REDUNDANT AND SUPERVISED SERIAL AND PARALLEL CONTACTS TO INCREASE RELIABILITY ON A VESSEL

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Abstract

One of the objectives of control systems in unattended engine rooms and especially in engine rooms of OMI type three vessels, that is, remotely controlled vessels without crew on board that are operated from land, is the detection and minimization of possible breakdowns and their consequences, since there is no crew to make repairs on board or they are not present in the engine room 24 hours a day.

For the correct operation of an electrical installation it is essential that the connections for electrical manoeuvres do not fail. These connections are those that control the auxiliary electrical generators and automation equipment. There are two main connections for electrical manoeuvres: connection of series contacts and connection of parallel contacts. In the engine room of a ship, we can find many series and parallel connection contacts. Some of them are important to guarantee the correct functioning of the different sections of the machine. Others are essential for critical equipment, such as the main or auxiliary electric motors. An adequate design of the electrical installation must minimize the risk of failure but must also allow early detection of problems and guarantee continuity of operation even if a failure occurs.

In this work, different types of contact connections in series and parallel are proposed with the objective of ensuring the correct operation at different levels of the electrical systems in the machine room, maintaining the service in case of failure and allowing early detection to avoid possible future problems. For each type of connection, series and parallel, three different configurations are presented, each one more reliable than the previous one, to be chosen depending on the requirements and criticality of the particular electrical system to be controlled. The main characteristics of each configuration are described, and a comparative study is carried out considering advantages, drawbacks, level of reliability, cost and types of systems where they can be applied.

1 INTRODUCTION

In industry in general and in shipbuilding in particular, the correct design of the electrical installation is important due to the need to electrify and control equipment and machinery. On the one hand, it is necessary to design the electricity generation facilities capable of supplying energy to the rest of the equipment (power circuits) and on the other hand, it is necessary to design control circuits in order to automatically control and monitor all the equipment of the installation (maneuver circuits). In both power and control installations, electrical contacts connected in series and/or parallel are used. These are effective connections, but not free of problems in case of failure.

Generally, in land applications, faults in electrical contacts can be resolved quickly and without much difficulty. It is possible to have specialized personnel capable of solving the problem and, if it is necessary to purchase spare parts or specific tools, they can also be obtained. In maritime applications, the correct functioning of electrical installations, and specifically essential equipment, is much more critical. In the event of a breakdown, it is the onboard personnel who are in charge of the repair, and it must also be taken into account that at sea there is no possibility of obtaining spare parts.

The appearance and development in recent years of unattended engine rooms and fully autonomous vessels has made the problem of electrical failures even more critical. In the case of the unattended engine room, it is also the onboard personnel in charge of solving electrical faults in the installation, but they are not permanently in the room 24 hours a day. In the event of a failure in the absence of personnel, a warning sounds in the cabin of the officer on duty notifying him so that he can solve the problem. In the case of the engine room of an autonomous ship (MASS, Maritime Autonomous Surface Ship), there are no personnel on board, so it is even more critical to avoid connection failures that could cause a plant failure (blackout) in essential electrical equipment.

Since it is very important to minimize the probability of failure due to electrical discontinuity in these contacts, the usual connections in land installations are not suitable since they do not provide sufficient reliability. In order to increase the reliability of electrical contacts there are different approaches. On the one hand, there is the issue of manufacturing resistant and reliable contacts (Gondres, 2018). Works in this area includes from the selection of materials (Zhou, 2012), (Zhang, 2024) to statistical aspects and test design to determine their useful life (Mroczkowski, 1988) (Maynard, 1988) (Karlsson 2004). On the other hand, various authors have studied how to improve reliability through monitoring techniques (McDonald, 2003), inspection (Lin, 2022) and development of maintenance plans (Martínez, 2013). Finally, there are works focused on the study of failures at the level of metal wear at the contact point of the contacts, taking into account parameters such as electrical amplitude or oscillation, to determine the contact failure (Wada, 2011).

In general terms, the use of redundant elements in the critical circuits of an installation is a common practice in the industry despite the higher cost of duplicating the different elements of the system.

In the present work, several configurations of normally open redundant series and parallel contacts are proposed for use in the engine room of a ship, with three different levels of reliability, to be chosen according to the criticality of the equipment to be powered. For each configuration the circuits are presented and their advantages and disadvantages are discussed.
The article is organized as follows: Section 2 presents Level 1, the lowest, consisting of applying simple redundancy to the contact. Section 3 describes the intermediate level, Level 2, which consists of applying redundancy not only to the contacts but to other elements of the circuit. Section 4 presents the highest level, Level 3 or high reliability level, which includes not only multiple redundancy but also an internal monitoring system to detect connection failures. In Section 5 a comparison and assessment of the 3 levels of reliability is made and the applications of each one are pointed. Finally, Section 6 presents the conclusions of the work.

2 SIMPLE REDUNDANCY (LEVEL 1 CONNECTION)

The level 1 connection is a connection with simple redundancy where only the electrical contact is redundant to compensate for a failure of said contact. The electrical and physical wiring diagram showing the connection of the parallel and series configurations is shown in Figures 1 and 2 respectively.

In the parallel configuration, the objective of the system is to electrically connect point A to point B by giving voltage to V1, closing all contacts in parallel at the same time. In the series configuration, the objective of the system is to electrically connect point A to point B by giving voltage to V1 and V2, closing the contacts independently.

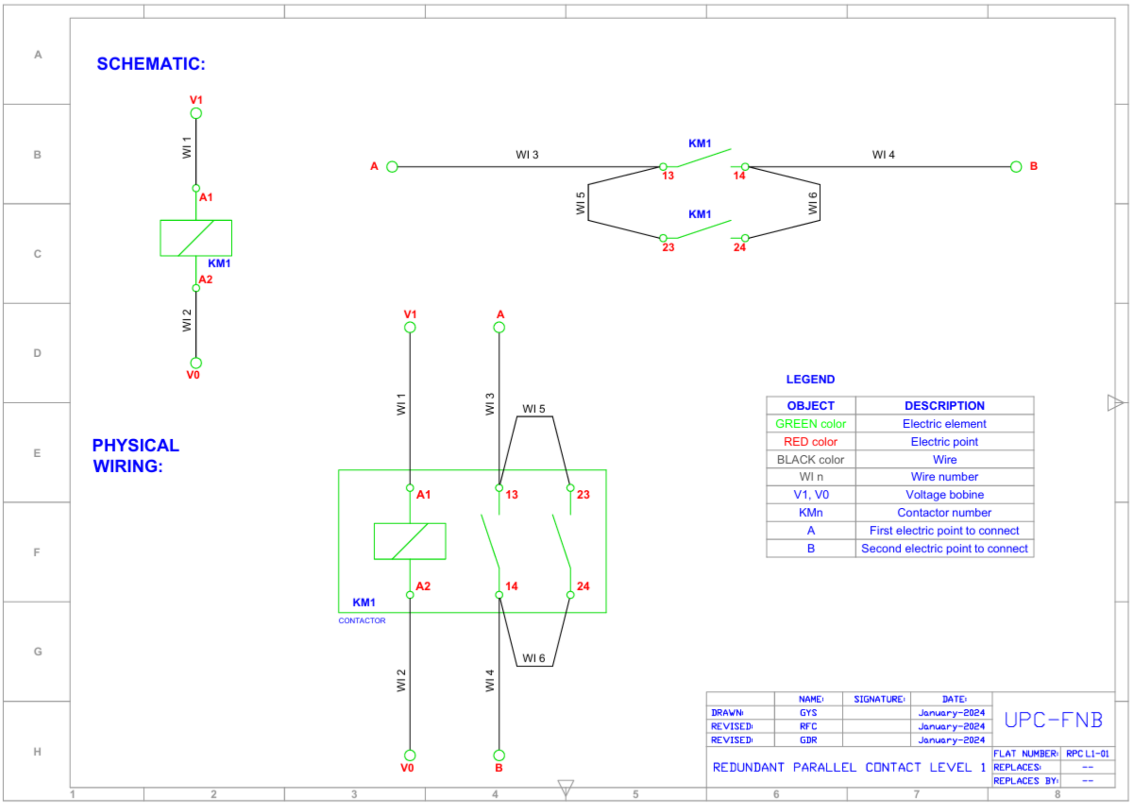

Figure 1. Level 1 parallel contact (simple redundancy)

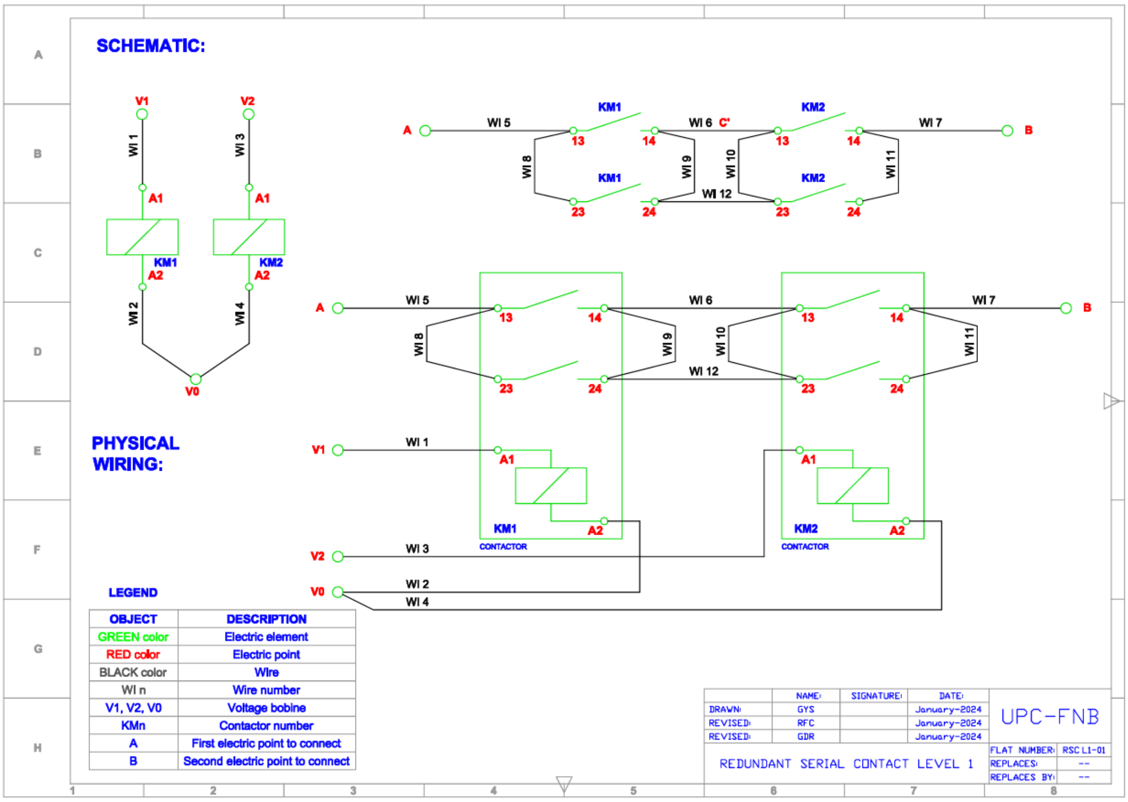

Figure 2. Level 1 serial contact (simple redundancy)

Figure 1 and Figure 2 show the case of two redundancy paths. In general, and for all three levels of reliability presented in this work, the number of redundant elements depends on the probability of failure and the severity of the consequences if it occurs. That is, if a connection acts more times in a period of time, or is located in a more corrosive environment, or if the occurrence of a failure can generate important consequences, the number of redundancies have to be increased to avoid total failure and to prevent electrical continuity from being interrupted.

Advantages: The advantage of this configuration is that if one contact fails, each of the others can do the work individually, therefore the connection continues to provide service. It is also a simple and economical configuration.

Drawbacks: The main drawback of the system is that if a non-redundant element fails, the connection stops providing service. On the other hand, the system does not detect if a contact failure occurs since the service continues to be provided through the redundant contacts.

Reliability: This connection has low reliability because not all elements are redundant. If the elements had double redundancy, this would have a reliability of 200% with respect to a single connection, or 300% in the case of triple redundancy. The level 1 connection shown in Figures 1 and 2, even having redundant contacts, has an overall reliability of 50% with respect to double redundancy, or 33% with respect to triple redundancy because it has non-redundant elements that can interrupt the continuity of the connection.

Cost: Regarding the cost of this connection, the redundant components are only the contacts (housed in the same contactor), while the non-redundant components are the connection elements, cables and drive coils, so the economic cost of this connection is low. In addition, it does not require other associated costs such as additional equipment, labor, additional space or more energy resources.

In summary, this configuration is suitable for low-importance connections where, if the connection fails, it will not affect the overall system service.

3 MULTIPLE REDUNDANCY (LEVEL 2 CONNECTION)

Level 2 connection is a configuration with redundancy of all elements of the system that may fail, including the relay coil, electrical contacts, cables, connections and any other additional element that may cause discontinuity of the connection. The electrical diagram and physical wiring showing the level 2 connection of the parallel and series configurations is shown in Figures 3 and 4 respectively. In the parallel configuration, as in level 1, the objective of the system is to electrically connect point A with point B by giving voltage to V1, closing all contacts in parallel at the same time. In the series configuration, the objective of the system is to electrically connect point A with point B by giving voltage to V1 and V2, closing the contacts independently.

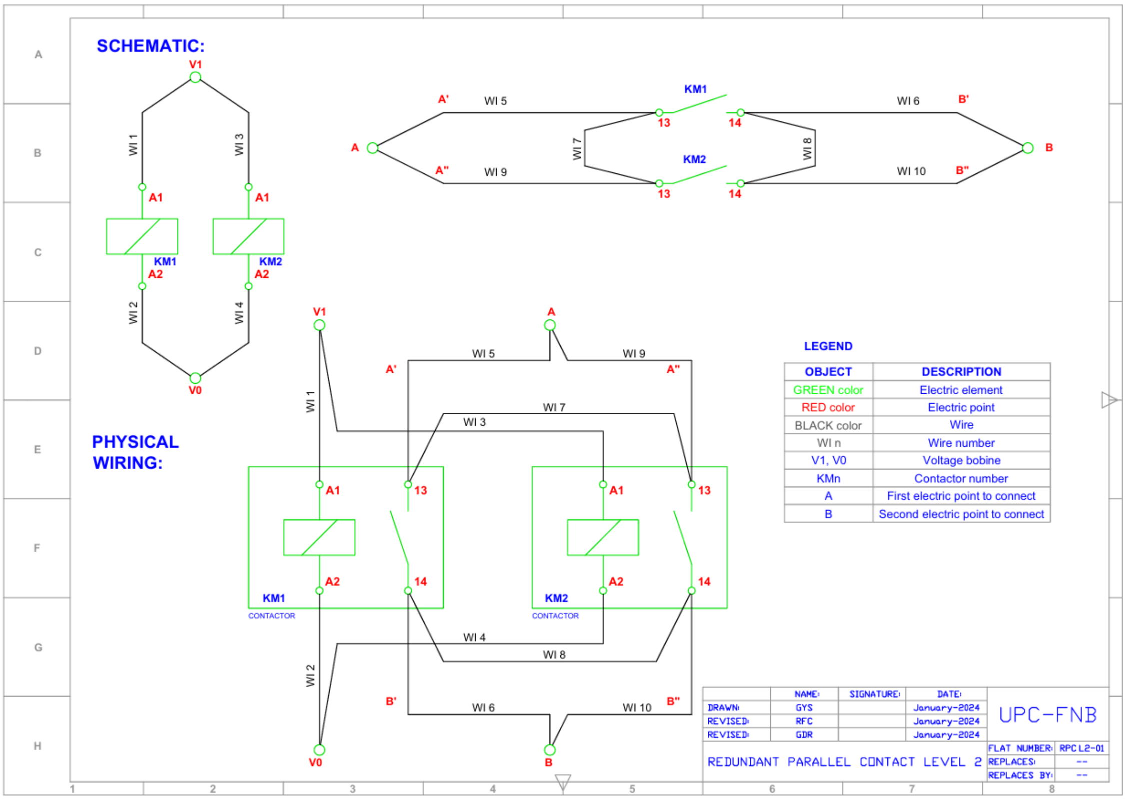

Figure 3. Level 2 parallel contact (multiple redundancy)

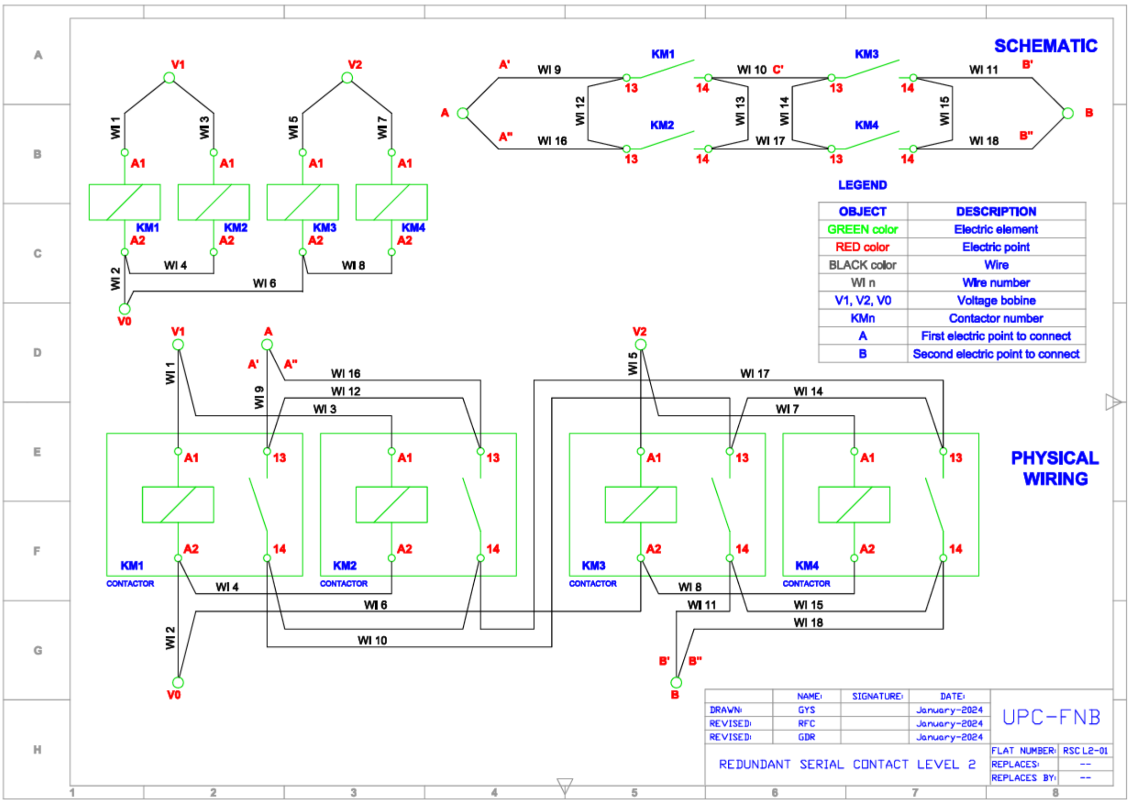

Figure 4. Level 2 serial contact (multiple redundancy)

Advantages: The advantage of the system is that if an element fails, the redundant ones can do the work individually, therefore the connection continues to provide service. Furthermore, it is a simple system. With few additional resources a level 1 connection can be adapted to level 2.

Drawbacks: The main drawback is that the system does not detect if a connection failure occurs in an element, since service continues to be provided through other redundant means.

Reliability: This connection presents good reliability because all the elements that can cause a connection to fail are redundant. The level 2 connection described has a reliability of 200% compared to a level 1 connection because all elements have double redundancy. It would be 300% in the case of triple redundancy of all elements, and so on.

Cost: Regarding the cost of this connection, the redundant components are all those that make up the connection: the contacts (housed in different contactors), connection elements, cables and drive coils, so the economic cost of this connection is half. Other associated costs come from the need to have more space, more labor, and more energy resources.

In summary, this configuration is suitable for very important connections where a connection failure would affect the overall system service.

4 MULTIPLE REDUNDANCY WITH SUPERVISION (LEVEL 3 CONNECTION)

Level 3 configuration is a connection with redundancy of all system elements that may fail, including the relay coil, electrical contacts, cables, connections and any additional elements that may cause discontinuity of the connection. The difference with level 2 is that it also has a supervision system capable of detecting internal connection failures by analyzing electrical continuity at various points in the system, thus determining if there is discontinuity in any of the redundant paths through a set of signals of control.

The electrical diagram and physical wiring showing the level 3 connection of the parallel and series configurations is shown in Figures 5 and 6 respectively. In the parallel configuration, as in levels 1 and 2, the objective of the system is to electrically connect point A to point B by giving voltage to V1, closing all contacts in parallel at the same time and monitoring internal connection failures. In the series configuration, the objective of the system is to electrically connect point A to point B by supplying voltage to V1 and V2, closing the contacts independently, and monitoring operation to detect internal connection failures.

Supervision system: The supervision system detects internal faults by measuring electrical consumption in Amperes (A) at different points. The first control point is the electrical consumption (A) of the contactor coils. When the coils are energized, they present electrical consumption, so if we detect this consumption it is concluded that the order is given and the coil is active. In the case of the elements that provide continuity, as they are voltage-free contacts, the connection is monitored by measuring the consumption of the connected electrical equipment.

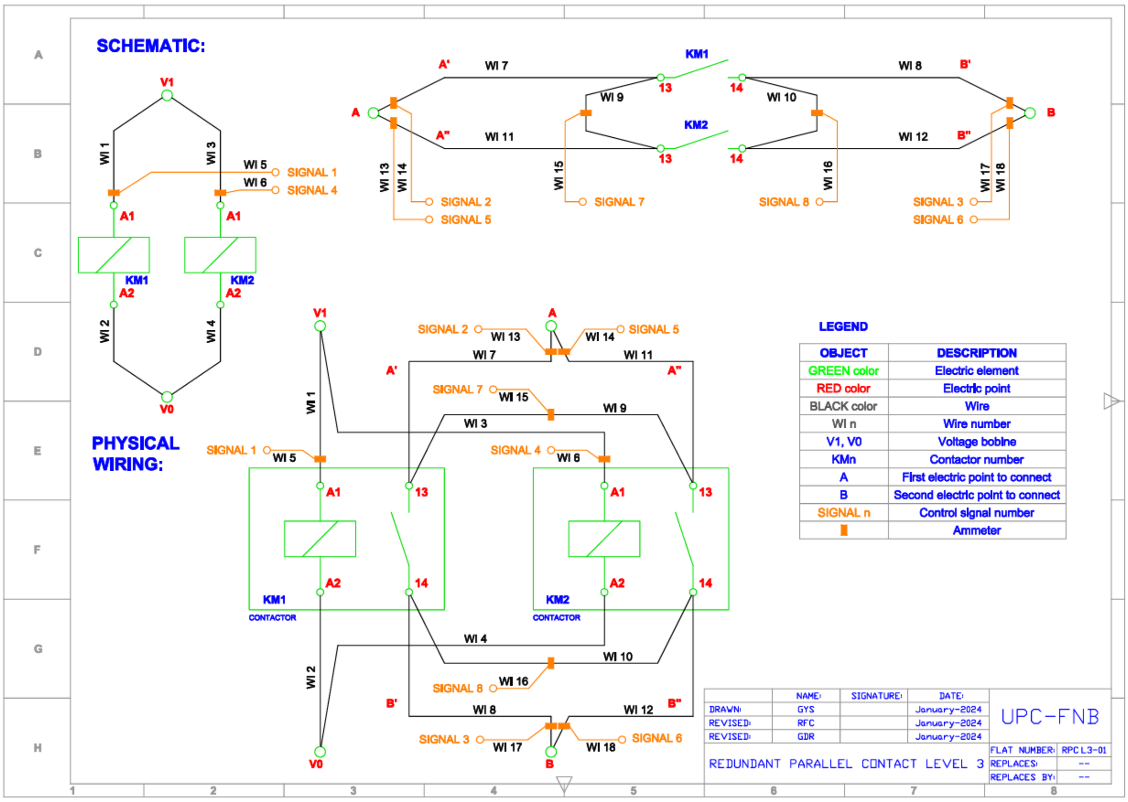

Figure 5. High reliability Level 3 parallel contact (multiple redundancy with supervision)

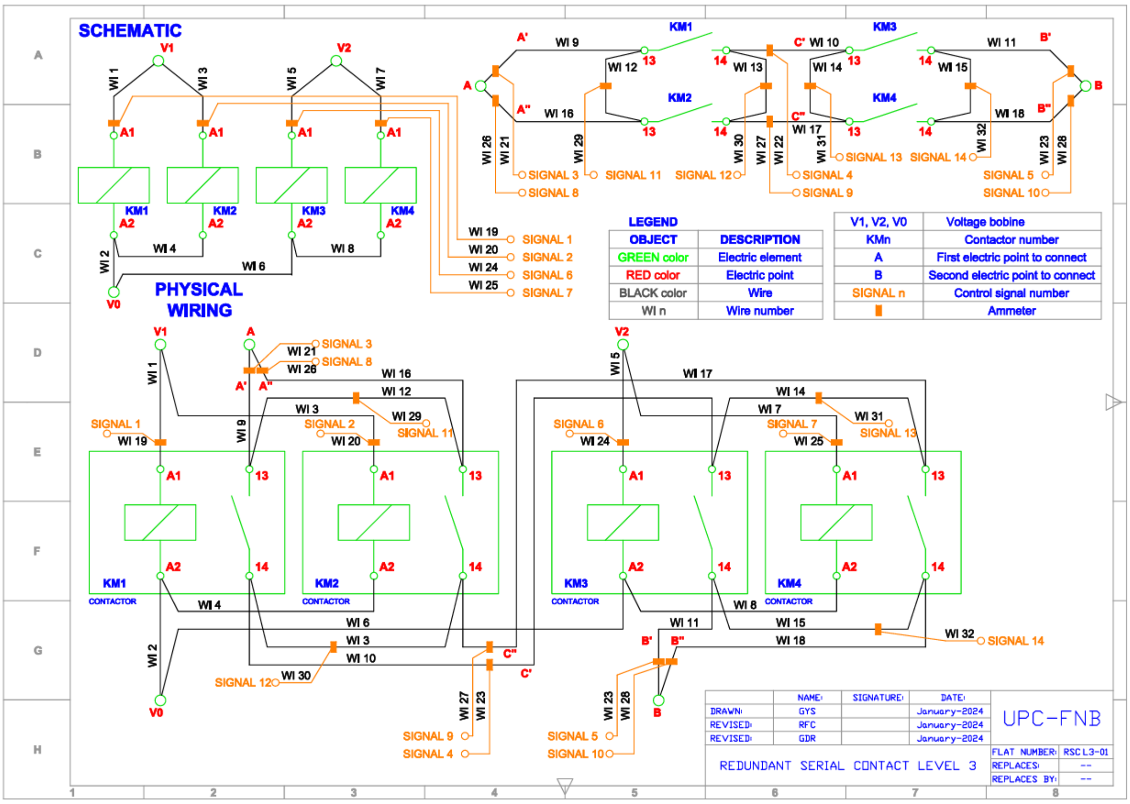

Figure 6. High reliability Level 3 serial contact (multiple redundancy with supervision)

The system is equipped with electricity consumption counters (A) at the input and output of each redundant path, in the connection bridges, and at the contacts inputs and outputs. When we have a connection by means of two redundant paths and we detect the same consumption at the input and output of each one, this indicates that the system is operating correctly and half of the total consumption passes through each path. In the case of triple redundancy without failure, a third of the consumption passes through each of the paths, and so on.

If these consumptions do not coincide, this indicates that there is a discontinuity in the section. In such a case, part of the consumption is derived through the bridges to another redundant path where it is detected with the ammeters.

To analyze consumption control signals, a reliable processor is required to acquire and interpret these readings. It can be the system's own general processor or a local processor installed in the contact itself that reports to the system's general processor.

Advantages: If a component fails, the redundant ones can do the work individually, and the connection continues providing service. In addition, the continuous monitoring system indicates the remaining reliability of the connection by giving information about the internal failures of the connection and allows making a prediction about service interruption.

Drawbacks: The main drawback is the increase in the cost due to the complexity of the installation and operation because to carry out the supervision, the control signals must be treated and analyzed.

Reliability: This connection has high reliability since all the elements that can cause a connection failure are redundant. The level 3 connection presented has a reliability of 200% compared to a level 1 connection because it has all the elements of double redundancy. It would be 300% in the case of triple redundancy of all elements, and so on.

Cost: The cost of this connection is high due to the monitoring system. As in level 2, the redundant components are all those that make up the connection: the contacts (housed in different contactors), connection elements, cables and drive coils. But the most significant cost increase comes from the required supervisory equipment in addition to the specialized equipment, labor required, and additional space.

In summary, this configuration is suitable for connecting essential services where the connection cannot fail. If the connection fails, the general service of the electrical equipment in the engine room would be directly affected, producing risk situations.

5 COMPARISON AND APPLICATION

Table 1 summarizes the number of components required for each configuration, the number of coils per voltage point, and the number of contacts per coils.

		DESCRIPTION		
CONNECTION TYPE	**LEVEL**	**INTERNAL REDUNDANCY**	**NUMBER OF COILS PER VOLTAGE POINT**	**NUMBER OF CONTACTS PER COIL**
PARALLEL	**1**	Electrical contact only	1	2 or more
PARALLEL	**2**	All the elements	2 or more	1
PARALLEL	**3**	All the elements	2 or more	1
SERIAL	**1**	Electrical contact only	1	2 or more
SERIAL	**2**	All the elements	2 or more	1
SERIAL	**3**	All the elements	2 or more	1

Table 1. Components for each configuration

Table 2 shows the main features of each configuration, including internal supervision, system complexity, effectiveness (ability to meet the design objective) and reliability.

		FUNCTIONALITY			
CONNECTION TYPE	**LEVEL**	**INTERNAL SUPERVISION**	**SYSTEM COMPLEXITY**	**EFFECTIVENESS**	**RELIABILITY**
PARALLEL	**1**	NO	LOW	HIGH	LOW
PARALLEL	**2**	NO	HALF	HIGH	HIGH
PARALLEL	**3**	YES	VERY HIGH	HIGH	VERY HIGH
SERIAL	**1**	NO	LOW	HIGH	LOW
SERIAL	**2**	NO	HALF	HIGH	HIGH
SERIAL	**3**	YES	VERY HIGH	HIGH	VERY HIGH

Table 2. Functionality for each configuration

5.1 COST ASSESSMENT

To determine the cost, it is necessary to take into account not only the direct acquisition costs of the equipment that compose each configuration but also the labor necessary for the installation, maintenance and treatment of the subsequent system and the space it occupies. Table 3 shows the costs associated to each configuration:

		COST				
CONNECTION TYPE	LEVEL	SYSTEM COST (€)	ADDITIONAL EQUIPMENT (units)	LABOR (h operator)	MAINTENANCE (h operator and €)	ADDITIONAL SPACE (m^3)
PARALLEL	1	LOW	NO	LITTLE	BIT	NO
PARALLEL	2	HALF	YES	LITTLE	BIT	LITTLE
PARALLEL	3	VERY HIGH	YES (many and complex)	A LOT	A LOT	A LOT
SERIAL	1	LOW	NO	LITTLE	BIT	NO
SERIAL	2	HALF	YES	LITTLE	BIT	LITTLE
SERIAL	3	VERY HIGH	YES (many and complex)	A LOT	A LOT	A LOT

Table 3. Cost comparison

Below, the number of necessary elements is detailed for each configuration assuming double redundancy, that is, two redundant paths. In the case of considering triple redundancy or higher, the number of devices must be multiplied by the corresponding factor.

LEVEL 1 PARALLEL: This connection only requires one relay or one contactor. As for the equipment, this configuration is made up of the contactor coil, the cables and connections that power it (non-redundant), the electrical contacts and the cables and connections (non-redundant) that connect them. Since there are few pieces of equipment and simple connections, few hours of assembly are needed, and it does not require too much maintenance or space for assembly.

LEVEL 2 PARALLEL: This configuration includes two relays or two contactors. This involves having two coils with separate cables and connections for each coil, one electrical contact per coil and independent cables and connections for each contact. This connection requires more equipment but maintains a simple connection, requiring only a few more hours for assembly than level 1. This configuration does not require much maintenance but does require doubling the assembly space. However, if the contactors have a small dimension, the additional space required will not be excessive.

LEVEL 3 PARALLEL: For the redundancy part this connection requires the same equipment as level 2: two contactors with two coils, one contact per coil, independent cables and connections. But it also needs the equipment to implement the supervision system, consisting of 8 current sensors, the processor for managing the signal readings and software capable of interpreting the failure situation. This configuration requires sophisticated equipment as well as complex wiring, requiring many more hours of assembly compared to previous levels. This configuration requires more maintenance and much more space for assembly, so indirect costs increase significantly from previous levels.

LEVEL 1 SERIES: This connection only requires one relay or contactor per voltage point to complete the assembly. At the equipment level, the configuration of two voltage points (V1 and V2) requires, for each voltage point: a contactor coil, the cables and connections that feed it (non-redundant), the electrical contacts of each coil and the cables and connections (non-redundant) that connect them. As it has little equipment and the connections are simple, few hours of assembly are needed, and it does not require too much maintenance or space for assembly.

LEVEL 2 SERIES: The configuration per voltage point (V1 and V2) includes two relays or two contactors. This involves having four coils with separate cables and connections for each coil, one electrical contact per coil, and separate cables and connections for each contact. This connection requires more equipment and increases the complexity of the assembly, but only requires a few hours more assembly than level 1. It also does not require much maintenance but doubles the required assembly space. However, considering that contactors take up little space, the space required will not be excessive.

LEVEL 3 SERIES: For the redundancy part, this requires the same equipment as level 2: two contactors with two coils, independent cables and connections, one contact per coil, and their independent cables and connections. But the supervision system must also be included. In this case, 14 current sensors, the signal reading management processor and software are needed to interpret a fault situation. This connection requires sophisticated equipment in addition to complex wiring, which is why many hours of assembly are required compared to previous levels. It also requires more maintenance and a lot of space for assembly, so indirect costs increase significantly from previous levels.

Thus, the economic cost of each connection depends on the level due to the number of relays and their characteristics. For the level 1 it is enough with a simple relay but for level 3 it is necessary a number of very expensive relays. Besides, all the components must be marine version. See Table 4.

5.2 APPLICATION IN AN ENGINE ROOM

Level 1 with simple redundancy is intended to connect, both in series and parallel, electrical points where it is not important that continuity fails, since in the event of a failure the operation is not totally affected. For example, in the lighting system, if the connection fails in an area, this results in less lux per m^2, but there is still ambient light. In this case, the ship's systems do not lose functionality as lighting is not an essential objective.

Level 2 with multiple redundancy in all elements is intended to connect important but non-critical electrical points in the engine room. For example, the supply through fluid pumps (water, fuel, oil...). These pumps are necessary for the operation of the system, but in the event of a connection failure, the redundant pumps are the ones that will work with their level 2 connection, maintaining the operation of the system.

Level 3 with multiple redundancy in all elements and a supervision system is intended to connect electrical equipment of vital importance for the operation of essential systems. If the connection fails, the operation of essential systems and therefore the integrity of the ship may be affected. For example, this is the case of the parallel connection of the electrical power auxiliaries (diesel auxiliaries, tail auxiliary, steam turbine and emergency auxiliary) where the connection must be ensured at the time of coupling and during operation. If this connection fails, a "blackout" could occur and all systems could be completely lost.

CONNECTION TYPE	LEVEL	ELEMENT	QUANTITY	UNIT	UNIT COST (€)	EQUIPMENT COST (€)	OBSERVATIONS
PARALLEL	1	2-contact relay	1	Units	29 €	29 €	Relay to connect non-essential low consumption installations
		Miscellaneous materials	1	Kit	50 €	50 €	Wires, connectors, terminals, etc., twenty meters away
		Labor construction	1	Hours	100 €	100 €	Includes labor, operator, plus necessary tools and equipment
		Maintenance (h/6 months)	1	Hours	100 €	100 €	Maintenance every 6 months
			TOTAL CONECTION			279 €	
PARALLEL	2	1 contact relay	2	Units	300 €	600 €	Relay for connecting essential medium-consumption equipment
		Miscellaneous materials	2	Kits	150 €	300 €	Wires, connectors, terminals, etc., twenty meters away
		Labor construction	2	Hours	100 €	200 €	Includes labor, operator, plus necessary tools and equipment
		Maintenance (h/6 months)	1	Hours	100 €	100 €	Maintenance every 6 months
			TOTAL CONECTION			1 200 €	
PARALLEL	3	1 contact relay	2	Units	12 000 €	24 000 €	Relay to connect essential, high-criticality, high-consumption equipment
		Current sensor	8	Units	30 €	240 €	
		System control	1	Units	2 000 €	2 000 €	Includes electronic control equipment (PC or PLC), software and hardware connection

	Miscellaneous materials	4	Kits	400 €	1 600 €	Wires, connectors, terminals, etc., twenty meters away
	Labor construction	8	Hours	100 €	800 €	Includes labor, operator, plus necessary tools and equipment
	Maintenance (h/6 months)	4	Hours	100 €	400 €	Maintenance every 6 months
		TOTAL CONECTION			**29 040 €**	

SERIAL 1	2 contact relay	2	Units	29 €	58 €	Relay to connect non-essential low consumption installations
	Miscellaneous materials	2	Kits	60 €	120 €	Wires, connectors, terminals, etc., twenty meters away
	Labor construction	1	Hours	100 €	100 €	Includes labor, operator, plus necessary tools and equipment
	Maintenance (h/6 months)	1	Hours	100 €	100 €	Maintenance every 6 months
		TOTAL CONECTION			**378 €**	

SERIAL 2	1 contact relay	4	Units	300 €	1 200 €	Relay for connecting essential medium-consumption equipment
	Miscellaneous materials	4	Kits	150 €	600 €	Wires, connectors, terminals, etc., twenty meters away
	Labor construction	2	Hours	100 €	200 €	Includes labor, operator, plus necessary tools and equipment
	Maintenance (h/6 months)	1	Hours	100 €	100 €	Maintenance every 6 months
		TOTAL CONECTION			**2 100 €**	

SERIAL 3	1 contact relay	4	Units	12 000 €	48 000 €	Relay to connect essential, high-criticality, high-consumption equipment
	Current sensor	14	Units	30 €	420 €	
	System control	1	Units	2 000 €	2 000 €	Includes electronic control equipment (PC or PLC), software and hardware connection
	Miscellaneous materials	8	Kits	400 €	3 200 €	Wires, connectors, terminals, etc., twenty meters away
	Labor construction	8	Hours	100 €	800 €	Includes labor, operator, plus necessary tools and equipment
	Maintenance (h/6 months)	4	Hours	100 €	400 €	Maintenance every 6 months
		TOTAL CONECTION			**54 820 €**	

Table 4. Economic cost of each configuration

Finally, another application of Level 3 is the activation of essential pumps (cooling pumps, fire pumps...) or the supply of energy for essential control and safety elements. The supervision system can help the land operator (if it is a fully autonomous vessel with remote human supervision from land) to decide how a level 3 contact should operate with an internal problem. Thus, in the case of various devices connected with level 3, if we detect in a connection an internal failure of a path while it continues to provide service (one path is damaged but the redundant ones are operational), the operator can decide to use other equipment and reserve faulty equipment as a last resort, while at level 1 or 2 we would not be able to detect said failure. For example, if there is an on-board auxiliary connected in parallel to the control panel and it is detected that this connection has an internal fault even though it is providing service, it can be decided to reserve this auxiliary and its connection as a last resort and prioritize the other auxiliaries so as not to force a premature failure in the connection of said auxiliary, or even decide to return to port if it is considered that the integrity of the ship may be endangered.

6 CONCLUSION

The systems of an autonomous ship must be built reliably and efficiently from the beginning. A common element to all systems and specifically in the generation of electrical energy are the electrical connections, which must be designed in a way that ensures their effectiveness and reliability. The importance of this requirement lies in the fact that since there is no personnel on board to act in the event of electrical failures, the operation of essential equipment must be ensured through the design of the installation itself.

In this work, three different configurations of series and parallel connections have been presented, with three levels of reliability to choose from according to the requirements of the system to be connected.

Level 1 connections are based on applying simple redundancy and are an economical option to slightly increase reliability. Level 2 connections are based on multiple redundancy and are a viable option to significantly increase reliability without excessively increasing costs or resources. Finally, level 3 connections, apart from multiple redundancy, include an electrical continuity monitoring system and are an option to connect essential elements vital for the integrity of the vessel, where absolute reliability is required, at the cost of high costs, resources and knowledge of the system.

The work has been illustrated for the case of normally open contacts but is also valid for the case of normally closed contacts, maintaining the same criteria of effectiveness and reliability.

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