CALCULATING THE RELIABILITY OF A ZERO-ENERGY STATE SYSTEM

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ABSTRACT

In Canada and other industrialized countries, workers who are required to carry out tasks in the hazardous zone of a machine when performing repairs, maintenance or unjamming activities must follow lockout procedures, unless safe alternative methods exist and can be applied. In Quebec the occupational health and safety regulation has been updated recently and several articles have been added on lockout procedures. That regulation allows for alternative control methods in addition to the traditional lockout/tagout, as long as the risk assessment deems the residual risk level to be acceptable. In Canada the CSA Z460 standard in the control of hazardous energies is viewed as a reference in the area. Lockout procedures have been extended to the construction sector for the control of hazardous energies as well. The lockout procedure consists of the following steps: stopping the equipment, isolating the energies, applying individual locks, dissipating residual energies, and verifying the absence of energies. Lockout procedures require lockout devices as well as training and audits. An important step in the lockout procedure is the verification step. Workers often neglect that step for various reasons. This article focuses on the use of dedicated safety electronic systems as an alternative to achieving a zero-energy state. These systems, rather than eliminating energy, control it to ensure workers' safety. They are characterized by their reliability and typically involve safeguards such as interlocking devices, safety scanners, light curtains, and other safety mechanisms, during operational tasks. The article also introduces a method for calculating the reliability of these zero-energy-state system, based on the ISO 13849 standard. This method aims to help businesses comply with both the local regulation and the CSA Z460 standard. It builds upon the work of Poisson et al. (2016) [1], who calculated a zero-energy-state system in scenarios involving complex energy return recuperation systems. This innovative approach could potentially replace the need for voltage testing or machine startups following a lockout procedure. This development is particularly relevant given the increased complexity of modern machinery and the challenges in ensuring that no other energy sources that could harm workers are present post-lockout. This approach could significantly change how businesses ensure worker safety and regulatory compliance.

1 INTRODUCTION

The various lockout/tagout standards, including the Canadian CSA Z460 standard, require validation after the implementation of the lockout/tagout procedure to ensure the absence of any hazardous energy on the equipment. In the case of electrical lockout/tagout, this validation can be done by measuring the voltage, for example. The control system proposed in this article aims to automate this step by ensuring continuous verification of the absence of danger. The main goal is to improve the verification step in lockout procedures, allowing for automatic verification of zero electrical energy. The safety function PL was calculated using ISO 13849-1 and measures were taken to counter Common Cause Failures and Systematic Failures. Standards such as ISO 12100, CSA Z432:23, and ANSI B11.TR3 are important references for machine safety. Lockout/tagout procedures and programs are crucial for worker safety, as outlined in standards such as CSA Z460:23 and ANSI Z244.1-2003.

2 LITERATURE REVIEW AND CONTEXTUALIZATION

2.1. Lockout/Tagout versus alternatives

The lockout/tagout (LOTO) refers to specific practices and procedures aiming to stop the release of hazardous energy to prevent any unexpected move of machinery parts and equipment during maintenance activities. Other methods, called alternatives, can also be used in some conditions. First, it is important to understand the difference between an alternative to lockout/tagout and zero energy lockout/tagout. During zero energy lockout/tagout, the hazardous energy sources of the machine are completely physically controlled (electrical switch in open position, pneumatic valve in closed position) and they are locked out. In the case of an alternative to lockout/tagout, the safety control system is used to secure the worker during their intervention. The energy of the machine is still present, but it is the control system that controls the energy. Therefore, this literature review will first discuss lockout/tagout and the corresponding standard, and then the standards on safety control systems.

The 2020 version of the CSA Z460 introduce a list of criteria to know when you can use an alternative to lockout tagout versus a completely zero energy status. Mainly the eights criteria are based on a production normal task then a longer maintenance task (Table 1). If we look at the 8 criteria listed, which state that the task is short-term, relatively minor, frequent during the shift, should minimize production interruptions, and is performed by production or maintenance staff, these criteria immediately bring to mind a regular production task. The remaining points focus more on ensuring necessity, so for example, the requirement even when the machine's optimal levels are reached excludes tasks due to poor equipment management, such as a leaking conduit or poorly adjusted conveyor, which should be addressed under normal circumstances. Regarding the concept of cyclical activity, this could involve weekly equipment greasing or simply daily quality sampling. The specific training requirement emphasizes the importance of having workers trained for their specific tasks. An example that wouldn't meet this criterion would involve involving a janitorial worker, who is not trained on the machine, to interact with it to replace a box. They are unfamiliar with the machine and not trained to understand the risks involved.

According to a case study [2], the use of alternative methods faces many challenges including the choosing of the right one and even understanding when and the way that these methods may be used, having the technical knowledge, and pursuing adequate and dedicated procedures for their application. One of the most important steps generally neglected is the risk assessment for alternative methods, which is a must in the Quebec regulation (ROHS). Electronically interlocked access, such as trapped key system or remote lockout, are considered as the most used alternative methods for lockout/tagout. Since these methods are using a control system, it’s crucial to undergoes a validation of the reliability of these systems with respect to ISO 13849-1 standard. So, including raising awareness, revising procedures, improving understanding, and conducting proper risk assessments are important recommendations to set up before using any alternative method for lockout/tagout.

2.2. LOTO system failures

Lockout/tagout (LOTO) is widely recognized as a highly effective method for controlling hazardous energy and preventing accidents in the workplace. When implemented correctly, LOTO procedures ensure that machinery or equipment is safely isolated from its energy sources during maintenance, repair, or servicing activities, thereby protecting workers from unexpected startup or release of stored energy. However, the reliability of lockout/tagout procedures depends on various factors. Proper training is essential for workers to understand LOTO procedures and follow them accurately. Workers need to be trained on identifying energy sources, applying lockout/tagout devices correctly, and verifying that energy isolation is effective. Clear and comprehensive LOTO procedures must be developed and documented for each piece of equipment or machinery. These procedures should outline the steps for safely isolating energy sources and provide guidance on the use of lockout/tagout devices. The effectiveness of lockout/tagout devices, such as locks, tags, and blocking mechanisms, is crucial for ensuring that energy isolation is maintained throughout the duration of the work. Employers should ensure that these devices are durable, standardized, and capable of withstanding attempts to bypass or remove them. In the context of a study by Chinniah in 2017 [3], 106 accidents were analyzed (Table 3) and it was highlighted that maintenance-related tasks still accounted for 66% of the events related to machine accidents that were studied. The higher the probability of an accident, the more necessary zero energy becomes. In fact, the root causes of LOTO system failure were found to be caused by personal, job, and management factors [4]

Table 3. *Accident per tasks analysis*

Tasks	Number of accidents	Percentage
Start-up	13	12.26%
Manufacturing	21	19.81%
Maintenance	37	34.90%
Production-related tasks (unblocking, adjustment, etc.)	33	31.13%
Circulation	2	1.90%
Total	106	100,00%

In a longitudinal study conducted by [5], an IoT based LOTO device has shown significant improvements in reducing safety incidents and injuries. The average LOTO implementation time on the machine was reduced by almost 50% after implementing the IoT based LOTO device. The IoT based LOTO device provides additional safety measures such as auto-locking and sending text messages to concerned personnel. The development of the IoT based LOTO device aimed to improve safety and accident prevention in manufacturing industries. However, the IoT method for implementing LOTO has some limitations included:

- Reliance on technology, which can lead to technical issues and failures that compromise safety.
- Cybersecurity risks, such as hacking and unauthorized access, which can compromise safety and access to hazardous energy sources in addition to Data privacy concerns, as IoT devices collect and transmit personal and sensitive information.
- Complexity and maintenance requirements, which can add complexity and cost to the safety management system.

- Compatibility and integration challenges, which may require additional effort and resources to integrate IoT devices into existing systems.
- Cost, including upfront costs for purchasing IoT devices and ongoing costs for maintenance and data management.
- Reliability and accuracy issues, as the reliability and accuracy of IoT devices and data can vary.
- Training and user adoption challenges, as proper training and education are essential for effective use of IoT-based LOTO devices.

2.3. Evolution of industrial context

As industrial systems become increasingly complex, driven in part by technological advancements such as those in the Industry 4.0 landscape, new opportunities for industrial automation emerge. However, this complexity also poses challenges to traditional safety measures [6]. Indeed, the determination of safety levels in machinery typically based on the architecture of the system and the probability of dangerous failures may be not efficient and should be accommodated for nonconventional and complex systems. In this study [7], authors tried to use Markov models and Petri nets as effective tools for calculating safety-related reliability measures in systems with diagnostics. They thus calculated the PFH (Probability of Dangerous Failures per Hour) using analytic equations derived from Markov models or through Petri net-based Monte Carlo simulations. The result demonstrates that the PFH value can be influenced by factors such as the diagnostic coverage, failure rates, and the frequency of testing and demands on the safety function.

A safety function is a function of the machine whose failure can result in an immediate increase in risk. An emergency stop initiated by a pushbutton or pull cord is the most common safety function for a LVMCC (low voltage motor control center) [8]**.** The safety starters subsystems use contactors as the output device to remove voltage from the motor. The design of the safety starter should meet basic safety principles and well-tried safety principles. The concept of safety channels distribution is useful when multiple safety motor controller units are part of the same safety zone. Standardization in the implementation of safety functions using LVMCCs can reduce delivery times, overall cost, and maximize operational productivity. International functional safety standards provide guidelines for the design and implementation of safety-related control systems.

2.4. Safety-related systems reliability

The 2023 revisions of ISO 13849-1, ISO 13849-2, and the 2021 edition of IEC 62061 were referenced for machinery safety-related systems in order to determine the most appropriate method for analyzing the safety system in question for our case study. The method selected was that proposed in ISO 13849-1 because the components for which the reliability characteristics were available had the features specified in this standard. In addition, ISO 13849-1 concerns the parts of control systems related to the safety of both electrical energy and non-electrical energy (hydraulic and pneumatic, for example), whereas IEC 62061 concerns only electrical/electronic energy. While the circuit studied in this article was electrical and the IEC is more suitable for PLCs, the ISO 13849-1 and ISO 13849-2 characteristics were chosen because the calculation method adopted will potentially be applied to other machines (similar to the one investigated in this article) for which the Zero Energy Verification safety function is fully electrical. The generic values given in ISO 13849-1 and ISO 13849-2 for component reliability were used. Both standards (IEC and ISO) were applicable in the present case because the circuit was strictly electrical/electronic. However, the IEC standard did not provide all the failure parameters needed. The electronic part of the safety system was analyzed in less detail than in GrieBnig et al. (2008) [9] because the manufacturer of the dedicated safety logic controller had already analyzed and calculated the performance level required (PLr) for its system.

3 STEPS TO ACHIEVE A STANDARD BASED

The steps to follow in order to be compliant in our analysis are as follows:

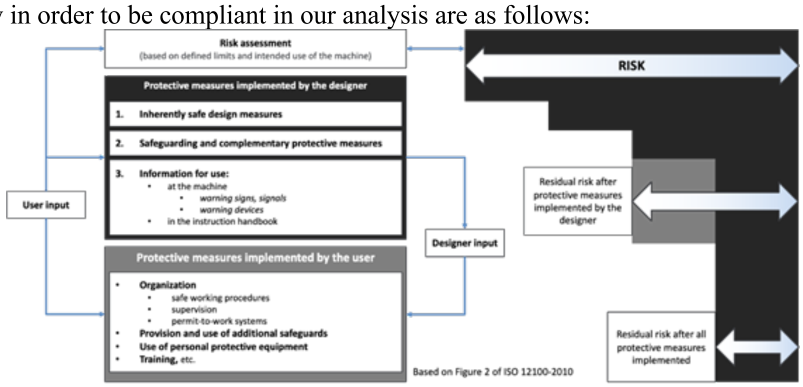

***Figure 2**. Compliant machine safety steps based on ISO 12000*

4 SCENARIO OF USING A SAFETY DEDICATED CONTROL SYSTEM TO SECURE A LOCKOUT PROCEDURE

During lockout/tagout by a worker, the safety system is validated by a magnetic ring. The interlocked door can only be opened if the control system detects that the switch is in the off position.

5 CALCULATION OF THE CONTROL SYSTEM TO CONFIRM ZERO ENERGY

5.1. Calculations steps

After the task risk analysis, components that would allow a signal to be sent to a dsPLC (dedicated safety programmable logic controller) to verify whether the equipment was energized. The main purpose was to determine whether the electrical disconnect device would function properly. By installing a mini contactor downstream from the fuses in the disconnect devices, it was possible to validate whether the electrical disconnect device had functioned properly. Validation was performed to ensure compliance with the standard stipulated in ISO 13849-1, namely IEC 60947. To ensure system reliability, it was decided to use a dsPLC instead in order to simplify calculations.

5.2. Validation of the Safety Function of the System Designed: Preliminary Steps

This section discusses the preliminary steps in the design of the safety function of the system and the performance analysis of the system. ISO 13849-1 was used to analyze system reliability. A PLc (ISO 13849-1) safety system could be used on the machine to control access to validate the zero-energy state (Figure 1). The ISO 13849-1 categories will be explained in Section 2.5.3. Jocelyn et al. (2014) [10] used ISO 13849-1 to analyze a safety system installed on a plastic injection moulding machine involving safety relays and hydraulic valves. Poisson et al. 2016 [1] has analysed a complex case study. The system who will be calculated are to suppose to be quite simple and it is supposed to be applied to numerous situations. This article analyzes a zero electrical energy verification system only, not the entire existing safety system. The same system can be transposed to other energy sources. The safety function analyzed here is referred to as “Zero Electrical Energy Verification.”

5.3. Estimation of Performance Level of the Designed System

The system consists of a validation system connected to the dsPLC on the equipment. A relay or mini-contactor compliant with IEC 60947 (according to the data sheet) is added to each of the disconnect devices downstream from the power supply and two contacts are identified – NO (Normally Open) and NC (Normally Closed) – and connected to a dsPLC. If any one condition is not respected, the signal is sent to the dsPLC, making it impossible for the machine to start up. The dsPLC is connected directly to a contactor in accordance with IEC 60947. This contactor power the motors downstream from the drives. As mentioned earlier, the safety system already in place on the machine was a PLc system compliant with ISO 13849-1.

The safety function involved is assured by a series of safety-related parts of a control system (SRP/CS as named in ISO 13849-1). According to the standard, the PL of each SRP/CS is required in order to estimate the performance level (PL) of the safety function. In this case study, the performance level was known for component forming the logic block of the safety function, but unknown for the SRP/CSs in the input and the output; an estimate of their respective PLs had to be calculated.

The logic part of the safety function is performed by one dedicated safety PLCs that have a safety level of PLe according to the manufacturer’s technical data sheet. Hence their PLs did not have to be calculated because the manufacturer had already done so.

The PL estimation process began with a determination of the designated architecture of the input and output blocks. The mean time to dangerous failure ($MTTF_d$) was then calculated to estimate the respective performance levels (PLs) of these two SRP/CSs. This was followed by the calculation of their respective average diagnostic coverages (DC_{avg}) and the verification of the other criteria needed to determine the category required by the designated architecture. Once all this information was available, it was possible, first, to determine, the input PL and the output PL. Second, it was possible to estimate the PL of the safety function based on Table 11 of ISO 13849-1.

The measures taken to counter common cause failure (CCF) and those to counter systematic failures were then verified to confirm the estimated value of the PL required for the safety function. Such measures ensure long-term system sustainability even during a power failure or when dust is present in the environment. It is very important to evaluate the points of failure (especially when using software like SIStema) in order to estimate the PL. This software is very practical for estimating the PL. However, it does not remind the user to verify whether measures have been taken to counter systematic failures. If such measures are not applied, the estimated PL cannot be confirmed.

5.3.1. Estimation of the MTTFd of the Input and Output Blocks

$MTTF_d$ is the Mean Time to Dangerous Failure (in years) of the SRP/CS. It is a computed value using probabilistic/reliability calculations based on the reliability features of the components forming the SRP/CS, as well as the frequency of the expected use (cycles). The $MTTF_d$ was calculated for the input (I1) and output (O1). In the present case study, I1 and O1 in the system are all supposed to be used at low load (below their rated load). The $MTTF_d$ of the contactors was calculated following the guidelines and formulas provided in Annex C of ISO 13849-1:

$$MTTF_d(I1) = \frac{B_{10d}}{0.1 * n_{op}}$$

$$n_{op} = \frac{\left(d_{op} * h_{op} * \frac{3600s}{h}\right)}{t_{cycle}}$$

For example, the worker lockout the equipment a maximum of once a day and for approximately 15 minutes per task, which gives 0.25h per day (h_{op}). The plant is open 363 days/yr (d_{op}) and the time between manufacturing cycles is 18s/cycle (t_{cycle}), which gives n_{op} = 18,150 cycles/yr. The B_{10d} = 20 million cycles is found in Table C.1 of ISO 13849-1 because the contactors are used at low load.

$$MTTFd\ (I1) = \frac{20\ cycles}{0.1 * 18{,}150\,\frac{cycles}{yr}} = 11{,}019\ yr$$

Given the obtained value of more than 100 years, the standard requires limiting the MTTFd to 100 years. Therefore, according to Table 5 of ISO 13849-1, the I1 contactor of the motor have a high $MTTF_d$.
The $MTTF_d$ for output components O1 is the same as that for the input devices because it is the same type of component: a low-voltage contactor.

5.3.2. Estimation of the DCavg of the Input and Output Blocks

DC_{avg} is the Average Diagnostic Coverage of the SRP/CS. Diagnostic coverage is a measure of the effectiveness of diagnostics, which may be determined as the ratio between the failure rate of the detected dangerous failures and the failure rate of total dangerous failures. The diagnostic coverage (DC) for the input and the output of contactors is the same and equal to 99% in accordance with Table E.1 of ISO 13849-1, due to the Normally Open and Normally Closed uses of the input and outputs signals and the monitoring of the logic (L).

5.3.3. Determination of the Category of the Input and Output Blocks

ISO 13849-1 explains the determination of categories as the "classification of the safety-related parts of a control system in respect of their resistance to faults and their subsequent behavior in the fault condition, and which is achieved by the structural arrangement of the parts, fault detection and/or by their reliability."
The input includes the relay downstream from the disconnect device (I1) to confirm the absence of voltage to validate that it is open. The output consists of an electrical contactor (01) for the motor.
The performance level of SRP/I1 is PLd because the components are IEC 60947 approved (Table 6, ISO 13849-2) and the DC_{avg} is high and similar to that of SRP/O1 because well-tried components are used.

5.3.4. Estimation of the PL of the Input and Output Blocks

These calculations give a PLd for SRP/CSs I1 and O1 because the $MTTF_d$ of the corresponding block is high and the high DC_{avg} is not covered with an average $MTTF_d$, such that this drops automatically to the PLd level (Table 7, ISO 13849-1).

5.3.5. Estimation of the Safety Function PL

ISO 13850 was used to calculate a minimum PLs, and a value of PLc was mentioned in the standard. In fact, the input (SRP/I1) calculated was PLd, while the dsPLC had been calculated by the manufacturer and having a performance level of PLe. The calculated output (SRP/O1) was PLd.

5.3.6. Verification of Measures to Counter CCFs (Common Cause Failures)

The system was not built yet, so the Common Cause Failures (CCF) will be necessary to be calculated prior and after the installation. To confirm that our modified system achieved the required PL, we had to ensure that two criteria were met: effective measures to protect against systematic failures and against common cause failures (CCFs).

5.3.7. Verification of Measures to Counter Systematic Failures

Systematic failures are related in a deterministic way to a certain cause, which can only be eliminated by modifying the design or the manufacturing process, operational procedures, documentation, or other relevant factors (ISO 13849-1). For example, the dsPLCs were equipped with a built-in battery that retained the program in memory in the event of a power failure. The circuits are supposed to be protected against short circuits by means of fuses. The other points are supposed to be checked prior and after the project.

6 DISCUSSION

Lockout/tagout is considered in many standards and regulations as the most effective method of controlling hazardous energy. Indeed, in the hierarchy of prevention methods, eliminating the danger at the source is at the top level and surpasses all other approaches that may not necessarily result in complete elimination of the hazard. Exposure to danger represents a hazardous situation that can lead to dangerous events even if preventive measures are implemented. In fact, residual risk, even at low levels, remains a risk to be managed and a major concern for managers, potentially causing significant damage. In the case of electrical energy, avoiding working under live conditions is an absolute priority. Indeed, it is the best way to ensure a safe working environment without dangers that could jeopardize the life and health of a worker. This is possible by using lockout/tagout. With the increased complexity of systems used in industry, simply validating the absence of voltage, or performing a startup test after lockout/tagout may no longer be sufficient. The use of a reliable control system to ensure the safety aspect of an intervention on equipment and to provide real-time confirmation of the proper functioning of the lockout/tagout procedure will be an effective solution to address this challenge. A reliable lockout/tagout procedure necessarily involves validation of its proper application through a voltage test and/or a startup test. Using an additional validation means, especially for complex systems, can only provide a higher level of security. After all, the last thing we want is to have unexpected re-energization of the equipment or a movement of some of the machine components despite the fact that the equipment is locked out. The proposed zero energy verification system will enable us to perform this task in the best possible way. However, it is important to ensure that we have an acceptable level of reliability that complies with ISO 13849-1. Without this, the system cannot provide the desired guarantee, and we cannot rely on its responsiveness when needed. An example system proposal was analyzed using various calculation steps, particularly for $MTTF_d$ and DC_{avg}. The $MTTF_d$ value obtained allowed for estimating the reliability level of the control system components. The calculation result is very reassuring and promising. Indeed, we achieve a high level of reliability (exceeding PL_d), a proof of the effectiveness and utility of the proposed system.

7 CONCLUSION

A control system for confirming the zero-energy status after the application of a lockout/tagout procedure is proposed. This is an automated validation tool that ensures the locked-out equipment remains safe while a worker performs maintenance tasks or other activities. The proposed control system supplements existing validation steps but can play a crucial role and become necessary in the case of a complex system where equipment may be powered by other components or have electrical feedback that make lockout/tagout ineffective. The ultimate goal is to provide a safer working environment during tasks involving exposure to electrical hazards. Future works are in progress for more complex systems considering other safety impacting factors.

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