Resistance test of the cables and the 50 k Ω potentiometer.

The tested IMDs were installed in the UNIC power supply cabinet according to the IMDs' connection diagram and the power supply concept diagram. In figure 25, ABB IMDs are installed, starting from the left, U1 to U5 can be seen. The specific insulation resistance threshold value R_a was set to 100 k Ω on all IMDs in all tests due to the max value of the ABB and BENDER IMDs being 100 k Ω . As the BENDER IMD has two R_a values, R_{a1} was set to 100 k Ω and R_{a2} to 95 k Ω .

When performing the test "Without IMDs", the IMDs were precluded from the system by disconnecting the supply wires.

A connection was established between UNITool and the UNIC system through the COM-10-1 module in the main cabinet. This was done by using a USB adapter and an ethernet cable connected between the module and the computer.



Figure 25. ABB CM-IWS.1S IMDs installed in the UNIC power supply cabinet.

4.3 Test procedure

The test procedure is explained collectively, as all the tests follow the same steps, except for step 4 when testing without IMD. NS7799_1 was constantly in a low state as no IMD was connected. However, a TTP (Trend Test Point) was still added to the Trending function to keep track of the channel tested.

1. Started the recording in UNITool Trending function for the specific module tested and verified that EDL was running.
2. The crocodile clip was permanently connected to earth (Figure 26).
3. An insulation fault was created between the module channel and earth by inserting the test probe in the correct connector PIN related to the tested channel's signal (Figure 27).
4. After each insulation fault, it was checked if the IMD detected the fault by verifying if ISO code NS7799_1 was in a high state. A TTP was added in the UNITool Trending function to track which channel signal was tested (Figure 28).
5. After the channels were tested for a module, the data collected in the trending function was saved and stored for later analysis.



Figure 26. Crocodile clip connected to earth.

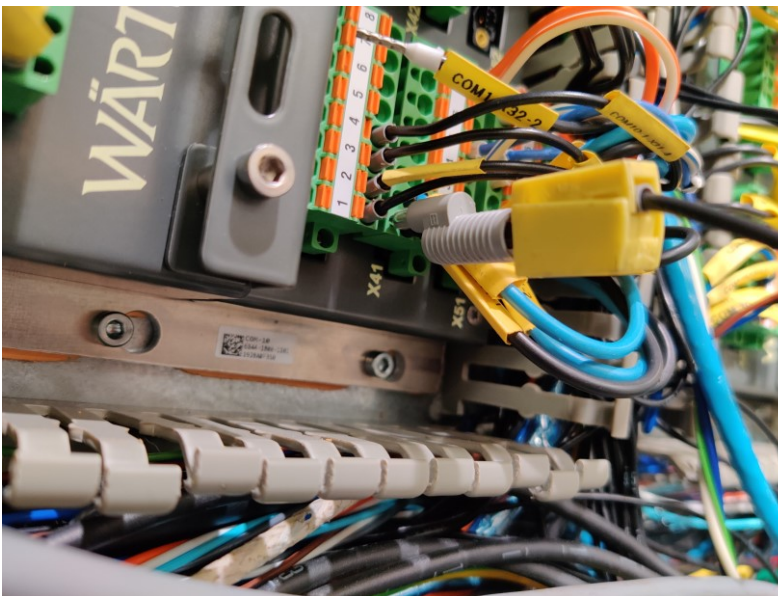


Figure 27. Test probe connected to a channel's connector pin.

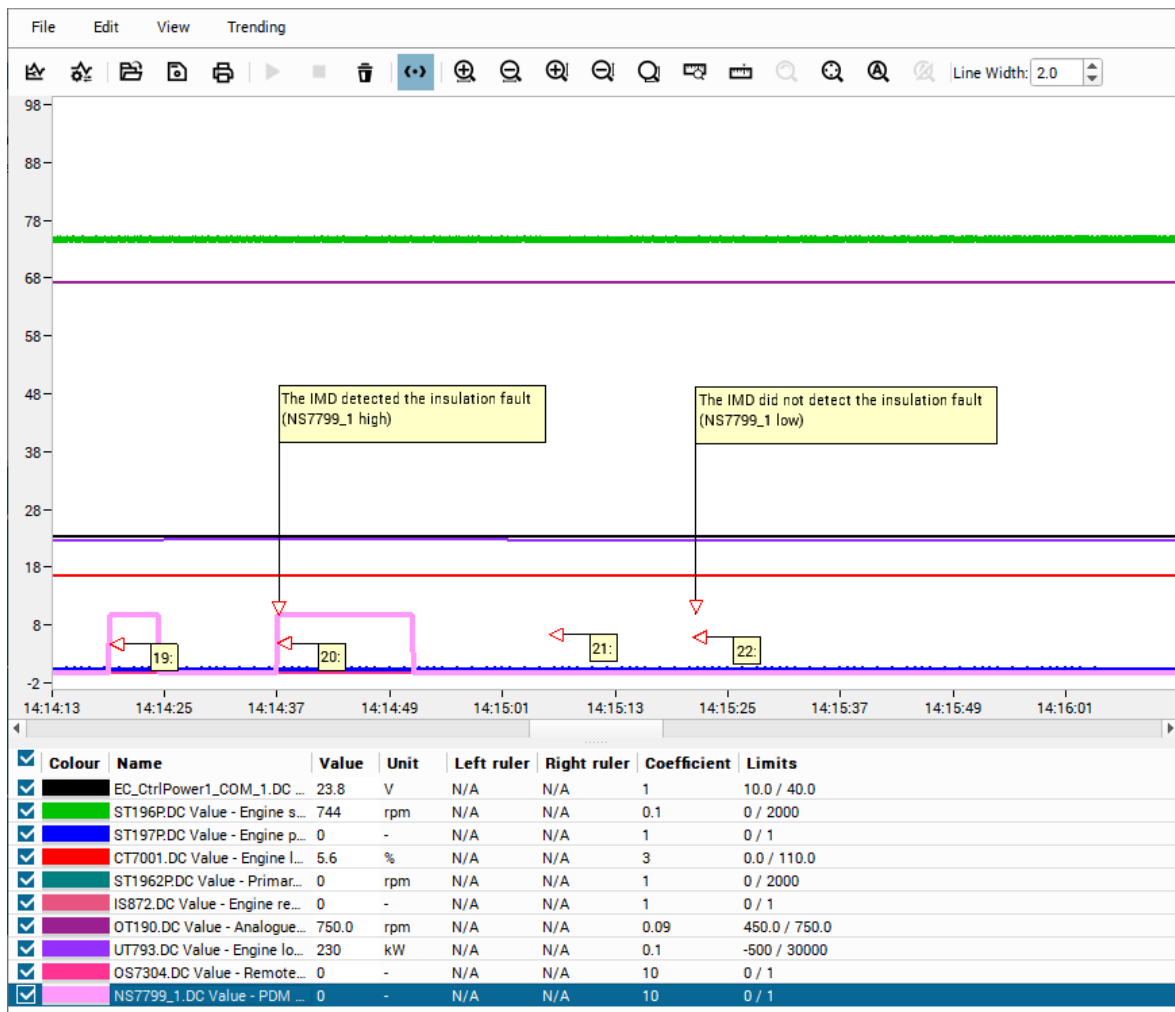


Figure 28. Trend Test Points and detection of insulation fault via NS7799_1.

4.3.1 Data management

All data gathered were inserted into separate test sheets by manually going through the trend windows and observing if the IMDs detected the insulation faults at specific timestamps by looking at the TTPs. The TTPs were also used to examine if the specific ISO code linked to the tested channel fluctuated during a fault and to track down errors in EDL caused by the insulation fault by recognising if an error had a similar timestamp compared to a TTP.

The test sheets were combined into two comparison tests sheets to facilitate the process of analysing and comparing the data acquired:

- In Appendix 1, a comparison between all four tests covering the detection of direct insulation faults.
- In Appendix 2, a comparison between all four tests covering the detection of 50 kΩ insulation faults.

Appendix 1 and 2 were further filtered into two separate conflicting measurements sheets:

- In Appendix 3, all conflicting measurements of direct insulation faults
- In Appendix 4, all conflicting measurements of 50 k Ω insulation faults

Colour coding was implemented in the Excel sheet to easier understand the faults detected and errors reported.

Table 4. Colour coding.

Colour	Definition
Green	The IMD detected the insulation fault
Red	The IMD did not detect the insulation fault
Yellow	EDL reported an error in the system caused by the insulation fault
Blue	The trending function reported an error in the system caused by the insulation fault
Purple	Both EDL and the trending function reported an error in the system caused by the insulation fault
White	UNITool did not report an error (no error in the system).

As there were many types of different combinations of IMD detection and UNITool errors, a best- to worst-case scenario list was implemented:

- CASE 1. The IMD detected the insulation fault, no disturbances or UNITool errors – **Best-case.**
- CASE 2. The IMD detected the insulation fault; EDL reported an error.
- CASE 3. The IMD detected the insulation fault; the trending function/both EDL and the trending function reported an error.
- CASE 4. The IMD did not detect the insulation fault; no UNITool errors.
- CASE 5. The IMD did not detect the insulation fault; EDL reported an error.
- CASE 6. The IMD did not detect the insulation fault; the trending function/both EDL and the trending function reported an error – **Worst-case.**

Note: this list can only be applied on non-isolated channels, as the Best-case scenario on an isolated channel would be CASE 4.

5 Analysis

An analysis of all the data gathered was performed. The analysed data was filtered into three main subjects:

- The IMDs detection and reset speed
- Faults detected, and errors reported during the tests.
- Conflicting measurements between the tests.

5.1 Detection/reset speed

A meaningful finding that could be immediately noticed when looking at the saved trending data was a substantial difference in insulation fault detection speed and automatic reset speed between the three IMDs. E.g. in Figure 29 at TTP 11, an error is reported in the UNITool trending function simultaneously as the insulation fault was performed. In the ABB test, the IMD detected the fault approximately 10 seconds after the error occurred compared to BENDER and DOLD, which detected it almost directly as the error appeared.

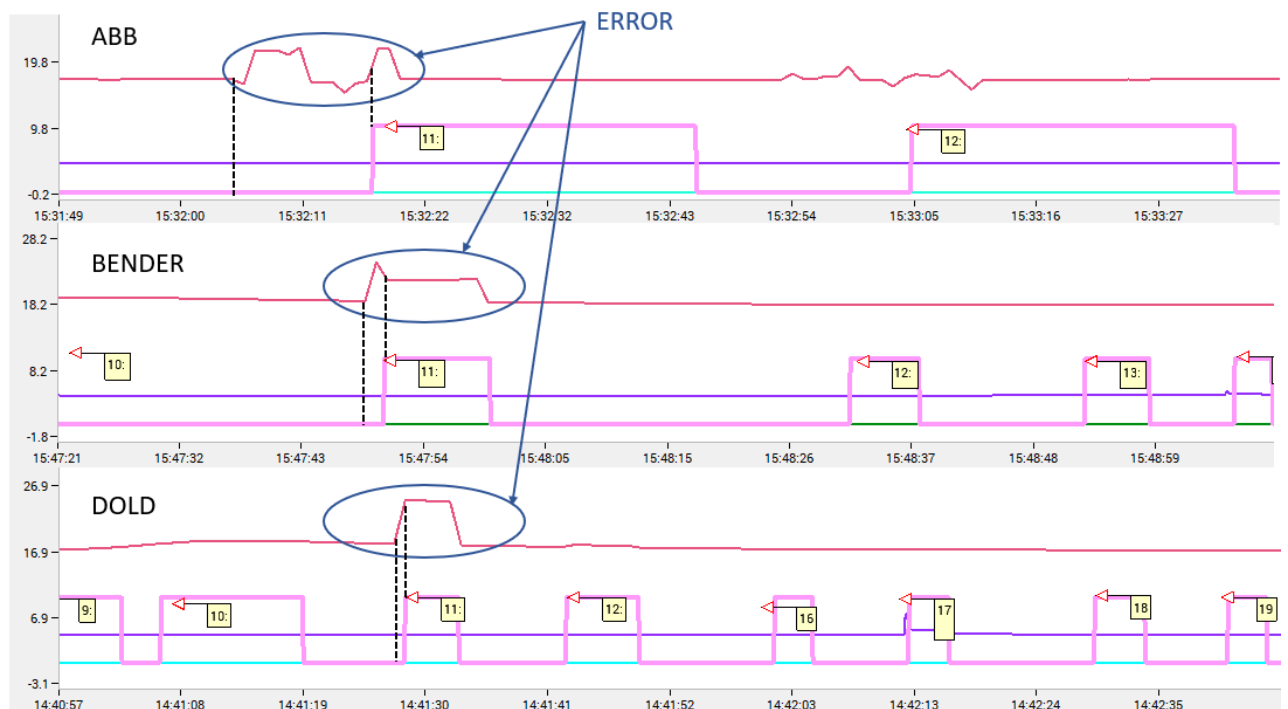


Figure 29. Detection and automatic reset speed comparison between the IMDs.

5.2 Faults and Errors

The two comparison sheets (Appendix 1 & 2) shows a chunk of red colour on a few channels on COM-10-1 and COM-10-2. These tested channels are galvanically isolated from the UNIC system and, therefore, not detected by the IMD or the system. In total, five isolated channels were tested, leading to ten signals not being detected.

The most typical trend errors that appeared were rapid fluctuations where a tested channel's linked ISO code spiked up when the insulation fault was performed and dropped back down when the fault ended. EDL errors that occurred were mainly machinery protection alarm or sensor failure. The EDL errors did not specifically occur on the tested channel's linked ISO code every time; they differed depending on which IMD was tested.

5.2.1 Total signals tested

A total of 88 channel signals were tested in each test. Comparing the faults detected by the IMDs when performing direct insulation faults (Table 5), DOLD managed to detect the most faults, followed by ABB and BENDER. However, both BENDER and DOLD increased the occurrence of UNITool errors by 11; whilst in the ABB test, the number of errors was equal to the test without IMD. Comparing the 50 k Ω insulation faults performed (Table 6), ABB managed to detect the most faults, followed by DOLD and BENDER. All IMDs increased the occurrence of UNITool errors.

Table 5. Total faults detected and errors reported – Direct insulation faults.

Direct insulation fault				
	ABB	BENDER	DOLD	Without IMD
Signals tested	88	88	88	88
Faults detected by the IMD	75	69	78	-
UNITool errors reported	20	31	31	20

Table 6. Total faults detected and errors reported – 50 k Ω insulation faults.

50 k Ω insulation fault				
	ABB	BENDER	DOLD	Without IMD
Signals tested	88	88	88	88
Faults detected by the IMD	78	60	70	-
UNITool errors reported	8	8	9	5

By implementing the best- to worst-case scenario list (presented in chapter 5.3.1) on the comparison sheets, two new tables were generated (Table 7 and Table 8) containing a comparison between all IMDs best- to worst-case scenarios.

The best-case scenarios happened most with ABB, followed by DOLD and BENDER. BENDER had the most number of CASES in the red area (CASE 4-6).

In the Direct insulation fault cases, CASE 5 and CASE 6 never happened when testing ABB or DOLD IMDs. In the 50 k Ω insulation fault cases, CASE 2 and CASE 5 never happened because the UNIC system manages to protect against insulation faults with higher resistance and, therefore, does not detect EDL errors.

Table 7. Case comparison – Direct insulation fault.

Direct insulation faults			
Best-Worst Case	ABB	BENDER	DOLD
CASE 1	55	43	47
CASE 2	7	19	19
CASE 3	13	7	12
CASE 4	13	13	10
CASE 5	0	4	0
CASE 6	0	2	0

Table 8. Case comparison – 50 k Ω insulation fault.

50 kΩ insulation fault			
Best-Worst Case	ABB	BENDER	DOLD
CASE 1	70	56	63
CASE 2	0	0	0
CASE 3	8	4	7
CASE 4	10	24	16
CASE 5	0	0	0
CASE 6	0	4	2

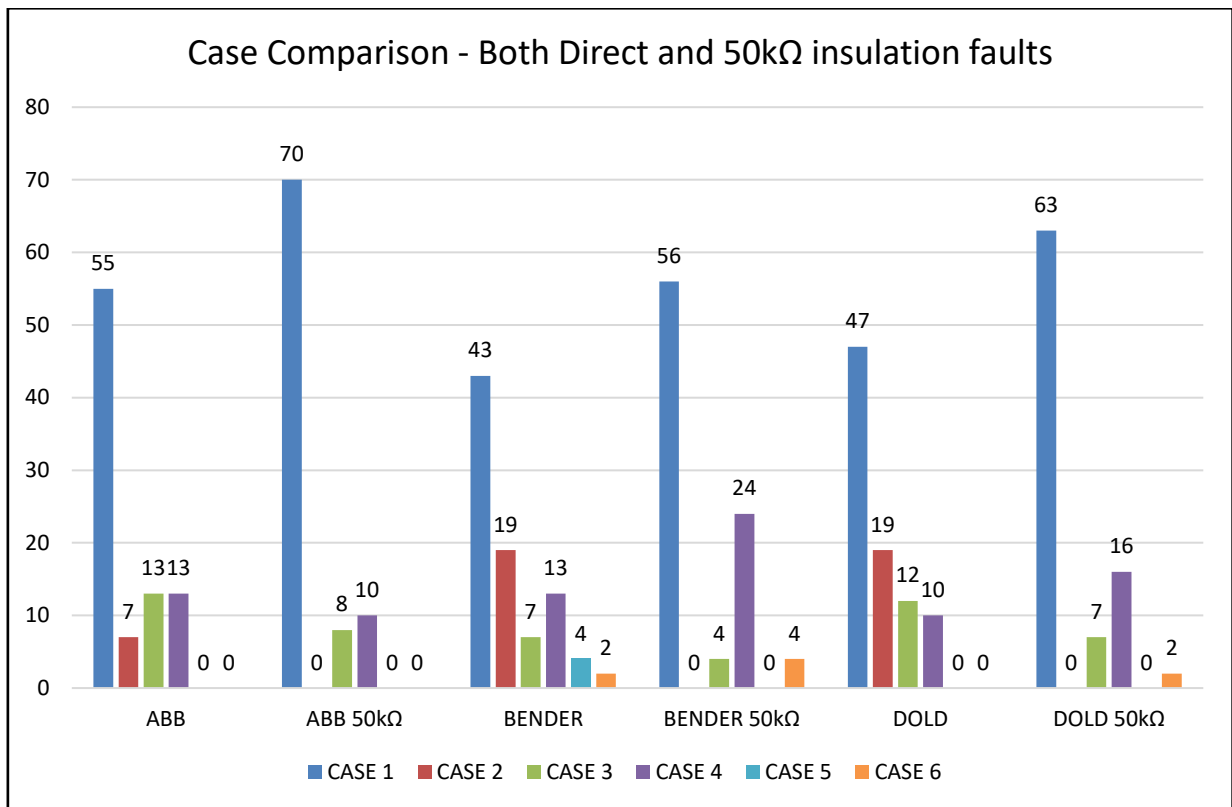


Figure 30. Clustered column presentation of Table 7 and 8.

5.3 Conflicting measurements

All conflicting measurements were taken into consideration except for the ones on ESM-21-1 when evaluating the IMDs.

When direct insulation faults were performed on the ESM-21-1 with the BENDER IMDs connected, an unexpected system error occurred on the majority of the channel signals where the engine went into shutdown mode. This system error also occurred with DOLD IMDs connected, but only on one channel signal (PSS 1 0V). The system error was caused by the ISO code IS7305, External Shutdown 4, and is linked to the emergency stop loop circuit, which has input to the ESM-21 module. During the investigation, it was also noticed that the U5 IMD showed a significant decrease in insulation resistance, as it should be $> 1 \text{ M}\Omega$, but displayed approximately $0.2 \text{ M}\Omega$. It can be concluded that there is an underlying insulation fault in the safety supply system and that the ESM-21 might be defective. Therefore, all test data gathered from the ESM-21 can not be used as it is not reliable.

The conflicts are presented in Appendix 3 and 4. When performing direct insulation faults, most of the conflicting measurements were caused by UNITool EDL errors that appeared only during BENDER, DOLD, and Without IMD. In the 50 k Ω insulation test, most of the conflicts were caused by BENDER IMD not detecting the faults performed. As the amount of EDL errors could differ between the tests, the following chapter presents these differences.

5.3.1 EDL conflicts – direct insulation faults

COM-10-1

- PSS1 (+): Sensor failure on LS103, LS107A, LS107B and LS204 in BENDER, DOLD, and Without IMD tests.
- FDI 1 (+): Sensor failure and Machinery protection alarm on ST196P and Machinery protection alarm on ST1962P in BENDER, DOLD, and Without IMD tests. BENDER and DOLD further increased EDL errors compared to the test Without IMD with Position measurement and Speed buffer overflow errors in COM-10-1 and all CCM modules.
- FDI 1 REF (0V): Speed buffer overflow error in COM-10-1 module ONLY in the DOLD test.
- FDI 2 (+): Machinery protection alarm on ST197P in BENDER, DOLD, and Without IMD tests. DOLD further increased EDL errors with Sensor failure on ST197P.
- FDO 1 (+): Machinery protection alarm on ST1962P in BENDER, DOLD, and Without IMD tests. BENDER and DOLD further increased EDL errors with Position measurement errors in all CCM modules.

COM-10-2

- AO 1 (+): Sensor failure on CV493 in ABB and BENDER tests.
- AO 1 (-): Sensor failure on CV493 in DOLD and Without IMD tests.

CCM-30-A1

- AI 2 (E): Sensor failure on PT105 in BENDER, DOLD, and Without IMD tests.

- AI 2 (+): Sensor failure on PT105 in BENDER and DOLD tests.
- FDI 3 (E): Sensor failure on LS103, LS107A, LS107B and LS204 ONLY in the ABB test.
- FDI 3 (-): Sensor failure on LS107A in ABB, BENDER, and DOLD tests.
- FDI 5 (-): Sensor failure on LS204 in ABB and DOLD tests.
- FDI 5 (E): Sensor failure on LS103, LS107A, LS107B and LS204 ONLY in the ABB test.

CCM-30-B1

- AI 3 (E): Sensor failure on PT155 and LS107B and Machinery protection alarm on PT155.
- AI 3 (+): Sensor failure and Machinery protection alarm on PT155 in ABB, DOLD, and Without IMD tests.

IOM-20-1

- PSS 1 (+): Sensor failure on LS103, LS107A, LS107B and LS204 in all tests. ABB further increased EDL errors with Sensor failures and Machinery protection alarms on PT115 and PT155. Same matter in the Without IMD test, except that it was on PT401 and CV792E.
- AI 3 (-): Sensor failure and Machinery protection alarm on PT115 in BENDER, DOLD, and Without IMD tests.

IOM-20-FE1

- HSD 1 (+): Sensor failure on LS103, LS107A, LS107B and LS204 in BENDER and DOLD tests. DOLD further increased EDL errors with Sensor failure and Machinery protection alarm on CV792E.
- AI 1 (E): Sensor failure on LS107B, ONLY in BENDER test.
- AI 1 (+): Sensor failure and Machinery protection alarm on PT301 in BENDER and DOLD tests.

- ADIO 1 (E): Sensor failure on LS107B, ONLY in BENDER test.
- ADIO 1 (+): Sensor failure and Machinery protection alarm on PT101 in BENDER and DOLD tests.
- ADIO 4 (E): Sensor failure on LS107B, ONLY in DOLD test.
- ADIO 4 (+): Sensor failure on LS107B, ONLY in BENDER test.

ESM-21-1

- PSS 1 (0V): External shutdown 4 error on IS7305 in BENDER and DOLD tests.
- FDI 3 (S): External shutdown 4 error on IS7305, ONLY in BENDER test.
- FDI 3 (-): External shutdown 4 error on IS7305, ONLY in BENDER test.
- AI 1 (1): External shutdown 4 error on IS7305, ONLY in BENDER test. Machinery protection alarm on NS718.
- AI 1 (2): Machinery protection alarm on NS718, ONLY in DOLD test.
- AI 1 (3): External shutdown 4 error on IS7305, ONLY in BENDER test. Machinery protection on TEZ402 and NS718 in all tests.
- AI 3 (-): External shutdown 4 error on IS7305, ONLY in BENDER test.

5.3.2 EDL conflicts – 50 k Ω insulation fault

Only when testing BENDER with 50 k Ω insulation faults, just one channel signal tested reported an EDL error.

ESM-21-1

- AI 1 (3): Machinery protection alarm on TEZ402, ONLY in BENDER test.

5.4 IMD proposal

The analysis of the test result points towards the DOLD IMD as a suiting candidate. The detection speed and automatic reset speed are essential factors in proposing the candidate as it is vital to detect the insulation fault as soon as possible when it occurs. The ABB IMD was much slower than BENDER and DOLD, and that leads to insulation faults that occur sporadically would not be detected by the ABB IMD.

BENDER had almost as fast detection and automatic reset speed as DOLD but can still be ruled out rather quickly when just looking at the faults detected and the best to worst-case scenario tables.

Even if DOLD increased the amount of UNITool EDL errors, ABB did not detect as many insulation faults and generated more fluctuations compared to DOLD in the Direct insulation fault comparison. EDL errors are not that critical compared to fluctuations of an ISO-code because a fluctuation, in the worst case, could generate a snowball effect, where it impacts multiple parameters due to its wrong and fast change in value.

In the 50 k Ω insulation fault comparison, ABB detected the most faults, followed by DOLD and BENDER. However, the UNIC system managed to protect against the insulation faults with higher resistance, as the errors reported by UNITool were minimal. The 50 k Ω insulation faults are, therefore, not as important compared to Direct ones.

According to the test data, DOLD would be the best candidate.

HOWEVER, if the standard IEC 61557 had to be implemented when proposing the IMD, the only possible candidate would be ABB, as it is the only one that can detect both asymmetrical and symmetrical insulation faults.

6 Results

It can be stated that the set goals for this thesis work have been fulfilled. The thesis has the following outcome of an Insulation Monitoring Device (IMD) proposal for the engine automation system and a determination of why Wärtsilä uses isolated (IT) systems on their marine applications.

The proposal is based on research and extensive tests performed on three different IMDs: ABB CM-IWS.1, BENDER isoUG425, and DOLD IL 5881.12/100. The research was executed by analysing the IMDs' datasheets and comparing them with IEC 61557-8 recommendations. IEC 61557-8 covers Insulation Monitoring Devices for low voltage IT distribution systems up to 1000 VAC and 1500 VDC. Both ABB and BENDER were in use within the engine automation system when the thesis project started, but their suitability in the system had never been evaluated. DOLD was a completely new candidate to be tested. When going through the datasheets of the IMDs, it could quickly be distinguished that major differences existed between the devices. E.g. the ABB IMD was the only device that could detect both asymmetrical and symmetrical insulation faults, and according to IEC 61557-8, an IMD must detect both types of faults.

The tests were conducted on a full-scale UNIC engine automation system by utilising a W31 lab engine at Wärtsilä's Engine Laboratory in Vaasa. Four tests were performed, one test without IMDs, and three tests with the different IMD types connected. Two types of asymmetrical insulation faults were simulated with different resistances: a fault with minimal resistance and a 50 k Ω fault.

The UNIC system is divided into four different domains, powered by redundant, isolated AC/DC power supply systems. For each redundant system, an IMD is implemented; this makes up for a total of four IMDs. The IMDs are configured to detect deterioration of the insulation resistance as soon as possible within the specific system. In practice, this means that the insulation resistance threshold value (R_a) is set to the highest available. ABB and BENDER had a max R_a value of 100 k Ω , whilst DOLD had a max value of 200 k Ω . The R_a value was set to 100 k Ω on all four devices in every test.

Before the testing could start, a test plan had to be constructed. The plan consisted of an Excel test sheet based on the utilised engine's wiring diagram and power supply concept drawing together with a draft partitioning & device database file. As the UNIC system is built upon so-called modules, the test sheet was divided according to the modules tested.

Only module channels containing unique connected equipment were added to the test sheet to generate as many different failure situations as possible.

Test data was collected by simulating insulation faults on module channels according to the test sheet to distinguish what faults were detected on which channel by the IMD and observing how the UNIC system reacted to the fault depending on which IMD was connected. Both the IMDs' and the system's behaviour were monitored through UNITool, a software program developed by Wärtsilä. The collected test data was later analysed. Colour coding and a best to worst-case scenario list were implemented (chapter 4.3.1) to facilitate the analysis process. All data can be seen in Appendix 1 & 2. The data were later filtered into conflicting measurements between the tests (Appendix 3 & 4).

Based on the analysed data (chapter 5), DOLD would be the best candidate due to its fast detection and reset speed and amount of detected faults in the system. BENDER was ruled out rather quickly due to its poor performance in overall fault detection. However, if IEC 61557-8 was considered when proposing the candidate, only the ABB IMD would be possible to use.

By utilising the IEC standard 60092-201 combined with theory and internal research regarding system design, electrical installation, and electrical safety in low voltage distribution systems, an apparent reason why Wärtsilä uses IT systems in their marine applications has been determined.

IEC 60092-201 is a document containing recommendations for system design of electrical installations in vessels; it has been concluded that two types of DC systems are standard: IT and TN-S systems, with two- and three-wire configuration. The IT system has its neutral conductor completely separated from earth, which makes it isolated (unearthed). The TN-S system is an earthed system, as its neutral conductor is directly connected to earth throughout the system. When comparing the systems (Table 2), a big difference between the systems can be seen. The IT system has many advantages over the TN-S system, E.g. Nothing happens if an individual touches a live unisolated conductor in the IT system. Secondly, the IT system will continue its operation during a first fault, and the TN-S system will shut down directly if an RCM is not implemented.

Wärtsilä applies IT system configurations in the UNIC power supply system, as it is ideal for their demands, which are the protection of insulation faults and the possibility of enabling steady operation even if an insulation fault is present.

7 Discussion

The thesis has been highly instructive and exciting, yet very challenging. From researching the devices and testing them to analysing data and evaluating it, the most challenging part has been the collection of theory and localisation of correct standards for the topic. A lot of research was done in the beginning stage regarding power distribution and standards around them; both shore and offshore standards were considered. As the evaluation of the IMDs was being performed on an engine specifically developed for marine application, it was decided to follow standards mainly about offshore. IEC 60092-201 Electrical installation in ships – System design was utilised. IEC 60092-201 referred to IEC 61557-8, which handles Insulation Monitoring Devices for low voltage IT distribution systems up to 1000 VAC and 1500 VDC. These two standards built up the framework of the thesis.

During the whole process with the thesis, I noticed that; writing down even the most minor ideas and thoughts has helped a lot with general phrasing and fluency when writing the thesis. E.g. chapter 4, which explains the practical work around the thesis, was by far the fastest chapter written due to all notes written down during and after the testing process.

The road to the result of the proposed IMD candidate has been time-consuming but also rewarding. The planning stage of the evaluation consumed by far the most time, as the produced Excel test sheet was re-modelled many times in order to have a perfect overview of it during the tests. The testing slots on the W8V31CR lab engine were limited due to other teams having more high-priority tests to be performed, making it relatively hard to schedule testing slots for the IMD comparison. Luckily, as the test procedure of simulating the insulation faults was relatively straightforward, each test did not last long, so we managed to complete all tests within three testing slots.

The reason for performing the test on an engine rather than on a lab-table system was that; the engine's automation system is much larger and more of a "real-life" example that produces more reliable test data. In addition, only asymmetrical insulation faults were executed, and the threshold value R_a was set to 100 k Ω in all IMD tests to make the testing equal between the devices, as the ABB IMD was the only one that could detect both asymmetrical and symmetrical faults. Furthermore, DOLD was the only IMD that could have a higher R_a value than 100 k Ω .

As mentioned in the results, two insulation faults with different resistances were performed. The fault with minimal resistance (direct insulation fault) was given to be performed

because, in reality, most insulation faults occur due to a conductor having direct contact with earth. The 50 k Ω was mainly added to distinguish how the devices and the UNIC system reacted to a fault with higher resistance. As it was noticed that the UNIC system managed to protect better against the higher resistance faults, they were not given as high priority as the direct insulation faults.

Unfortunately, during the test with BENDER, an unexpected system error occurred on the Engine Safety Module (ESM-21), where the engine went into shutdown mode on a few channels while simulating the insulation faults. As a result, test data gathered from that module was not reliable and not used in the evaluation. The ESM-21 module was most likely defective, but there was no time to investigate further due to the tight testing schedule on the engine. For future testing, the ESM-21 module should be switched to a new one and tested again with all the IMDs, to see if the test result differs.

The proposed DOLD candidate will most likely be implemented in the engine automation system even if it is not an IMD according to IEC 61557-8, as Wärtsilä does not have any requirements for detecting symmetrical faults. However, since the IMDs were all tested with the threshold value (R_a) set to 100 k Ω , and as DOLD's R_a value is possible to set to 200 k Ω , DOLD should be tested with that threshold value to see if the test results differ before considering implementing it on production engines. If referring to theory, the higher R_a value should generate a better result, as the devices get more sensitive, leading to earlier detection of insulation resistance deterioration. Additionally, it must also be verified that it is possible to get the DOLD candidate marine certified, as it is a mandatory requirement in order to get it implemented on marine engines.

Furthermore, as the engine automation system is genuinely complex, the localising of an insulation fault often leads to the exclusion method, making it rather time-consuming. E.g. if an insulation fault is present somewhere in the system, one module at a time has to be de-energised to see when the fault disappears. Therefore, further research could be done on insulation fault location systems (IFLS) to investigate how and if it is even possible to implement it on such an extensive system that UNIC is.

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Module	Channel	Channel Connection	Channel Isolation	ISO-code	ISO-code description	Monitored supply	Signal	Direct insulation fault detection										
								ABB			BENDER			DOLD			Without IMD	
								IMD	UNITool	TTP	IMD	UNITool	TTP	IMD	UNITool	TTP	UNITool	TTP
COM-10-1	PSS 1	Power Cabinet PSS 1 supply	Non-isolated	EC_CtrlPower1_COM_1	Control power supply 1, COM 1	24VDC PSS1 (U1)	+	Yes	No	1	Yes	Yes	1	Yes	Yes	1	Yes	45
							-	Yes	No	2	Yes	No	2	Yes	No	2	No	46
	FDI 1	Lenord & Bauer HALL Speedsensor	Non-isolated	ST196P	Engine speed, Primary	24VDC PSS1 (U1)	E	Yes	No	3	Yes	No	3	Yes	No	3	No	47
							+	Yes	No	4	No	Yes	4	Yes	Yes	4	Yes	48
							-	Yes	No	5	Yes	No	5	Yes	No	5	No	49
							REF(OV)	Yes	No	6	Yes	No	6	Yes	Yes	6	No	50
	FDI 2	Pulstronic Speed/position sensor	Non-isolated	ST197P	Engine phase, Primary	24VDC PSS1 (U1)	E	Yes	No	7	Yes	No	7	Yes	No	7	No	51
							+	Yes	No	8	No	Yes	8	Yes	Yes	8	Yes	52
							-	Yes	No	9	Yes	No	9	Yes	No	9	No	53
							REF(OV)	Yes	No	10	Yes	No	10	Yes	No	10	No	54
DI 3	External connections	Non-isolated	OS7304	Remote stop	24VDC PSS1 (U1)	+	Yes	No	11	Yes	No	11	Yes	No	11	No	55	
						-	Yes	No	12	Yes	No	12	Yes	No	12	No	56	
ADI 1	External connections Analogue mode	Isolated	UT793	Engine load feedback	24VDC PSS1 (U1)	+	No	No	13	No	No	13	No	No	13	No	57	
						-	No	No	14	No	No	14	No	No	14	No	58	
AI 2	External connections	Isolated	OT190	Analogue speed reference	24VDC PSS1 (U1)	+	No	No	15	No	No	15	No	No	15	No	59	
						-	No	No	16	No	No	16	No	No	16	No	60	
DO 3	External connections	Isolated	IS872	Engine ready for start	24VDC PSS1 (U1)	+	No	No	17	No	No	17	No	No	17	No	61	
						-	No	No	18	No	No	18	No	No	18	No	62	
FDO 1	CCM-30	Non-isolated	ST1962P	Primary position pulse train	24VDC PSS1 (U1)	+	Yes	No	19	Yes	Yes	19	Yes	Yes	19	Yes	63	
						-	Yes	No	20	Yes	No	20	Yes	No	20	No	64	
ADO 4	External connections	Isolated	CT7001	Engine load for propulsion control	24VDC PSS1 (U1)	+	No	No	21	No	No	21	No	No	21	No	65	
						-	No	No	22	No	No	22	No	No	22	No	66	
COM-10-2	AO 1	External connections	Non-Isolated	CV493	LT cooling water thermostat control	24VDC PSS1 (U1)	+	Yes	Yes	1	No	Yes	1	Yes	No	1	No	9
							-	Yes	No	2	Yes	No	2	Yes	Yes	2	Yes	10
ADI 1	External connections Digital mode	Isolated	GS799	Busbar parallel with grid status	24VDC PSS1 (U1)	+	No	No	3	No	No	3	No	No	3	No	11	
						-	No	No	4	No	No	4	No	No	4	No	12	
CCM-30-A1	PSS 1	Power Cabinet PSS 1 supply	Non-isolated	EC_CtrlPower1_CCM_A1	Control power supply 1, CCM A1	24VDC PSS1 (U1)	+	Yes	Yes	1	Yes	Yes	1	Yes	Yes	1	Yes	51
							-	Yes	No	2	Yes	No	2	Yes	No	2	No	52
	PSD 1A	Power Cabinet PSD 1A supply	Non-isolated	EC_DriverPower_1A_CC	Power supply driver channel volt 1A	110VDC PSD1 (U3)	+	Yes	No	3	Yes	No	3	Yes	No	3	No	53
							-	Yes	No	4	Yes	No	4	Yes	No	4	No	54
	PSD 3A	Power Cabinet PSD 3A supply	Non-isolated	EC_DriverPower_3A_CC	Power supply driver channel volt 3A	24VDC PSD1 (U2)	+	Yes	No	5	Yes	No	5	Yes	No	5	No	55
							-	Yes	No	6	Yes	No	6	Yes	No	6	No	56
	DRV 7	L'ORANGE Injection valve	Non-isolated	CV1011A	FO injector control, cyl A01	110VDC PSD1 (U3)	+	Yes	No	7	Yes	No	7	Yes	No	7	No	57
							-	Yes	No	8	Yes	No	8	Yes	No	8	No	58
	DRV 11	Bosch Rexroth Solenoid valve	Non-isolated	CV2011A	VIC control valve, cyl A01	24VDC PSD1 (U2)	+	Yes	Yes	9	Yes	Yes	9	Yes	Yes	9	Yes	59
							-	Yes	No	10	No	No	10	Yes	No	10	No	60
	Temp 1	Pentronic Thermocouple	Non-isolated	TE5011A	Exh gas temp, cyl 01A	24VDC PSS1 (U1)	+	Yes	Yes	11	Yes	Yes	11	Yes	Yes	11	Yes	61
							-	Yes	Yes	12	Yes	No	12	Yes	Yes	12	No	62
AI 2	Danfoss Pressure sensor	Non-isolated	PT105	FO press, after safety valve	24VDC PSS1 (U1)	E	Yes	No	16	Yes	Yes	13	Yes	Yes	16	Yes	66	
						+	Yes	No	17	Yes	Yes	14	Yes	Yes	17	No	67	
FDI 3	Bedia Level Sensor (NC)	Non-isolated	LS107A	FO leakage, dirty fuel FE, A-bank	24VDC PSS1 (U1)	E	Yes	Yes	18	Yes	No	15	Yes	No	18	No	68	
						+	Yes	No	19	Yes	No	16	Yes	No	19	No	69	
						-	Yes	Yes	20	Yes	Yes	17	Yes	Yes	20	No	70	
FDI 5	Bedia Level Sensor (NO)	Non-isolated	LS204	LO low level wet sump	24VDC PSS1 (U1)	+	Yes	No	21	Yes	No	18	Yes	No	21	No	71	
						-	Yes	Yes	22	Yes	No	19	Yes	Yes	22	No	72	
						E	Yes	Yes	23	Yes	No	20	Yes	No	23	No	73	
FDI 1	COM-10-1 FDO 1	Non-isolated	ST1962P_A1	Primary position pulse train, A1	24VDC PSS1 (U1)	+	Yes	No	24	Yes	No	21	Yes	No	24	No	74	
						-	Yes	No	25	Yes	No	22	Yes	No	25	No	75	

CCM-30-B1	AI 3	Trafag Pressure sensor (2500 bar)	Non-isolated	PT155	FO rail pressure sensor 2	24VDC PSS1 (U1)	E	Yes	No	1	Yes	No	1	Yes	No	1	Yes	5
							+	Yes	Yes	2	Yes	Yes	2	Yes	Yes	2	Yes	6
IOM-20-1	PSS 1	Power Cabinet PSS 1 supply	Non-isolated	EC_CtrlPower1_IOM_1	Control power supply 1, IOM 1	24VDC PSS1 (U1)	+	Yes	Yes	1	Yes	Yes	1	Yes	Yes	1	Yes	9
	AI 3	Trafag Pressure sensor (2500 bar)	Non-isolated	PT115	FO rail pressure, sensor 1	24VDC PSS1 (U1)	-	Yes	No	2	Yes	No	2	Yes	No	2	No	10
+							Yes	Yes	3	Yes	Yes	3	Yes	Yes	3	Yes	11	
IOM-20-TCA	ADIO 16	Pentronic Thermocouple	Non-isolated	TE511	Exh gas temp TC A inlet	24VDC PSS1 (U1)	E	Yes	Yes	1	No	Yes	1	Yes	Yes	1	Yes	21
							+	Yes	Yes	2	No	Yes	2	Yes	Yes	2	Yes	22
	FDI 1	ABB LP turbocharger	Non-isolated	SE518-1	Low press TC A speed	24VDC PSS1 (U1)	E	Yes	No	3	Yes	No	3	Yes	Yes	3	No	23
							+	Yes	Yes	4	Yes	Yes	4	Yes	No	4	No	24
							-	Yes	No	5	Yes	No	5	Yes	No	5	No	25
							REF (0V)	Yes	No	6	Yes	No	6	Yes	No	6	No	26
	FDI 2	ABB HP turbocharger	Non-isolated	SE518-2	High press TC A speed	24VDC PSS1 (U1)	E	Yes	No	7	Yes	No	7	Yes	No	7	No	27
							+	Yes	Yes	8	Yes	No	8	Yes	No	8	Yes	28
							-	Yes	No	9	Yes	No	9	Yes	No	9	No	29
							REF (0V)	Yes	No	10	Yes	No	10	Yes	No	10	No	30
IOM-20-FE1	HSD 1	Parker VIC Solenoid	Non-isolated	CV261	VIC main control valve	24VDC PSS1 (U1)	+	Yes	No	1	Yes	Yes	1	Yes	Yes	1	Yes	25
							-	Yes	No	2	Yes	No	2	Yes	No	2	No	26
	AI 1	Danfoss Pressure sensor	Non-isolated	PT301	Starting air press, engine inlet	24VDC PSS1 (U1)	E	Yes	No	3	Yes	Yes	3	Yes	No	3	No	27
							+	Yes	No	4	Yes	Yes	4	Yes	Yes	4	No	28
	ADIO 1	Danfoss Pressure sensor	Non-isolated	PT101	FO press, engine inlet	24VDC PSS1 (U1)	E	Yes	No	5	Yes	Yes	5	Yes	No	5	No	29
							+	Yes	No	6	Yes	Yes	6	Yes	Yes	6	No	30
ADIO 6	Pentronic PT-100	Non-isolated	TE101	FO temp, engine inlet	24VDC PSS1 (U1)	E	Yes	Yes	37	Yes	Yes	7	Yes	Yes	7	Yes	31	
						+	Yes	Yes	38	Yes	Yes	8	Yes	Yes	8	Yes	32	
ADIO 4	Pulstronic Speed/position sensor	Non-isolated	GS792D	Turning gear disengaged	24VDC PSS1 (U1)	-	Yes	No	39	Yes	No	9	Yes	No	9	No	33	
						E	Yes	No	10	Yes	No	10	Yes	Yes	10	No	34	
						+	No	No	11	Yes	Yes	11	Yes	No	11	No	35	
						-	No	No	12	Yes	No	12	Yes	No	12	No	36	
ESM-21-1	PSS 1	Power Cabinet PSS 1 safety supply	Non-isolated	-	-	24VDC PSS Safety 1 (U5)	+24V	Yes	No	1	Yes	No	1	Yes	No	1	No	25
							0V	Yes	No	2	Yes	Yes	2	Yes	Yes	2	No	26
	FDI 3	Pulstronic Speed/position sensor	Non-isolated	ST173	Engine speed 1	24VDC PSS Safety 1 (U5)	+	Yes	No	3	Yes	No	3	Yes	No	3	No	27
							S	Yes	No	4	No	Yes	4	Yes	No	4	No	28
							-	Yes	No	5	Yes	Yes	5	Yes	No	5	No	29
	AI 1	Pentronic PT-100	Non-isolated	TEZ402	HT water temp, jacket outlet A-bank	24VDC PSS Safety 1 (U5)	1	Yes	No	6	Yes	Yes	6	Yes	Yes	6	No	30
							2	Yes	No	7	Yes	No	7	Yes	Yes	7	No	31
							3	Yes	Yes	8	Yes	Yes	8	Yes	Yes	8	Yes	32
AI 3	Danfoss Pressure sensor	Non-isolated	PTZ201	LO press, engine inlet	24VDC PSS Safety 1 (U5)	+	Yes	No	9	Yes	No	9	Yes	No	9	No	33	
						-	Yes	No	10	Yes	Yes	10	Yes	No	10	No	34	
DO 13	Eugen Seitz AG Solenoid valve	Non-isolated	CVZ134	Stop/shutdown solenoid valve	24VDC PSS Safety 1 (U5)	+	No	No	11	No	No	11	Yes	No	11	No	35	
						-	Yes	No	12	No	No	12	Yes	No	12	No	36	

Module	Channel	Channel Connection	Channel Isolation	ISO-code	ISO-code description	Monitored supply	Signal	50 kΩ insulation fault detection										
								ABB			BENDER			DOLD			Without IMD	
								IMD	UNITool	TTP	IMD	UNITool	TTP	IMD	UNITool	TTP	UNITool	TTP
COM-10-1	PSS 1	Power Cabinet PSS 1 supply	Non-isolated	EC_CtrlPower1_COM_1	Control power supply 1, COM 1	24VDC PSS1 (U1)	+	Yes	No	23	Yes	No	23	Yes	No	23	No	1
							-	Yes	No	24	Yes	No	24	Yes	No	24	No	2
	FDI 1	Lenord & Bauer HALL Speedsensor	Non-isolated	ST196P	Engine speed, Primary	24VDC PSS1 (U1)	E	Yes	No	25	Yes	No	25	Yes	No	25	No	3
							+	Yes	No	26	No	No	26	No	26	No	4	
							-	Yes	No	27	Yes	No	27	Yes	No	27	No	5
							REF(OV)	Yes	No	28	Yes	No	28	Yes	No	28	No	6
	FDI 2	Pulstronic Speed/position sensor	Non-isolated	ST197P	Engine phase, Primary	24VDC PSS1 (U1)	E	Yes	No	29	Yes	No	29	Yes	No	29	No	7
							+	Yes	No	30	No	No	30	No	30	No	8	
							-	Yes	No	31	Yes	No	31	Yes	No	31	No	9
							REF(OV)	Yes	No	32	Yes	No	32	Yes	No	32	No	10
DI 3	External connections	Non-isolated	OS7304	Remote stop	24VDC PSS1 (U1)	+	Yes	No	33	Yes	No	33	Yes	No	33	No	11	
						-	Yes	No	34	Yes	No	34	Yes	No	34	No	12	
ADI 1	External connections Analogue mode	Isolated	UT793	Engine load feedback	24VDC PSS1 (U1)	+	No	No	35	No	No	35	No	No	35	No	13	
						-	No	No	36	No	No	36	No	No	36	No	14	
AI 2	External connections	Isolated	OT190	Analogue speed reference	24VDC PSS1 (U1)	+	No	No	37	No	No	37	No	No	37	No	15	
						-	No	No	38	No	No	38	No	No	38	No	16	
DO 3	External connections	Isolated	IS872	Engine ready for start	24VDC PSS1 (U1)	+	No	No	39	No	No	39	No	No	39	No	17	
						-	No	No	40	No	No	40	No	No	40	No	18	
FDO 1	CCM-30	Non-isolated	ST1962P	Primary position pulse train	24VDC PSS1 (U1)	+	Yes	No	41	Yes	No	41	Yes	No	41	No	19	
						-	Yes	No	42	Yes	No	42	Yes	No	42	No	20	
ADO 4	External connections	Isolated	CT7001	Engine load for propulsion control	24VDC PSS1 (U1)	+	No	No	43	No	No	43	No	No	43	No	21	
						-	No	No	44	No	No	44	No	No	44	No	22	
COM-10-2	AO 1	External connections	Non-Isolated	CV493	LT cooling water thermostat control	24VDC PSS1 (U1)	+	Yes	No	5	No	No	5	No	No	5	No	1
							-	Yes	No	6	Yes	No	6	Yes	No	6	No	2
	ADI 1	External connections Digital mode	Isolated	GS799	Busbar parallel with grid status	24VDC PSS1 (U1)	+	No	No	7	No	No	7	No	No	7	No	3
							-	No	No	8	No	No	8	No	No	8	No	4
CCM-30-A1	PSS 1	Power Cabinet PSS 1 supply	Non-isolated	EC_CtrlPower1_CCM_A1	Control power supply 1, CCMA1	24VDC PSS1 (U1)	+	Yes	No	26	Yes	No	23	Yes	No	26	No	1
							-	Yes	No	27	Yes	No	24	Yes	No	27	No	2
	PSD 1A	Power Cabinet PSD 1A supply	Non-isolated	EC_DriverPower_1A_CC	Power supply driver channel volt 1A	110VDC PSD1 (U3)	+	Yes	No	28	Yes	No	25	No	No	28	No	3
							-	Yes	No	29	Yes	No	26	Yes	No	29	No	4
	PSD 3A	Power Cabinet PSD 3A supply	Non-isolated	EC_DriverPower_3A_CC	Power supply driver channel volt 3A	24VDC PSD1 (U2)	+	Yes	No	30	Yes	No	27	Yes	No	30	No	5
							-	Yes	No	31	Yes	No	28	Yes	No	31	No	6
	DRV 7	L'ORANGE Injection valve	Non-isolated	CV1011A	FO injector control, cyl A01	110VDC PSD1 (U3)	+	Yes	No	32	Yes	No	29	Yes	No	32	No	7
							-	Yes	No	33	Yes	No	30	Yes	No	33	No	8
	DRV 11	Bosch Rexroth Solenoid valve	Non-isolated	CV2011A	VIC control valve, cyl A01	24VDC PSD1 (U2)	+	Yes	No	34	No	No	31	No	No	34	No	9
							-	Yes	No	35	No	No	32	Yes	No	35	No	10
	Temp 1	Pentronic Thermocouple	Non-isolated	TE5011A	Exh gas temp, cyl 01A	24VDC PSS1 (U1)	+	Yes	Yes	36	Yes	Yes	33	Yes	Yes	36	No	11
							-	Yes	No	37	Yes	No	34	Yes	Yes	37	No	12
	AI 2	Danfoss Pressure sensor	Non-isolated	PT105	FO press, after safety valve	24VDC PSS1 (U1)	E	Yes	No	41	Yes	No	35	Yes	No	41	No	13
+							Yes	No	42	Yes	No	36	Yes	No	42	No	14	
FDI 3	Bedia Level Sensor (NC)	Non-isolated	LS107A	FO leakage, dirty fuel FE, A-bank	24VDC PSS1 (U1)	E	Yes	No	43	Yes	No	37	Yes	No	43	No	15	
						+	Yes	No	44	Yes	No	38	Yes	No	44	No	16	
						-	Yes	No	45	Yes	No	39	Yes	No	45	No	17	
FDI 5	Bedia Level Sensor (NO)	Non-isolated	LS204	LO low level wet sump	24VDC PSS1 (U1)	+	Yes	No	46	Yes	No	40	Yes	No	46	No	18	
						-	Yes	No	47	Yes	No	41	Yes	No	47	No	19	
						E	Yes	No	48	Yes	No	42	Yes	No	48	No	20	
FDI 1	COM-10-1 FDO 1	Non-isolated	ST1962P_A1	Primary position pulse train, A1	24VDC PSS1 (U1)	+	Yes	No	49	Yes	No	43	Yes	No	49	No	21	
						-	Yes	No	50	Yes	No	44	Yes	No	50	No	22	

CCM-30-B1	AI 3	Trafag Pressure sensor (2500 bar)	Non-isolated	PT155	FO rail pressure sensor 2	24VDC PSS1 (U1)	E	Yes	No	3	Yes	No	3	Yes	No	3	No	1
							+	Yes	Yes	4	No	Yes	4	Yes	Yes	4	no	2
IOM-20-1	PSS 1	Power Cabinet PSS 1 supply	Non-isolated	EC_CtrlPow er1_IOM_1	Control power supply 1, IOM 1	24VDC PSS1 (U1)	+	Yes	No	5	Yes	No	5	Yes	No	5	No	1
							-	Yes	No	6	Yes	No	6	Yes	No	6	No	2
	AI 3	Trafag Pressure sensor (2500 bar)	Non-isolated	PT115	FO rail pressure, sensor 1	24VDC PSS1 (U1)	+	Yes	No	7	Yes	No	7	Yes	No	7	No	3
							-	Yes	Yes	8	Yes	Yes	8	Yes	Yes	8	No	4
IOM-20-TCA	ADIO 16	Pentronic Thermocouple	Non-isolated	TE511	Exh gas temp TC A inlet	24VDC PSS1 (U1)	E	Yes	Yes	11	No	Yes	11	No	Yes	11	Yes	1
							+	Yes	Yes	12	No	Yes	12	No	Yes	12	Yes	2
	FDI 1	ABB LP turbocharger	Non-isolated	SE518-1	Low press TC A speed	24VDC PSS1 (U1)	E	Yes	No	13	Yes	No	13	Yes	No	13	No	3
							+	Yes	No	14	No	No	14	Yes	No	14	No	4
							-	Yes	No	15	Yes	No	15	Yes	No	15	No	5
							REF (0V)	Yes	No	16	Yes	No	16	Yes	No	16	No	6
	FDI 2	ABB HP turbocharger	Non-isolated	SE518-2	High press TC A speed	24VDC PSS1 (U1)	E	Yes	No	17	Yes	No	17	Yes	No	17	No	7
							+	Yes	No	18	No	No	18	Yes	No	18	No	8
							-	Yes	No	19	Yes	No	19	Yes	No	19	No	9
							REF (0V)	Yes	No	20	Yes	No	20	Yes	No	20	No	10
IOM-20-FE1	HSD 1	Parker VIC Solenoid	Non-isolated	CV261	VIC main control valve	24VDC PSS1 (U1)	+	Yes	No	13	Yes	No	13	Yes	No	13	No	1
							-	Yes	No	14	Yes	No	14	Yes	No	14	No	2
	AI 1	Danfoss Pressure sensor	Non-isolated	PT301	Starting air press, engine inlet	24VDC PSS1 (U1)	E	Yes	No	15	Yes	No	15	Yes	No	15	No	3
							+	Yes	No	16	No	No	16	Yes	No	16	No	4
	ADIO 1	Danfoss Pressure sensor	Non-isolated	PT101	FO press, engine inlet	24VDC PSS1 (U1)	E	Yes	No	17	Yes	No	17	Yes	No	17	No	5
							+	Yes	No	18	No	No	18	Yes	No	18	No	6
	ADIO 6	Pentronic PT-100	Non-isolated	TE101	FO temp, engine inlet	24VDC PSS1 (U1)	E	Yes	Yes	19	Yes	Yes	19	Yes	Yes	19	Yes	7
							+	Yes	Yes	20	Yes	Yes	20	Yes	Yes	20	Yes	8
	ADIO 4	Pulstronic Speed/position sensor	Non-isolated	GS792D	Turning gear disengaged	24VDC PSS1 (U1)	-	Yes	No	21	Yes	No	21	Yes	No	21	No	9
							+	Yes	No	22	Yes	No	22	Yes	No	22	No	10
							-	Yes	No	23	Yes	No	23	Yes	No	23	No	11
							-	Yes	No	24	Yes	No	24	Yes	No	24	No	12
ESM-21-1	PSS 1	Power Cabinet PSS 1 safety supply	Non-isolated	-	-	24VDC PSS Safety 1 (U5)	+24V	Yes	No	13	Yes	No	13	Yes	No	13	No	1
							0V	Yes	No	14	Yes	No	14	Yes	No	14	No	2
	FDI 3	Pulstronic Speed/position sensor	Non-isolated	ST173	Engine speed 1	24VDC PSS Safety 1 (U5)	+	Yes	No	15	Yes	No	15	Yes	No	15	No	3
							S	Yes	No	16	No	No	16	No	16	No	4	
							-	Yes	No	17	Yes	No	17	Yes	No	17	No	5
	AI 1	Pentronic PT-100	Non-isolated	TEZ402	HT water temp, jacket outlet A-bank	24VDC PSS Safety 1 (U5)	1	Yes	No	18	No	No	18	Yes	No	18	No	6
							2	Yes	No	19	No	No	19	Yes	No	19	No	7
							3	Yes	Yes	20	No	Yes	20	Yes	Yes	20	Yes	8
	AI 3	Danfoss Pressure sensor	Non-isolated	PTZ201	LO press, engine inlet	24VDC PSS Safety 1 (U5)	+	Yes	No	21	Yes	No	21	Yes	No	21	No	9
							-	Yes	No	22	No	No	22	Yes	No	22	No	10
DO 13	Eugen Seitz AG Solenoid valve	Non-isolated	CVZ134	Stop/shutdown solenoid valve	24VDC PSS Safety 1 (U5)	+	Yes	No	23	No	No	23	Yes	No	23	No	11	
						-	Yes	No	24	Yes	No	24	Yes	No	24	No	12	

Module	Channel	Channel Connection	Channel Isolation	ISO-code	ISO-code description	Monitored supply	Signal	Conflicting Measurements - Direct insulation fault										
								ABB			BENDER			DOLD			Without IMD	
								IMD	UNITool	TTP	IMD	UNITool	TTP	IMD	UNITool	TTP	UNITool	TTP
COM-10-1	PSS 1	Power Cabinet PSS 1 supply	Non-isolated	EC_CtrlPower1_COM_1	Control power supply 1, COM 1	24VDC PSS1 (U1)	+	Yes	No	1	Yes	Yes	1	Yes	Yes	1	Yes	45
	FDI 1	Lenord & Bauer HALL Speedsensor	Non-isolated	ST196P	Engine speed, Primary	24VDC PSS1 (U1)	+	Yes	No	4	No	Yes	4	Yes	Yes	4	Yes	48
							REF(OV)	Yes	No	6	Yes	No	6	Yes	Yes	6	No	50
	FDI 2	Pulstronic Speed/position	Non-isolated	ST197P	Engine phase, Primary	24VDC PSS1 (U1)	+	Yes	No	8	No	Yes	8	Yes	Yes	8	Yes	52
FDO 1	CCM-30	Non-isolated	ST1962P	Primary position pulse train	24VDC PSS1 (U1)	+	Yes	No	19	Yes	Yes	19	Yes	Yes	19	Yes	63	
COM-10-2	AO 1	External connections	Non-Isolated	CV493	LT cooling water thermostat control	24VDC PSS1 (U1)	+	Yes	Yes	1	No	Yes	1	Yes	No	1	No	9
							-	Yes	No	2	Yes	No	2	Yes	Yes	2	Yes	10
CCM-30-A1	DRV 11	Bosch Rexroth Solenoid valve	Non-isolated	CV2011A	VIC control valve, cyl A01	24VDC PSD1 (U2)	-	Yes	No	10	No	No	10	Yes	No	10	No	60
	Temp 1	Pentronic Thermocouple	Non-isolated	TE5011A	Exh gas temp, cyl 01A	24VDC PSS1 (U1)	-	Yes	Yes	12	Yes	No	12	Yes	Yes	12	No	62
	AI 2	Danfoss Pressure sensor	Non-isolated	PT105	FO press, after safety valve	24VDC PSS1 (U1)	E	Yes	No	16	Yes	Yes	13	Yes	Yes	16	Yes	66
							+	Yes	No	17	Yes	Yes	14	Yes	Yes	17	No	67
	FDI 3	Bedia Level Sensor (NC)	Non-isolated	LS107A	FO leakage, dirty fuel FE, A-bank	24VDC PSS1 (U1)	E	Yes	Yes	18	Yes	No	15	Yes	No	18	No	68
							-	Yes	Yes	20	Yes	Yes	17	Yes	Yes	20	No	70
FDI 5	Bedia Level Sensor (NO)	Non-isolated	LS204	LO low level wet sump	24VDC PSS1 (U1)	-	Yes	Yes	22	Yes	No	19	Yes	Yes	22	No	72	
						E	Yes	Yes	23	Yes	No	20	Yes	No	23	No	73	
CCM-30-B1	AI 3	Trafag Pressure sensor (2500 bar)	Non-isolated	PT155	FO rail pressure sensor 2	24VDC PSS1 (U1)	E	Yes	No	1	Yes	No	1	Yes	No	1	Yes	5
							+	Yes	Yes	2	Yes	Yes	2	Yes	Yes	2	Yes	6
IOM-20-1	PSS 1	Power Cabinet PSS 1 supply	Non-isolated	EC_CtrlPower1_IOM_1	Control power supply 1, IOM 1	24VDC PSS1 (U1)	+	Yes	Yes	1	Yes	Yes	1	Yes	Yes	1	Yes	9
	AI 3	Trafag Pressure sensor (2500 bar)	Non-isolated	PT115	FO rail pressure, sensor 1	24VDC PSS1 (U1)	-	Yes	Yes	4	Yes	Yes	4	Yes	Yes	4	Yes	12
IOM-20-TCA	ADIO 16	Pentronic Thermocouple	Non-isolated	TE511	Exh gas temp TC A inlet	24VDC PSS1 (U1)	E	Yes	Yes	1	No	Yes	1	Yes	Yes	1	Yes	21
							+	Yes	Yes	2	No	Yes	2	Yes	Yes	2	Yes	22
	FDI 1	ABB LP turbocharger	Non-isolated	SE518-1	Low press TC A speed	24VDC PSS1 (U1)	E	Yes	No	3	Yes	No	3	Yes	Yes	3	No	23
							+	Yes	Yes	4	Yes	Yes	4	Yes	No	4	No	24
FDI 2	ABB HP turbocharger	Non-isolated	SE518-2	High press TC A speed	24VDC PSS1 (U1)	+	Yes	Yes	8	Yes	No	8	Yes	No	8	Yes	28	

IOM-20-FE1	HSD 1	Parker VIC Solenoid	Non-isolated	CV261	VIC main control valve	24VDC PSS1 (U1)	+	Yes	No	1	Yes	Yes	1	Yes	Yes	1	Yes	25
	AI 1	Danfoss Pressure sensor	Non-isolated	PT301	Starting air press, engine inlet	24VDC PSS1 (U1)	E	Yes	No	3	Yes	Yes	3	Yes	No	3	No	27
							+	Yes	No	4	Yes	Yes	4	Yes	Yes	4	No	28
	ADIO 1	Danfoss Pressure sensor	Non-isolated	PT101	FO press, engine inlet	24VDC PSS1 (U1)	E	Yes	No	5	Yes	Yes	5	Yes	No	5	No	29
							+	Yes	No	6	Yes	Yes	6	Yes	Yes	6	No	30
	ADIO 4	Pulstronic Speed/position sensor	Non-isolated	GS792D	Turning gear disengaged	24VDC PSS1 (U1)	E	Yes	No	10	Yes	No	10	Yes	Yes	10	No	34
							+	No	No	11	Yes	Yes	11	Yes	No	11	No	35
-							No	No	12	Yes	No	12	Yes	No	12	No	36	
ESM-21-1	PSS 1	Power Cabinet PSS 1 safety supply	Non-isolated	-	-	24VDC PSS Safety 1 (U5)	0V	Yes	No	2	Yes	Yes	2	Yes	Yes	2	No	26
	FDI 3	Pulstronic Speed/position sensor	Non-isolated	ST173	Engine speed 1	24VDC PSS Safety 1 (U5)	S	Yes	No	4	No	Yes	4	Yes	No	4	No	28
							-	Yes	No	5	Yes	Yes	5	Yes	No	5	No	29
	AI 1	Pentronic PT-100	Non-isolated	TEZ402	HT water temp, jacket outlet A-bank	24VDC PSS Safety 1 (U5)	1	Yes	No	6	Yes	Yes	6	Yes	Yes	6	No	30
							2	Yes	No	7	Yes	No	7	Yes	Yes	7	No	31
							3	Yes	Yes	8	Yes	Yes	8	Yes	Yes	8	Yes	32
	AI 3	Danfoss Pressure sensor	Non-isolated	PTZ201	LO press, engine inlet	24VDC PSS Safety 1 (U5)	-	Yes	No	10	Yes	Yes	10	Yes	No	10	No	34
DO 13	Eugen Seitz AG Solenoid valve	Non-isolated	CVZ134	Stop/shutdown solenoid valve	24VDC PSS Safety 1 (U5)	+	No	No	11	No	No	11	Yes	No	11	No	35	
						-	Yes	No	12	No	No	12	Yes	No	12	No	36	

Module	Channel	Channel Connection	Channel Isolation	ISO-code	ISO-code description	Monitored supply	Signal	Conflicting Measurements - 50 kΩ insulation fault detection											
								ABB			BENDER			DOLD			Without IMD		
								IMD	UNITool	TTP	IMD	UNITool	TTP	IMD	UNITool	TTP	UNITool	TTP	
COM-10-1	FDI 1	Lenord & Bauer HALL Speedsensor	Non-isolated	ST196P	Engine speed, Primary	24VDC PSS1 (U1)	+	Yes	No	26	No	No	26	No	No	26	No	No	4
	FDI 2	Pulstronic Speed/position	Non-isolated	ST197P	Engine phase, Primary	24VDC PSS1 (U1)	+	Yes	No	30	No	No	30	No	No	30	No	No	8
COM-10-2	AO 1	External connections	Non-Isolated	CV493	LT cooling water thermostat control	24VDC PSS1 (U1)	+	Yes	No	5	No	No	5	No	No	5	No	No	1
CCM-30-A1	PSD 1A	Power Cabinet PSD 1A supply	Non-isolated	EC_DriverPower_1A_CCM_A1	Power supply driver channel volt 1A	110VDC PSD1 (U3)	+	Yes	No	28	Yes	No	25	No	No	28	No	No	3
	DRV 11	Bosch Rexroth Solenoid valve	Non-isolated	CV2011A	VIC control valve, cyl A01	24VDC PSD1 (U2)	+	Yes	No	34	No	No	31	No	No	34	No	No	9
							-	Yes	No	35	No	No	32	Yes	No	35	No	No	10
Temp 1	Pentronic Thermocouple	Non-isolated	TE5011A	Exh gas temp, cyl 01A	24VDC PSS1 (U1)	-	Yes	No	37	Yes	No	34	Yes	Yes	37	No	No	12	
CCM-30-B1	AI 3	Trafag Pressure sensor (2500 bar)	Non-isolated	PT155	FO rail pressure sensor 2	24VDC PSS1 (U1)	+	Yes	Yes	4	No	Yes	4	Yes	Yes	4	no	No	2
IOM-20-1	AI 3	Trafag Pressure sensor (2500 bar)	Non-isolated	PT115	FO rail pressure, sensor 1	24VDC PSS1 (U1)	-	Yes	Yes	8	Yes	Yes	8	Yes	Yes	8	No	No	4
IOM-20-TCA	ADIO 16	Pentronic Thermocouple	Non-isolated	TE511	Exh gas temp TC A inlet	24VDC PSS1 (U1)	E	Yes	Yes	11	No	Yes	11	No	Yes	11	Yes	No	1
							+	Yes	Yes	12	No	Yes	12	No	Yes	12	Yes	No	2
	FDI 1	ABB LP turbocharger	Non-isolated	SE518-1	Low press TC A speed	24VDC PSS1 (U1)	+	Yes	No	14	No	No	14	Yes	No	14	No	4	
	FDI 2	ABB HP turbocharger	Non-isolated	SE518-2	High press TC A speed	24VDC PSS1 (U1)	+	Yes	No	18	No	No	18	Yes	No	18	No	8	
IOM-20-FE1	AI 1	Danfoss Pressure sensor	Non-isolated	PT301	Starting air press, engine inlet	24VDC PSS1 (U1)	+	Yes	No	16	No	No	16	Yes	No	16	No	No	4
	ADIO 1	Danfoss Pressure sensor	Non-isolated	PT101	FO press, engine inlet	24VDC PSS1 (U1)	+	Yes	No	18	No	No	18	Yes	No	18	No	No	6
ESM-21-1	FDI 3	Pulstronic Speed/position	Non-isolated	ST173	Engine speed 1	24VDC PSS Safety 1 (U5)	S	Yes	No	16	No	No	16	No	No	16	No	No	4
	AI 1	Pentronic PT-100	Non-isolated	TEZ402	HT water temp, jacket outlet A-bank	24VDC PSS Safety 1 (U5)	1	Yes	No	18	No	No	18	Yes	No	18	No	No	6
							2	Yes	No	19	No	No	19	Yes	No	19	No	No	7
							3	Yes	Yes	20	No	Yes	20	Yes	Yes	20	Yes	No	8
	AI 3	Danfoss Pressure sensor	Non-isolated	PTZ201	LO press, engine inlet	24VDC PSS Safety 1 (U5)	-	Yes	No	22	No	No	22	Yes	No	22	No	No	10
DO 13	Eugen Seitz AG Solenoid valve	Non-isolated	CVZ134	Stop/shutdown solenoid valve	24VDC PSS Safety 1 (U5)	+	Yes	No	23	No	No	23	Yes	No	23	No	No	11	