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DESIGN OF THE MECHATRONIC SYSTEM FOR ACCESS CONTROL TO PROTECTED AREAS OF PRODUCTION LINES

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Abstract One of the critical characteristics of machine plants is safety at work. Safety barriers are one of the measures to reduce risk at work. Barriers are often used when controlling access to zones of increased danger is necessary. The type of protection depends on the type of industrial plant, risk assessment, and applicable regulations. To achieve the desired functionality, proper application and complete integration of the protection system into an existing management system are necessary. The paper shows the structural solution of the protection system in the printing plant of the “Tetra Pak” company from Gornji Milanovac. The main requirement is to provide entry to the protected zone only after the entry request has been sent and processed. Another requirement is to stop the plant in a predefined position. To meet the requirements, it is necessary to determine the required SIL (System Integrity Level) from the reference standard and determine the electronic components properly. In addition, complete knowledge of all processes and cycles of the production line is necessary. Safety electrical components were used to implement the project: Safety PLC, Electromagnetic Safety Locks with Call buttons, Emergency-Stop buttons, and optoelectronic and inductive sensors.

Keywords: Safety el. components; safety PLC, SIL (Sistem Integrity Level).

1. INTRODUCTION

Protective barriers are one of the measures that reduce the risk in plant operation. Their primary function is to provide working space, reduce the risk of injury to operators and workers who maintain the equipment, and increase safety at work. Protective barriers should prevent access to dangerous plant areas until the necessary conditions are met. Such protection is used in all branches of industry, especially in sectors with a high automation degree.

This type of protection method depends on the needs of industrial plants, risk assessment and respective occupational safety regulations in place.

Such protection also has significant financial justification. Reducing workplace injuries affects a company’s reputation and the costs associated with workers’ injuries and insurance. By providing physical barriers around machines, production lines, and robots, companies protect their employees – an essential resource.

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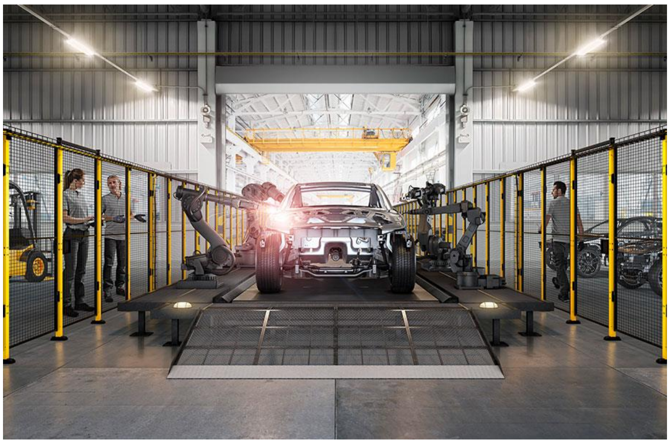

Figure 1. Use of Protective barriers on robotic production lines in the automotive industry.

This paper communicates the implementation of this type of protection in the specific case of the press line in the company "Tetra Pak" from Gornji Milanovac. During the execution of this project, a safety programmable logic controller (Safety PLC), protective panels, electromagnetic safety locks with call buttons, and optoelectronic and inductive sensors were used.

2. STANDARDS AND SAFETY MEASURES APPLIED TO PROTECT ACCESS TO MACHINERY

One of the critical operating parameters of any machine is operational safety. Aiming to regulate this area, different standards and legal regulations were introduced. The most important standard in this field is ISO13849-1 [4]. Among other things, the standard covers the area of designing complex electrical, electronic and programmable systems with a safety function. The implementation of standards means that the system needs to be validated when designing a system and configuring its structure. In other words, the probability of system failure has to be calculated.

The very notion of the standard is related to machine security. Still, it is directly related to safety measures implemented to protect access to machines. The standard is based on a probabilistic approach for assessing the safety of control systems. The standard is mainly applied to electrical, electronic and programmable components.

Within the EN ISO 13849-1 standard, there are two protection structures, **PL** (Performance Level) and **SIL** (Safety Integrity Level). The requirements for choosing one of the listed structures depend on the user's needs and the industry branch where the standard is applied.

PL (Performance Level) is a technologically neutral concept that can be used for electrical, mechanical, pneumatic, and hydraulic safety solutions. PL is a measure of the reliability of the safety function. It is divided into five levels, from **a** to **e**. The five PL levels (a-e) correspond to specific ranges of PFHD-values (probability of dangerous failure per hour). This parameter indicates how likely a dangerous failure will occur in one hour.

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SIL (Safety Integrity Level) refers to the functional safety of electrical, electronic and programmable electronic control systems. SIL sets requirements for machine safety control. The reliability level of such a system is classified according to the safety integrity level (SIL) from **1** to **3**. If a safety circuit must comply with a specific SIL, the designer must calculate the probability of system failure in addition to constructing the system structure.

Table 1. Relationship between performance level (PL) and Safety Integrity Level (SIL).

PL	SIL
a	No correspondence
b	1
c	1
d	2
e	3

The PL of the system shall be determined by the estimation of the following aspects: Category (structural requirement), Mean time to dangerous failure (MTTFd), Diagnostic coverage (DC) and Common cause failure (CCF).

The design of safety-related parts of control systems is an iterative process completed in several steps.

2.1. Define the Requirements of the Safety Functions

This is the most important step. First of all, the required properties must be defined for the safety functions. For safety gate guarding on a machine, for example, hazardous movements must be shut down when the safety gate is opened. It must not be possible for the machine to restart while the safety gate is open.

2.2. Determination of Required Performance Level PLr

The greater the risk, the higher the requirements of the control system. The contribution of reliability and structure can vary depending on the technology used. The level of each hazardous situation is classified into five stages from **a** to e. With **a**, the **control function's contribution to risk reduction** is low, and with PL **e,** it is high. The risk graph can be used to determine the required Performance Level (PLr) for the described safety function.

According to EN ISO 13849-1, PLr is evaluated using three factors: severity of injury (S), frequency and/or exposure to hazard (F) and the possibility of avoiding hazard or limiting harm (P). Each of the factors has two possible values, 1 and 2. Once the factors S, F and P have been determined, PLr can also be determined.

Figure 2 shows the graph based on which PLr (Performance Level Required) is determined for different levels of risk from low to high.

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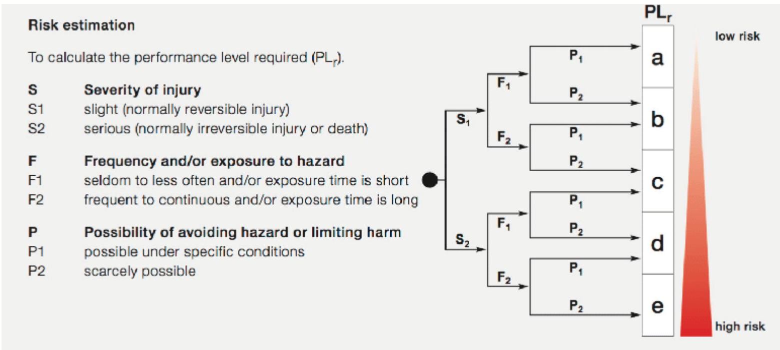

Figure 2. Performance Level Required (PLr).

2.3. Design and Technical Implementation of the Safety Functions

The safety function is separated into sensor, logic and actuator to determine the achieved Performance Level. Each of these subsystems contributes to the safety function. All the necessary performance data is available from the component producer. Producers provide a user-friendly calculation tool for this purpose.

2.4. Verification

This step determines how the achieved Performance Level matches the required Performance Level. The achieved PL must be greater than or equal to the PLr required from the risk assessment. This means a “green light” for the machine design.

2.5. Validation

Alongside the purely qualitative requirements for the design of safety systems, it is also important to avoid systematic failures. This happens during validation.

3. PROBLEM AND TECHNICAL REQUIREMENTS DEFINING

One of the basic technical requirements that the system should meet is to enable operators to access the plant only after the request has been sent and processed by the management system and the plant has been halted. Access permission cannot be obtained at an arbitrary production line time and position. It is necessary to bring the machines to the ‘‘best position’’ to stop the plants. By the most favourable position, we mean the position where the production line, after stopping and intervention, can be put into regular operation with minimal losses in time and material.

To meet the request, it is impossible to stop the plant immediately using the Emergency Stop button. It requires the use of complex electronic components. In the control program of the PLC, it is necessary to define the appropriate conditions for stopping the plant, i.e., a combination of input signals on the PLC.

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In the first step, it is necessary to determine the Performance level required (PLr) to select system components properly. In the specific case, by entering parameters S, F and P into ABB Software Tool ***SISTEMA*** [6], we conclude that the required Performance level is **PLr-d/SIL-2**. Considering the high level of required PLr, it is necessary to use electronic components with a safety function – Safety PLC. In addition to standard control functions, the Safety PLC must carry out additional monitoring functions and ensure redundancy should there be any errors and failures, both with peripherals and communication as well as with the central control unit. Safety PLCs usually contain a redundant microprocessor that takes over the function of the primary microprocessor in the event of failure.

The operation of the Safety PLC is based on the “protection layers” concept, which enables reaching the required level of protection. In industrial practice, it is most often PL-e/SIL-3. The protection layers include four parts: safety input modules, safety communication (data exchange network), safety (redundant) microprocessor, and safety output modules.

After selecting components, we must determine the realized PL for which we use software tools delivered by safety equipment manufacturers. Within those tools, there are libraries with parameter values for individual electronic components.

In this case, we used the Siemens ***Safety Evalution Tool*** to determine PL, i.e., SIL. By entering the parameters for the selected components, we determined that the achieved performance level was **PL-e/SIL-3**, which was above the required level.

4. DESIGN SOLUTION

The protective barrier system consists of a 40 m protective fence, 11 doors and 11 electromagnetic locks with buttons. It was designed to have manual buttons, microswitches and electromagnetic locks on the door. By pressing the manual button, the operator sends a request to the PLC to enter the protected area. The signals from the buttons go to the safety input modules. Through safety communication, they are forwarded to the CPU to be processed. Based on their states and the control program loaded into the working memory of the PLC, the output states in the safety output modules are set. The output modules are connected to the electromagnetic locks on the protective fences. When the conditions for safe entry and stay in the protected zone (defined in the PLC control program) are met, a signal is sent via the safety output module to the solenoid of the electromagnetic lock, which is then unlocked. After the intervention, the operator leaves the protected zone. Closing the door initiates contact with the microswitch of the lock. It sends a signal to the security input module as confirmation that the fence has closed. This confirmation is necessary to restart the plant. By starting the plant, all electromagnetic locks are locked, thus preventing any attempt to enter the secured area while the plant is in its operating mode.

4.1. System Components Description

After setting up the protection system concept, it is necessary to choose adequate components and equipment. These include a suitable safety programmable logic controller (Safety PLC), electromagnetic safety locks with call buttons, emergency-stop buttons, and optoelectronic and inductive sensors for determining the position of the rolls and protective panels.

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The main criteria when choosing components are that they satisfy the safety function and the acceptable price.

4.1.1. Protective Panels

The first step in the selection of components is the selection of protective fences - barriers. The company “AXELENTE” was chosen as the leader in producing this type of equipment [5]. One of the main reasons for choosing this type of fence is its high quality, easy assembly and disassembly, and high flexibility. The panels used have the catalogue number W321-220100.

4.1.2. Safety Electromagnetic Locks

Figure 3 shows an electromagnetic lock with call buttons and LED indication.

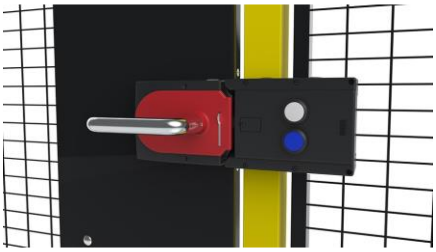

Figure 3. Electromagnetic lock with a call button.

Figure 3 shows the blue button used for calling, i.e., approval of the control element to enter the safe zone. The white LED indicator shows the state when the lock is locked.

The lock has an intelligent system whose position is detected by RFID transponders. Such a device detects a signal in the lock mechanism that has a unique code. This prevents misuse of the system and enables the achievement of the highest safety category 4/PL-e according to EN ISO 13849-1, i.e., SIL 3 according to EN 62061.

There is a mechanical unlocking system under the lock itself, enabling it to be opened in the event of a power failure. The handle is made of a robust and easy-to-grip material that can be rotated 90 degrees.

4.1.3. PLC Controler (SIEMENS ET 200 SP)

The main electronic component of the system is the PLC. For this project, we chose *Siemens ET 200 SP* [7]. The selected controller belongs to the class of the new generation of Siemens controllers, which offers several advantages. Firstly, there is a possibility of expansion of input and output modules and the integrated Safety card. Figures 4a and 4b show the selected Siemens controller model.

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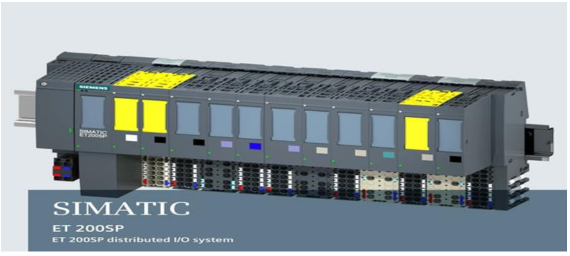
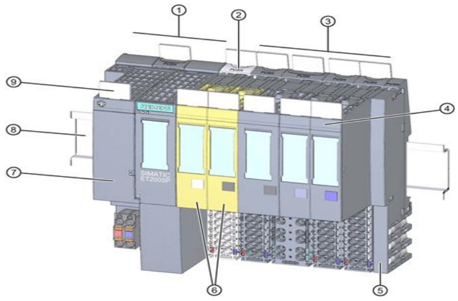


(a)



(b)

Figure 4. Siemens contoler ET 200 SP.

The PLC consists of the following components: 1. Interface module, 2. Network connection panel, 3. Voltage distribution by modules, 4. Input/output module, 5. Server module, 6. Safety input/output module, 7. Bus adapter, 8. DIN rail for PLC installation.

4.2. Security System Structure

The entire Safety system works by opening any of the eleven doors, interrupting the closed door signal. This is achieved using two pairs of contacts located in the lock itself. The light indication on the lock is turned on by sending the signal that the door is open. Emergency Stop buttons are also part of the Safety system. Emergency Stop buttons and locks are connected via two channels to the PLC for safety reasons.

The built-in PLC has five Safety modules - three modules for input and two for output signals. Both types of modules can receive up to 16 signals. The 7U2 digital input card is connected to the lock status signals, starting from address I0.0 to address I1.2. Signals from the call button for entering the safe zone, from address I1.3 to I1.7, are also connected to the same card and Emergency Stop buttons. The second card has the same set-up with addresses I3.2 to I3.7.

The following essential system components are optoelectronic and inductive sensors. Thanks to these sensors, we have information about the position of the roll at all times. After meeting the required conditions, a signal is sent to the output modules to stop the line.

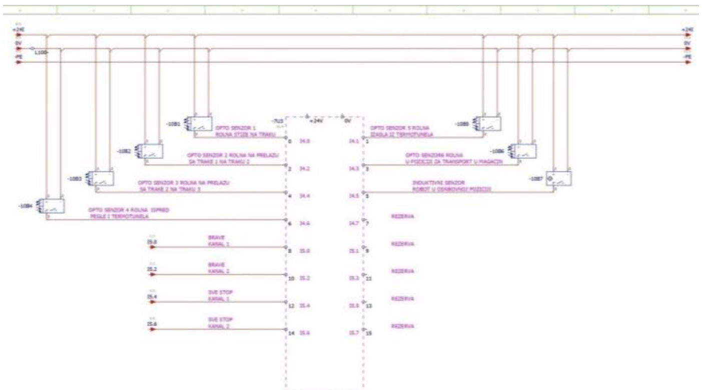


Figure 5. Digital input card with roll position sensors.

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4.3. Ladder Diagram

The Ladder diagram [1], according to which the machine performs certain functions, is developed in Siemens Simatic software, version S7. In the first step, the conditions for starting the machine are defined. The first condition is that all locks and all Emergency Stop buttons are closed. When all conditions are met, the plant can start. It is one of the main requirements of Safety protection.

The part of the program which sends an invitation to enter the safe zone is made in the second step.

Step three is the most important and complex because the position where the line will stop depends on it. All the conditions found in that line of code must be met to stop a line at the required position. The first condition is that the optoelectronic sensor, whose address is I4.0, detects the position of the roll on conveyor no. 1. The optoelectronic sensor, whose address is I4.2, has the task of sending information that the roll has moved from the conveyor 1 to conveyor 2. The optoelectronic sensor with address I4.3 has the function of sending information that the roll has moved from conveyor 2 to conveyor 3. That information is essential for restarting the line. The roll must not remain in position between the two conveyors.

The transfer of the roll from the conveyor to the pallet with finished products is carried out by a robot. An essential condition is that the position of the robot arm must be in its initial position.

The next critical point in the entire system is the thermal tunnel. The line must not be stopped while the roll is in the thermal tunnel because it could overheat and catch fire. Because of all the above, the signal about the roll exit from the thermal tunnel is of great importance.

Due to the magnitude of the drive, many locks, and the Emergency Stop buttons, it is necessary to have light signalling on the control panel about the status of all locks and buttons. The last step of the program provides a light indication of an open door and activated Emergency Stop buttons.

5. CONCLUSION

The paper presents the structural solution of the mechatronic protection system on the press line in the “Tetra Pak” plant from Gornji Milanovac. The solution offers a description of the system and all its components. The protection system includes Safety PLC, protective panels, safety locks with call buttons, Emergency Stop buttons, and optoelectronic and inductive sensors. The set requirements were met by implementing a system of protective barriers and equipment to control access to the protected zone. First, following SIL, protection level 3 was achieved, which was above the required value (SIL 2). In this way, the requirement of the standard was met, and the future upgrade of the system without replacing the main parts was also made possible. In addition, it was possible for the machine to take the most favourable position when stopping, which was one of the company’s main requirements.

The most common cause of work-related injuries is human negligence and non-compliance with prescribed procedures. This type of protection does not allow workers to disobey prescribed steps and defined procedures.

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No technical system is absolutely safe, and work-related injuries occur despite the application of the protection system. However, by applying the concept of "protection layers" and with the use of safety PLCs, the protection level degree 3 (according to SIL) can be achieved, which significantly reduces the risk of injuries and reduces it to an acceptable level.

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