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Development and validation of safe electrical systems, equipment and routines

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Abstract

This report aims at enhancing electrical safety on ro-ro cargo and ro-ro passenger vessels. Complementing qualitative operational guidelines from report D08.6, this study delves into a quantitative technical implementation to curtail electrical risks and potential fires on board. The emphasis rests on safeguarding reefer units, pivotal for cargo preservation, and accommodating the surge of electric vehicles (EVs) necessitating in-voyage charging. The maritime sector's conventional lack of control over these electric loads accentuates the risks they pose. The report also presents the development and validation of a hardware-based solution for fire prevention through a secure electrical infrastructure for reefers and EVs.

In this solution, a common insulation monitoring unit is moved from the distribution transformer outputs to individual reefer inputs along with insulation fault locators. Further, energy meters are incorporated for in-depth monitoring of each load unit's vital parameters. This facilitates precise identification of load units when deviations from their normal electrical behaviour occurs. During demonstrative testing on 5 reefer units, the system automatically identified all electrical faults, whether natural or simulated, flagging incorrect parameters, faulty measurements, deviations, and corresponding reefer units.

In the face of potential electrical fires from faulty reefers and EVs, this report presents a tangible quantitative solution for preventing such hazards and providing a secure electrical ecosystem aboard relevant vessels. The practical implementation and demonstrative outcomes pave the way for future expansion and integration into maritime operations, ultimately fostering safer journeys and reducing fire risks substantially.

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Content

1 Executive summary

This report presents the work done as part of developing and validating safe electrical systems on board ro-ro cargo and ro-ro passenger vessels. Along with qualitative operational guidelines developed and presented in report D08.6, this report details a more quantitative technical implementation to ensure electrical safety and to minimise risk of electrical related fires on board. The focus in on reefer units being transported and electric vehicles that need charging during the voyage. These loads are always no different from "black boxes" for a ship operator as they have no control over the inherent safety, quality, make and upkeep of these electric loads. Historically, it has also been the case that a significant number of electrical fires on board have originated from faulty reefer units.

1.1 Problem definition

Ro-ro ships are an important component of the global maritime transportation system, but concerns have been raised over the number of significant fire incidents on ro-ro ships in recent years. This has prompted the International Maritime Organization (IMO) and maritime stakeholders to underscore the importance of improving the fire safety in ro-ro spaces. To date, only a limited number of studies focusing on these issues have been conducted. These studies have, to a varying degree, analysed critical aspects in previous ro-ro ship fires, thereby shedding some light on common fire causes in ro-ro shipping.

There is also a need to address the challenges ahead, including the ongoing cargo transformation involving alternative fuel vehicles. Moreover, these fire safety challenges are not limited to ro-ro passenger ships but apply to all types of ro-ro ships, including vehicle carriers and general ro-ro cargo ships. Hence, there is a need to update the fire protection of ro-ro ships from a wide and long-term perspective.

Connected Reefers and Electrical Vehicles (EV) onboard ro-ro cargo and ro-ro passenger ships have been seen as a potential hazard due to the risk of fire. Fire onboard a ro-ro ship is extremely dangerous and fire extinguishing is very hard. With a rise in the number of EVs on board, equipped with lithium-ion batteries, extinguishing these fires are almost impossible. The best solution is to prevent the fire, and this can be done by continuously monitoring the reefers and the Electrical Vehicles onboard.

1.2 Technical approach

In order to design a hardware based quantitative solution to prevent fire situations by proving a safe electrical infrastructure to reefers and EVs, multiple ship visits and interactions with the crew was crucial. With the chief electrical engineer on board and multiple electrical drawings of the ship's electrical infrastructure, the needed connection lines between the distribution transformer and the load units on cargo deck were mapped. The design of the solution considered factors such as effectiveness in identifying faults, cost of components and installation, ease of procurement as there were delays due to Covid-19 and the global silicon shortage, et cetera. The solution was then installed and tested on Stena Scandinavica.

1.3 Results and achievements

A qualitative approach to monitor reefer units and charging EVs was developed, implemented as a solution on Stena Scandinavica, and the results from the installation, as a demonstrator, are presented. The point of insulation monitoring and fault location was changed from the output of the distribution transformer to the inputs of the reefer units. In addition, energy meters were added to monitor all crucial parameters of each load unit (reefer or a charging EV). With these, the system allows precise identification of a load unit when there is a deviation from its normal electrical behaviour.

As part of the demonstrator, this solution was tested on 5 reefer units. All electrical faults, natural or simulated, were automatically identified. The incorrect parameter, the faulty measurement, the deviation from the expected value and the reefer unit are all raised as flags.

1.4 Contribution to LASH FIRE objectives

The LASH FIRE project further aims to support the recently adopted IMO Strategic Plan (2018-2023), including the following identified strategic direction:

"Integrate new and advancing technologies in the regulatory framework - balancing the benefits derived from new and advancing technologies against safety and security concerns, the impact on the environment and on international trade facilitation, the potential costs to the industry, and their impact on personnel, both on board and ashore.".

This report contributes to "Objective 1: LASH FIRE will strengthen the independent fire protection of ro-ro ships by developing and validating effective operative and design solutions addressing current and future challenges in all stages of a fire."

WP8 explores and implements State of the Art technology when it comes to monitoring connected Reefers and Electrical Vehicles and gives advice and recommendations to decision makers either in ro-ro spaces, engine room or on the bridge.

1.5 Exploitation

The results of this deliverable, D08.5, is best used along with the outcomes and implementation presented in deliverable D08.6. D08.6 presents a qualitative approach towards monitoring reefer units and EVs by providing guidelines and together with the quantitative approach presented in this report, a wholistic solution to safer reefer units and EVs on board can be realized.

The results from both aforementioned deliverables are primarily aimed at ship operators that regularly deal with transporting reefer units and passenger EVs that need charging during voyage. The finding from the visits and the consequent recommendations may also be of interest to classification societies and regulatory bodies to introduce rules that add towards a safer future.

2 List of symbols and abbreviations

EV	Electric vehicle
CPU	Central processing unit
GB	Giga bytes
GHz	Giga hertz
IMO	International maritime organisation
LAN	Local area network
PE	Protective earth
Ro-ro	Roll on – roll off
USB	Universal serial bus
V	Volts
W	Watts
Wh	Watt-hours

3 Introduction

Main author of the chapter: Vasudev Ramachandra, RISE

Reefers have been a significant part of ro-ro cargo and ro-ro passenger vessels for many decades. While usually the refrigeration is powered by the reefer's diesel generator unit, closed ro-ro cargo spaces do not allow running of engines. Instead, during voyage, they are powered by the vessel's electric grid. This solution eliminates the need to deal with ventilating the exhaust gasses from the closed space and the noise from the engines, however, the electrical vulnerabilities and faults of the reefers are now a part of the vessel. This is especially a problem as numerous reefers are plugged into and out of the system on a daily basis and the vessel has no control over the condition, upkeep, historical behaviour, et cetera of any of these units. These are synonymous to "black box" electrical loads where only the requirement of the load in terms of power supply is known but nothing about its behaviour during load consumption.

As of today, little or no active monitoring of connected reefer units on deck take place as standard procedure. In case an anomaly is detected in any electrical load by the existing checks or by accident, evaluation of the anomaly is manual and time consuming. A runner is sent to the cargo deck where s/he is tasked with identifying the faulty reefer unit among many such closely parked units using handheld devices such as thermal cameras or portable insulation fault locators. While this works for non-critical faults, it is not the case with drastic cases where there are sparks, smoke or fires are involved. The tightly packed cargo deck along with a faulty unit whose severity is unknown poses a risk to not just the cargo or the reefer unit but also to the persons in charge of identifying these units on deck.

While reefers form the majority of the black box loads, a large increase in sales and use of electric vehicles (EVs) are also reflected in their transport on ro-ro passenger vessels. This increase has revealed the need to charge them during voyages; a service which many ship operators are willing and wanting to provide, provided sufficient safety is ensured. Although there is both a demand and a profitable supply to provide, lithium-ion batteries used in these EVs have been drawing attention to fires they might cause and the difficulty in extinguishing them compared to conventional fires. This becomes more of a concern onboard a ship and can be a risk to both lives and other EVs and cargo. This concern is certainly warranted for as multiple cases of fires onboard ships have been witnessed due to EVs. Fremantle Highway, a ship with around 500 EVs on board caught fire off the coast of Netherlands on the 25th of July 2023. While the source of fire is uncertain, it spread to the EVs and burned for over a week. One life was also lost, and the rest of the crew needed to be evacuated while some were forced to jump off board (Staff and agencies in The Hague, 2023). This is not an isolated incident as an estimated 8 ships have sunk recently with battery fires suspected of playing a role, including the Felicity Ace, with 4,000 cars on board, that sank in 2022 (Pinn, 2023).

With EVs and their chargers subject to higher levels of general safety as compared to reefer units, they can perhaps be considered not as drastic as a fully black box load while charging on board. Nonetheless, EVs connected to the vessel's grid to be charged do not share the state of health of the battery with the vessel, making it similar to a reefer unit from the point of view of being aware of its electrical behaviour.

This report presents a quantitative solution to actively monitor and identify electrical faults in such connected reefer units and charging EVs on board and hence provide a safe electrical system. The objective is to be able to recognize faults enough in advance to facilitate the load's disconnection if necessary and prevent electrical related fires on board relevant ships.

4 Electrical systems on board – An overview

Main author of the chapter: Vasudev Ramachandra, RISE

To develop a robust and a safe electrical system on board, it is first important to understand the existing infrastructure and the nature of the loads that will consume power. Most of the cargo that demand and consume power on the decks are mainly reefer units. In addition, with a rise in electric mobility, electric and hybrid cars that need charging during the voyage are also increasing as electrical loads on the deck. From the ship operator's perspective, these loads, reefers units and charging electric vehicles, are perceived as a "black box" as operators have no control of the build, maintenance, or the condition of the electric consumer.

The following section discusses specifics of the requirements, some regulations and shortfalls of electrical networks that power the two relevant electrical loads.

4.1 Reefer units

Insulation faults on reefer units have been a frequent occurrence. This can be owed to the harsh conditions the reefer units can be subjected to over the years. While many insulation faults are not problematic and a few times even ignored, severe ones are capable of causing fires. Although reefer fires might not intuitively be as drastic as a lithium-ion EV battery fire, they are capable of substantial damage. In August 2022, Stena Scandica witnessed a fire originating in a reefer unit that managed to cause a blackout on the ship, putting it adrift and at the risk of grounding itself (SVT, 2022).

Most often, on ships carrying refrigerated cargo, the electrical network is designed as unearthed power supply (IT - insulated terra), where there is no active conductor directly connected to the protective conductor (PE). This has the advantage that the first insulation fault will not lead to automatic tripping of the circuit breaker that protects the dedicated power supply line. In order to detect an insulation fault before a possible second fault at another location in the network (and thus cause a hazard situation) the insulation resistance between active conductors and earth (ship's hull) is continuously monitored with an insulation monitoring device. If the monitored insulation drops below a pre-set value an alarm is activated. The schematic in Figure 1 shows an example insulation monitoring device that monitors the insulation resistance for a single-phase AC system. Hardware and design specific to the solution is discussed in 5.2.2.

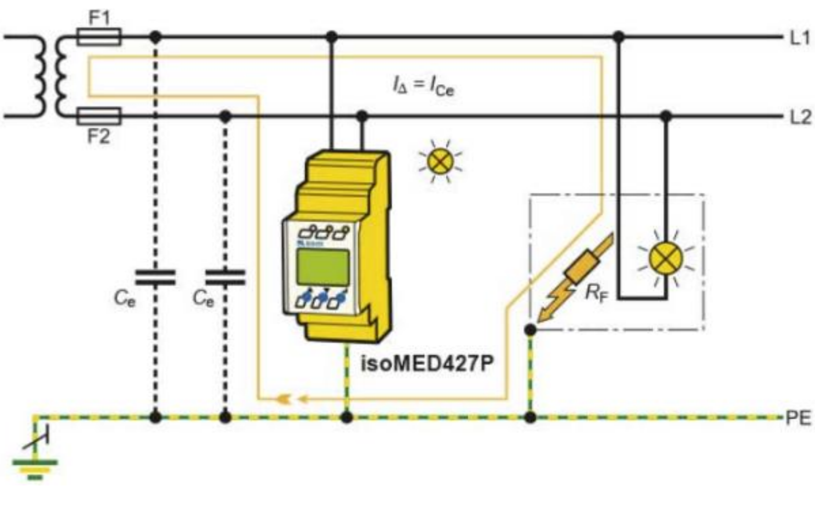

Figure 1 Example schematic of insulation monitoring for a single-phase AC system

Usually, earth faults of the electrical system are monitored and detected only for the complete electrical distribution as a single unit. In this way exact fault source cannot be located in a short period of time nor during ongoing operation. Additionally, the crew will very often ignore the earth fault alarm as it is not critical for the ship's operation in an IT electrical system (vastly used on ship's low voltage networks). In such cases we have an ongoing hazard in the cargo space without the crew really being aware nor reacting on it.

The IMO Guideline Circ. 1615 is asking that the electrical system should detect detrimental loads or earth faults so that the affected socket can be isolated. Today in vast majority of the ships this is achieved by installing a residual current circuit breaker in each socket output and a global earth fault detection system described above. This circuit breaker will protect the supply line from severe electrical faults (exp. short circuit or higher overload) but smaller deviations from normal operations will pass undetected and thus still present a possible fire hazard. Earth faults will be detected and alarmed, but amending the fault is very time consuming for the crew, as earth faults are hard to locate without the insulation faults locating system, plus they are not representing critical situation for the ship so are very often left to be dealt with later, which again represents a possible fire hazard.

As a compliment to the insulation measuring unit, insulation fault locators can be used on board. These are capable of localising insulation faults automatically and precisely within a short time and even small deterioration can be detected at an early stage and reported to the crew. In case of further deterioration of the insulation the supply can be disconnected before critical currents are reached. In this way the fault can be isolated before the hazard situation is reached which is not the case with circuit breakers as they can react only on real fault currents. The disadvantage of this system is that it requires a current measuring device - current transformer, for each socket outlet. An additional electronic device to read the measured currents from the current transformer is needed for approximately every twelve current transformers. This additional equipment should be installed in the distribution box of the sockets outlets as so will contribute to the size of the box which is generally located in the cargo area. Additional equipment and software also represent a noticeable additional cost per each socket outlet.

Electrical faults leading to possible fires in reefer units can be broadly classified as faults within the reefer units and faults in the connection between the reefer unit and the ship's electrical network.

4.1.1 Electrical faults within reefers

Electrical faults in reefer units refer to problems or malfunctions that occur within the electrical systems of these units. Electrical faults may occur due to damaged or frayed wiring, loose connections, or faulty components within the reefer unit's electrical system. These issues can result in intermittent power supply, temperature fluctuations, or complete failure of the unit. For instance, the compressor is a critical component of the refrigeration system in reefer units and electrical faults in the compressor can lead to improper cooling, increased power consumption, or even compressor failure. Electrical leakage due to compromised insulation and safety occurs when there is an unintended flow of current to unintended paths. This can also lead to energy wastage, increased power consumption, and potential safety hazards. In extreme failures, drastic conditions like arcing and localized heating can be observed.

4.1.2 Electrical faults between reefer and ship's grid

Electrical faults between a reefer unit and a ship's grid can occur due to several factors. Electrical faults can arise from the plugs and sockets used to connect the reefer unit to the ship's electrical grid. Over time, wear and tear on these components can lead to lose connections or damaged contacts. Loose plugs or sockets can cause intermittent power supply or arcing, which can result in electrical faults and potential hazards. During the handling and movement of reefer units on the ship, there is a risk of mechanical abuse. Rough handling, impacts, or mishandling of the units can cause damage to the electrical connections or internal wiring, leading to electrical faults. Proper training of crew members involved in handling reefer units and the use of appropriate operating procedures can help minimize the risk of mechanical damage. Ships operating in marine environments are exposed to saltwater, which can lead to the deposition of salt on electrical contacts and connections. Salt deposits can create a conductive path, causing leakage currents, short circuits, or corrosion of electrical components. Regular cleaning and maintenance of electrical connections are essential to prevent the accumulation of salt deposits and ensure the integrity of the electrical system.

4.2 Electric vehicles

Unlike in the case of reefer units, it is mandated for electric vehicles and charging units to be connected over a grounded network. This implies that the first insulation fault in the load will immediately result in a protective device, like a circuit breaker, disconnecting the load from the supply. From a safety perspective, grounded systems are safer as monitoring and taking corrective actions are easier and often times faster. While this is true, the batteries that power the electric vehicles are still on a floating ground system inside the car. This demands a similar insulation monitoring but on a smaller scale as in the case of the reefer units. However, this part of insulation monitoring is a part of the safety system within the car and is not accessible for external monitoring systems.

Charging of an electric vehicle can be conducted over several standard modes. Modes one and two can be deemed irrelevant as they deal with slow AC charging that draws power from a standard wall socket. The safety requirements for these two modes are relatively simple and can only be used for private use by electric vehicle owners. Mode 3, while still dealing with AC charging, allows charging at higher powers and has more safety requirements. Mode 3 requires A dedicated power socket incorporating charge monitoring and a dedicated cable. Mode 4 deals with fast charging via direct current. Since fast charging associates to higher costs and higher requirements for infrastructure, together with the lack of the need to fast charge electric vehicles on board, it be deemed irrelevant. This leaves only mode 3 as an option for charging electric vehicles on board a ro-ro vessel.

5 Developed solution

To significantly minimize the risk of accidents due to electrical faults, it is crucial to monitor relevant electrical parameters in real time and facilitate better recognition of faults. In lieu of this, a central monitoring system is developed that gathers relevant data from various sensors connected to different loads and processes the data to determine if there is an anomaly in the system. The system is designed to identify the specific kind of electrical fault and also to identify the particular load unit in which the fault occurs. The solution also allows for remote disconnection of the identified load unit if need be.

The relevant electrical parameters that need real time measurements and monitoring, common to reefer units and EVs, are instantaneous power consumed, individual phase voltages and currents, and system frequency. In addition to these, reefer units need constant insulation monitoring as they are on an ungrounded system and hence insulation measurement units with fault locators are used.

5.1 Schematic

On board, from the output of the isolation transformers, multiple lines are tapped to feed reefer units on the cargo deck. These lines first enter a cabinet space where they go through individual breaker units which are capable of being tripped remotely. The line is then drawn out of the cabinet space and pulled into the cargo deck where it feeds individual reefer sockets via a manual breaker that is accessible to personnel on deck. Within the cabinet space, all three phases of each line, after passing through the breaker, passes through an insulation fault location current transformer. For the current and voltage sensing, the individual phases then pass through three separate current transformers that are connected to the energy metres. A simplified version of the power and signal lines of the entire solution is as shown Figure 2. A more detailed electrical line diagram is attached as 11.1ANNEX A.

The above description implies that the energy meters that measure instantaneous power, voltage and currents are placed in series with every load connection. These meters measure parameters specific to individual loads and transmit them to the computer via RS485 serial communication protocol. The on-board computer used is a TLSense J4125v3 router. With 4GB of RAM and Intel Celeron J4125 quad core 2.7 GHz CPU, this router has adequate computing capacity to handle data from these sensors. The router also has five 2.5Gbit LAN ports, and four USB 3.0 ports and hence supports all communication protocols needed to communicate with the selected sensors.

Specifics of the energy metres and insulation monitoring unit, along with the insulation fault locator, are discussed in the next section.

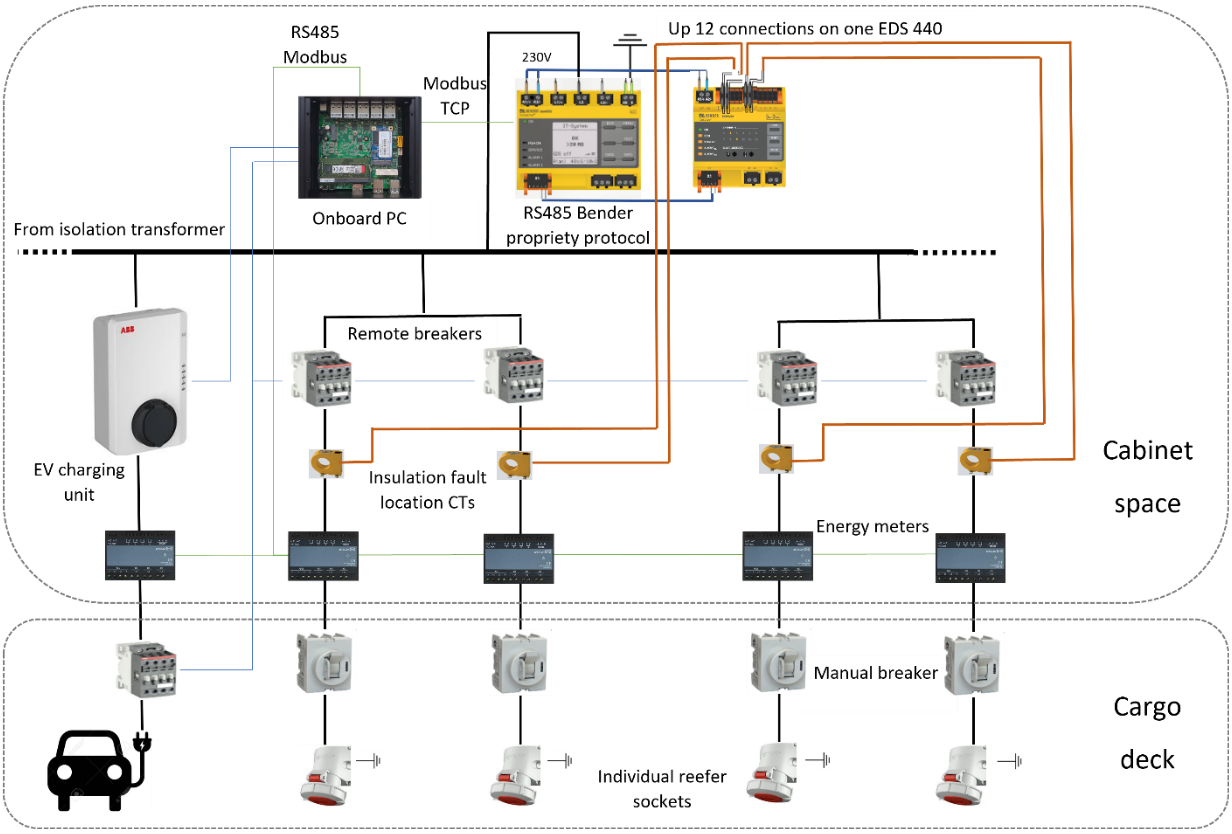

Figure 2 Schematics of the monitoring system

5.2 Measurements

5.2.1 Energy meter

DEIF's MTR-4-015 transducer, shown in Figure 3, in combination with ASR 21.5 current transformer is chosen as the energy meter to measure instantaneous power, voltages, currents, et cetera. With RS485 as its mode of communication, multiple units can be easily connected in series with a 2-wire system. The energy meter is rigged in a three-phase 4-wire configuration as the output of the distribution transformer to the reefer connections are in a delta configuration. Each phase cable has a current transformer.

Figure 3 DEIF MTR-4-015 transducer

The on-board computer has no serial port to support a physical connection for a 2-wire RS485 device and hence a standard serial to USB converter, UPort-1150 by Moxa, Figure 4, is used as an interface between the two.

Figure 4 Moxa UPort-1150

5.2.2 Insulation measurement and fault location

Bender’s ISO685-D-P is used as the insulation monitoring device. This unit monitors the ground fault by constantly measuring the insulation resistance and relaying it to the computer. It is complemented by the EDS440 which is an insulation fault locator. These are as shown in Figure 5.

When an insulation monitoring device detects an insulation fault, it initiates a fault location process. In IT systems, a residual current flows during the first insulation fault, primarily determined by the system's leakage capacitances. The fault location process involves briefly closing the fault current circuit with a defined resistance to generate a locating current that contains an identifiable signal. The locating current is generated at regular intervals by the locating current injector, the ISO685-D-P unit, limited in amplitude and time, and alternately connects the system conductors to the earth through the defined resistance. The resulting locating current depends on the insulation fault's size and the system voltage, and it is limited based on specific settings. Since reefers are not sensitive or critical loads (unlike say IT systems in hospitals powering life supporting equipment), locating current does not cause harmful reactions in any part of the system. The locating current flows from ISO685-D-P through the live lines to the insulation fault position, passing through the fault and the protective earth (PE) before returning to the locating current injector. The measuring current transformer on the insulation fault path detects this locating current pulse and signals it to the connected insulation fault locator.

Figure 5 Bender EDS440 and ISO685

For operational installation on board, it is necessary for all components to be wheel marked and type certified, which in the case of this demonstrator, is not necessary. For instance, the DEIF MTR-4 comes with a type approval certificate while the Moxa UPort does not. While this report aims at discussing the technical approach and the results achieved, all components considered for the cost analysis, which is discussed in chapter 6, are certified for marine use.

5.3 Software and algorithm

The necessity for customized software on the computer tasked with collecting data from different yet distinct sensors stems from the intricate nature of sensor communication protocols and the need to transform raw data into actionable insights. Each sensor employs a unique communication protocol, in this case RS495 and TCP/IP, potentially resulting in data incompatibility. A dedicated software acts as an intermediary, bridging the communication gap between these sensors and the computer. By incorporating protocols translation, the software ensures that the computer can seamlessly comprehend and process data from all sensors, regardless of their dissimilarities. This harmonization of data from diverse sources simplifies subsequent processing and analysis, resulting in a cohesive and effective data-driven decision-making process.

Moreover, the role of the software extends beyond data integration. It encompasses data processing, transforming raw sensor readings into meaningful information. For instance, data acquired from the Bender ISO685 is in a 16-bit hexadecimal form, and for any meaningful interpretation, it needs to be converted as a signed, base 10, integer. Based on the processed data, the software can then trigger automated actions or alerts tailored to predefined thresholds. This automation reduces the human intervention required for real-time monitoring and management, enhancing operational efficiency. In essence, the software acts as an intelligent intermediary that not only unifies sensor data but also enhances its utility by enabling informed actions based on sophisticated data processing and analysis.

The program is a script written in Python and is designed to request and acquire raw data from sensors, transform the data to a uniform computable format, compare them to preset values, compute deviations if any and finally output relevant information and actions. The process flow of the program is visualised as a flowchart in Figure 6.

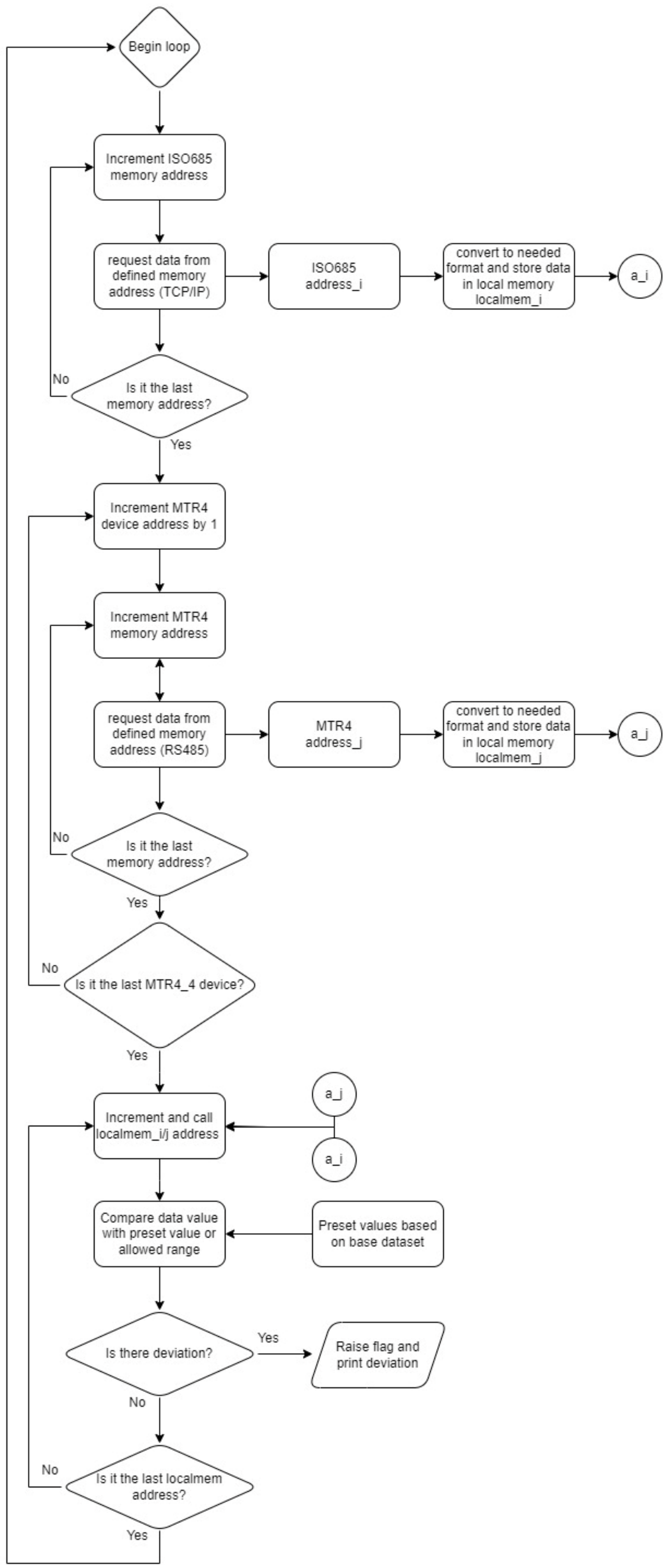

Figure 6 Flowchart illustrating the process of monitoring electrical parameters

The algorithm is design to run in a loop starting with requesting data and ending with raising flags, if any. The specific addresses in each sensor unit which stores data that is of interest is known from the data sheet of that particular sensor. A list of these addresses can hence be mapped to the list of parameters that need to be read and analysed. This data acquisition is done in an order that starts from the first address in the first sensor and increments until that last address is reached. The sensor number is then incremented, and the acquisition starts from the first address of the second sensor until the last is reached. Once all sensors of on type is covered, the sensor type is changed, and the data acquisition continues until all addresses from all sensors are covered. Each of these read data is converted to a desired format and saved locally for future analysis. Once the data acquisition is complete, each of these converted parameters are compared to corresponding reference values that are preset based on a base data set. If at any point in this section of the algorithm a deviation beyond allowed limits is noted, a flag is raised that specifies the parameter, the measured value, the deviation and the load unit in which this deviation has been measured. The process continues to compare the remaining parameters and other flags are raised as necessary. Once all locally saved parameters are compared to their corresponding preset values, the loop repeats by acquiring newly measured data from the first address of the first sensor. This goes on as long as it is not manually stopped.

While this approach certainly performs as intended, it is not the most effective in terms of the delay between acquiring a measurement and finding it to be an anomaly if it is one. To understand this better, a single sensor with *n* parameters can be considered. If the 2^{nd} measurement is the one reflecting a fault, it will be *n-2* more data acquisition processes and 2 data comparison processes before the fault can be identified as one. In effect, if each acquisition and each comparison is considered as one process each, there will be *n* processes before any faulty measurement can be identified as a fault. In this demonstrator it does not make much of a difference as there are only 7 sensors in all and hence it is 7 processes before a fault can be identified. Although the time for each process can be programmed to happen in milliseconds, if there are 100s of reefer units, the delay can be a few seconds. A simple fix can be to not have the overall loop divided into first the acquisition half and then the comparison half but to rather acquire from on memory address, compare it, raise a flag if necessary, and then move on to the next acquisition. While the delay between measuring and evaluating a measurement is minimal, the time between measurements itself is increased in this approach.

Advanced algorithms can be developed in the future where the previously measured parameters from one particular address can be extrapolated to estimate the future value until it is actually measured. This approach essentially blurs the digital nature of the current approach and opens the possibility of “predicting” a fault based on the previous values. However, a much larger and diverse base dataset is needed to model such algorithms and the effectiveness has to be experimentally evaluated.

6 Cost effectiveness of solution

As with any cost effectiveness evaluation, a comparison of costs of the solution is to be made with intended benefits to deem the solution financially viable or not. In the case of a predominantly hardware solution such as this, the costs can be estimated easily and effectively. The costs of the components, their service costs over their lifetimes, their end-of-life values, installation costs and maintenance costs along with the software development costs make up the overall cost of the solution. However, defining and quantifying the benefits are not as straightforward.

With safety being the primary intention of installing such a system, it is key to categorize the specific scenarios where the solution has an impact. In LASHFIRE, different nodes have been defined to aid in developing a risk model and conducting appropriate cost effectiveness analysis. The risk model is detailed in the deliverable report "D04.4 Holistic risk model" (De Carvalho, Lewandowski, & Cassez, 2022) and the development of these nodes are detailed in the deliverable report "D04.5 Development of holistic risk model report" (Lewandowski, De Carvalho, & Cassez, 2022). Of the different nodes, ignition, late decision and failure of extinguishment are three nodes that are affected by this solution and a detailed analysis of this is detailed in chapter 6.4 of deliverable report "D04.6 Cost-effectiveness assessment report" (Radolovic, 2023).

With the impact of the solution precisely defined, cost effectiveness can then be determined for different scenarios, such as for existing ships or new builds on ro-ro cargo ships or ro-ro passenger ships.

In effect, as shown in Table 1, this solution is found cost effective for ro-ro passenger vessels for both existing ships and new builds. However, it is not found cost effective for ro-ro cargo ships. This is due to the fact that a lot lesser lives are on board ro-ro cargo ships as compared to ro-ro passenger ships and hence the "effect on safety of life" is reduced. Details of this evaluation including total costs and effect on different nodes is presented in deliverable reports "D04.6 Cost-effectiveness assessment report" (De Carvalho & Lewandowski, Cost-effectiveness assessment report, 2023) and “D04.7 Cost-effectiveness assessment report: Uncertainty and sensitivity analysis report” (De Carvalho & Lewandowski, Cost-effectiveness assessment report: Uncertainty and sensitivity analysis report, 2023). Deliverable report “D05.7 Ship integration cost and environmental assessment” also details the costs of integrating the solution on to new builds and existing ships.

	New build	Existing
Ro-ro passenger	Cost effective	Cost effective
Ro-ro cargo	Not cost effective	Not cost effective

Table 1 Summary of cost effectiveness of the solution

7 Validation of solution

7.1 Demonstrator

To demonstrate the solution, a test bed was set up on Stena Scandinavica. This test bed involved monitoring of five individual reefer sockets out of the 90 available on board. The set up included all aspects of the solution, and all mentioned parameters were monitored. Figure 7 shows the cabinet with the installed solution. While the reefers are parked on deck 3, the monitoring system and the breaker cabinet is situated on deck 4.

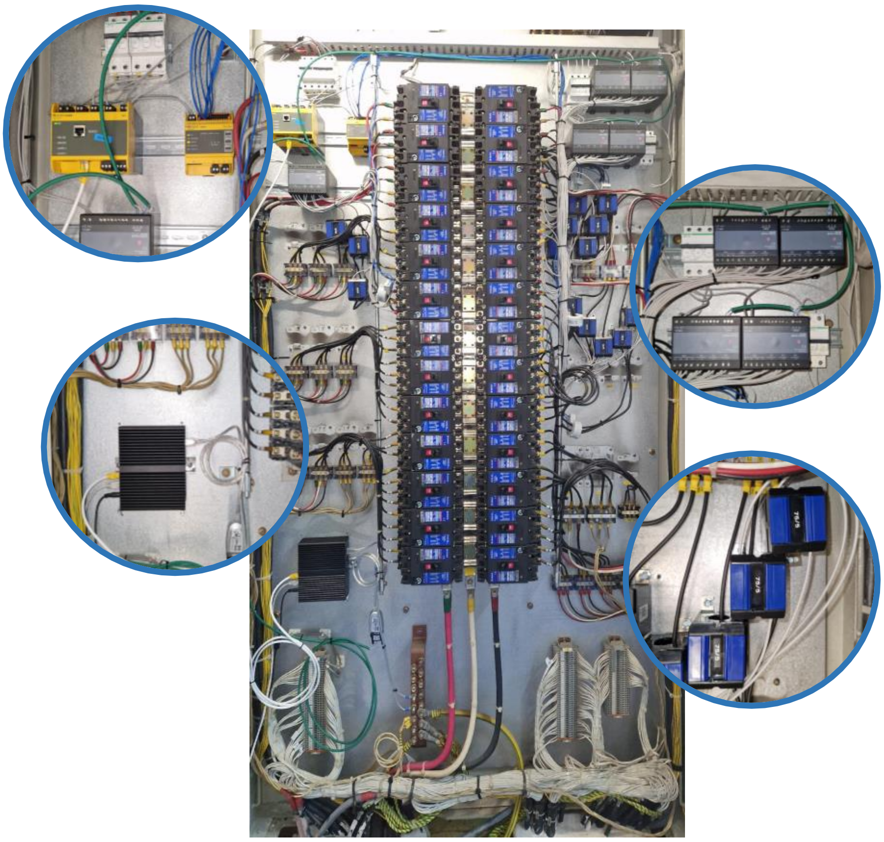

Figure 7 Cabinet with installation of the monitoring solution. Inset, clockwise from the top: Insulation measurement unit and fault locator, energy meters, current transformers for the energy meters, central computer for data acquisition and processing

First, Individual socket lines from deck 3 that connect to their respective breakers were traced to this cabinet. Energy metres, the insulation measurement unit and fault locators were then installed for the five specific connections. The central computer to acquire and process data from these sensors was also installed in the same cabinet.

Initially, all the physical electrical connections were made, and the sensors were rightly configured. It was ensured that relevant data was being measured and stored conveniently. For the energy metre, the individual phase voltages of each socket, the individual frequencies, currents through individual phases, overall power consumption and the face differences were primary parameters that were checked for and configured. Proper communication between the energy metres and with the on-board computer was ensured via serial communication protocol RS485. For the insulation monitoring part of the solution, firstly proper communication between the insulation fault locator and the insulation monitoring unit was ensured. Then, communication via TCP/IP was configured with the onboard computer.

The algorithm that collects and processes the data from the sensors was then tested. This was done by first collecting live data from connected reefer units on multiple voyages. With this data, trends and expected values for the measured parameters were obtained. This gave the acceptable values and limits off the electrical parameters during normal operation of these reefer units. Based on this, the algorithm was tuned to recognise an anomaly when any of these parameters were measured to be out of bounds.

A key challenge was to safely test the overall solution. The solution was not tested in lab as originally intended due to extreme delays in procuring all needed hardware. The delays were due to Covid-19 first and then the global silicon shortage. Destructive testing on board was certainly not possible and this ruled out deliberately creating short circuits or insulation faults in the reefer units during voyage. Since the solution had also not been benched onshore, even mild stress tests were deemed unsafe to test on board. With these restrictions, two methods of still being able to test abnormal conditions for identified.

The first was to reduce the window of acceptable deviation in the measured parameters. This meant that the solution would be tuned to be extremely conservative and hence consider the slightest of deviations to be a fault. For instance, practically under normal operating conditions, a phase voltage between 240V and 245V was found to be acceptable. However, to test with this method of reducing the window of acceptable deviation, the limits in the algorithm for normal operation was set as any voltage between 243V and 243.5V. Every time the measured value was out of bounds of this defined window, the system recognised it as a phase voltage fault.

The second was to induce faults via software. The actual measured values were masked by made-up values which were synonymous to an electrical fault in the system. This method was particularly useful in testing the system against parameters like frequencies which usually don't fluctuate much during normal operation. The same is also true for insulation faults.

Once both methods had been used to verify detection of deviation among all measured parameters, the algorithm was tested against a simulation with random faults in random refers among the five connections.

7.2 results

Both methods discussed in the previous section were used to test the final solution. Initially, with normally operating functional reefers connected to the sockets on the cargo deck, measurements were made. Figure 8 shows alarm status for phase voltages and power measurement made on one of these 5 units. The limits for determining under voltages in all three phases were set to 245V as in practice the voltages are usually between 248V and 250V. Since the reefer was operating normally, no alarms are raised as seen from the screen grab of the energy metre interface.

Measurements

Alarm group 1	State	Events
1: U1 < 245,0 V	Off	0
2: U2 < 245,0 V	Off	1
3: U3 < 245,0 V	Off	0
4: P > 4,500 kW	Off	0
5: -		
6: -		
7: -		
8: -		

Figure 8 Normal operation. No deviations.

For the same reefer unit, one of the undervoltage limits on one phase, phase three, was deliberately changed to 265V instead of 245V. Although the reefer operates normally, the system now recognises the measured voltage as a fault as it is below the reference value set. This was done to demonstrate that the system can recognise the measured value and determine that it is faulty compared to its set reference. This was also done with all other reefers operating normally to demonstrate that simultaneous measurements of multiple reefers will still result in identifying and isolating a particular fault in a particular reefer unit.

Measurements

Alarm group 1	State	Events
1: U1 < 245,0 V	Off	0
2: U2 < 245,0 V	Off	0
3: U3 < 265,0 V	Alarm On	1
4: P > 4,500 kW	Off	0
5: -		
6: -		
7: -		
8: -		

Figure 9 Undervoltage alarm raised for one of the phases.

Similarly, an alarm for power consumption beyond expected level is detected as shown in Figure 10. This one of the crucial parameters as faults such as short circuits in the reefer electronics, in the sockets or in the cable results in a sharp increase in the consumed power.

Measurements

Alarm group 1	State	Events
1: U1 < 245,0 V	Off	0
2: U2 < 250,0 V	Off	0
3: U3 < 245,0 V	Off	0
4: P < 4,500 kW	Alarm On	1
5: -		
6: -		
7: -		
8: -		

Figure 10 Overpower consumption alarm raised for a reefer

The system not only recognises deviations from the normal and raises flags but provides necessary information to decision makers that help in deciding if the alarm can be ignored, kept an eye on or if it has to be acted upon immediately.

```
Undervoltage in phase 3 of reefer 2
Measured: 248.4 V
Deviation of: 16.6 V
-------------------------------------------
Power consumption error in reefer 4
Measured: 4794 W
Deviation of: 294 W
-------------------------------------------
```

Figure 11 Output information

Figure 12 shows live monitoring of insulation levels and shows that the system is healthy with a insulation resistance of more than 20 MΩ. Since this demonstrator only considered 5 reefer sockets, it was a lot less frequent to see an insulation fault or a dip as compared to other electrical faults. This also points towards the need for more testing and data collection on a greater number of sockets simultaneously.

Overview: iso685-S-P Alarm/meas.values

SYSTEM-1-0: iso685-S-P

Art. No.: B91067130 / Serial No.: 2205527187 / D440 V1.29 / D439 V1.27 / D456 V1.26

#		Alarm	Test	Channel description	Measured value
1	✓	--	--	R Insulation fault	> 20 MΩ
2	✓	--	--	R Insulation fault	> 20 MΩ

Figure 12 Live insulation monitoring showing well acceptable insulation resistance level of >20MΩ

These results show that the solution is capable of monitoring many key parameters of multiple load units simultaneously. With more measured data from operational reefer units on board, the best reference limits for all parameters can be better justified, which is missing in demonstration.

8 Conclusion

Main author of the chapter: Vasudev Ramachandra, RISE

With faulty reefers being a possible source of electrical related fires and EVs being a new field of service that is to be provided on board, it is imperative to monitor their electrical health in real and base safety actions such as detailed monitoring or remote disconnection on the real time data. The solution presented in this report has been practically demonstrated to identify faults, their magnitudes and the specific units in which the faults are occurring. It provides for a safe electrical infrastructure on board and reduces the chances of a fire due to an electrical fault. With the benefit of remote disconnection of individual faulty units, the solution also makes it a safer environment for crew woo would otherwise have to identify and disconnect faulty units manually on the deck. The solution also monitors an EV that is being charged and allows for its remote disconnection if need be.

The results presented are based on monitoring 5 reefer sockets/units. The next step would be to further this solution to monitor more units on multiple vessels. With a larger data set, the accuracy with which a fault is identified can be improved. An artificially intelligent model can also be developed to monitor the loads and reduce manual decision making.

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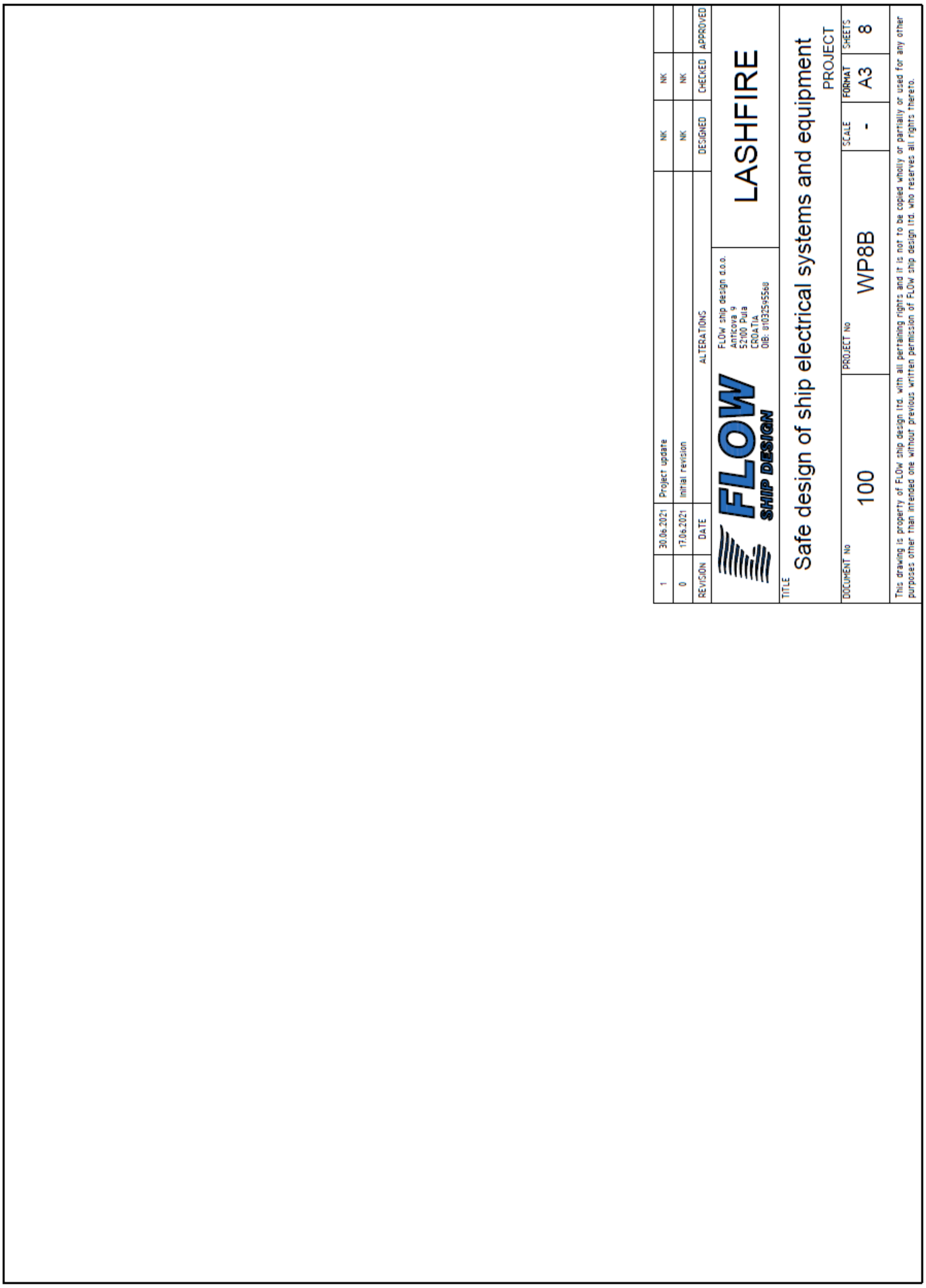
10 Indexes

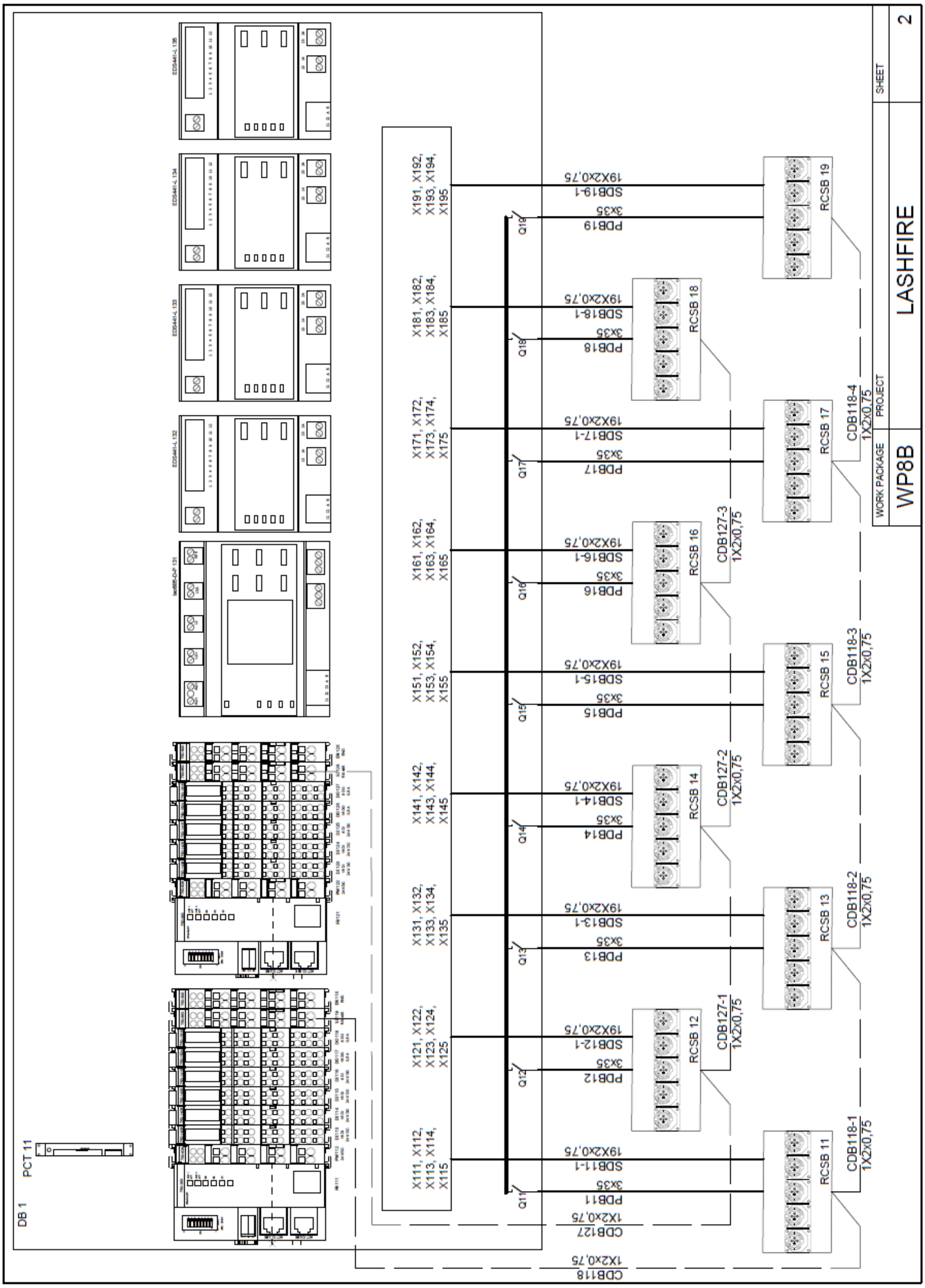
10.1 Index of figures

10.2 Index of tables

11 ANNEXES

11.1 ANNEX A: Detailed wire diagram of solution

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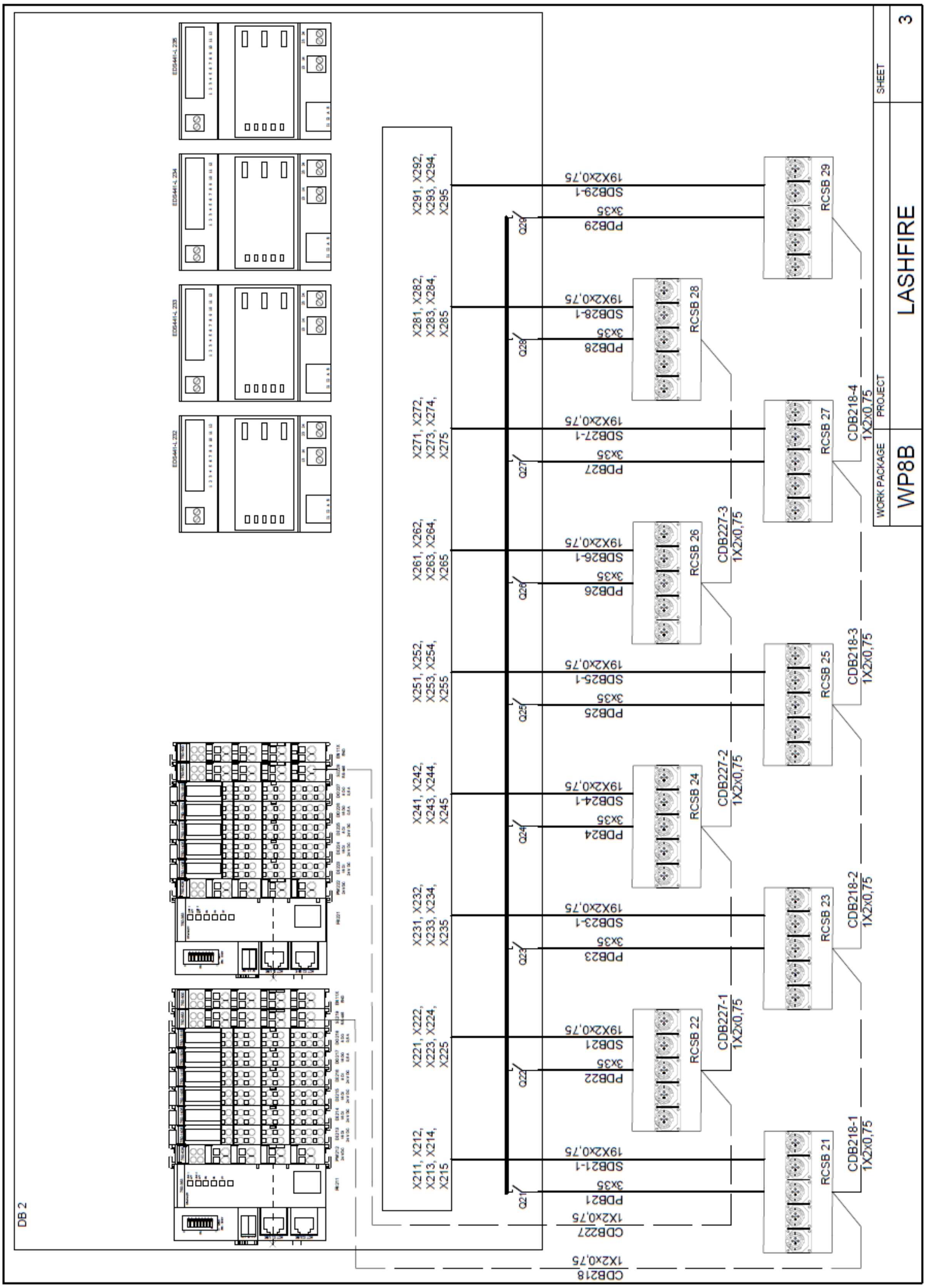
WP8B
PROJECT
LASHFIRE
SHEET
2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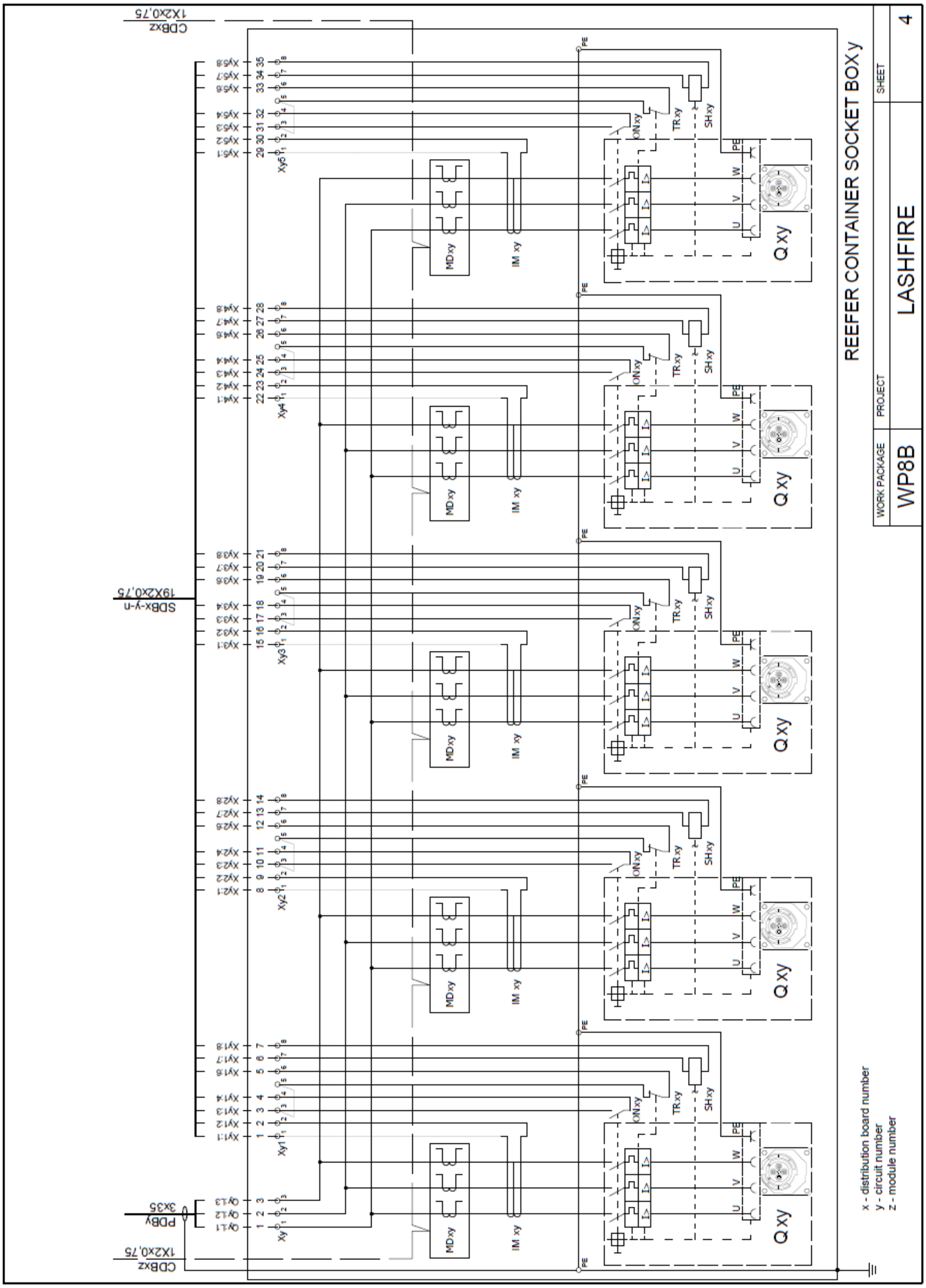
WP8B
PROJECT
LASHFIRE
SHEET
3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PROJECT
LASHFIRE
SHEET
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SDBx-y-n
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PDBy
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MDxy
IM xy
Q xy
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TRxy
SHxy
PE