Logic Solvers for Overpressure Protection

Introduction

A growing level of attention has recently been given to the automated control of potentially hazardous processes such as the overpressure or containment of dangerous substances. Several independent protection methods provide measures to reduce the risk from such hazards to personnel, the environment and assets. A significant level of this risk reduction is allocated to *safety instrumented functions* (SIF). The integrity of the *safety instrumented system* (SIS) to perform these functions (known as *functional safety*) is therefore critical and the requirements for determining and achieving functional safety are given in IEC 61511-1[REF 1]. This standard is now adopted as the predominant worldwide standard for such systems in the process industry.

The integrity requirements of the SIS have implications on all the *elements* that comprise the system such as sensors, interfaces, controllers, logic solvers, actuators and valves. All the connections that make up the complete control loop are also taken into consideration. One of the key instruments in this loop is the logic solver (decision maker), which initiates the final element to make the process safe if the need arises.

The aim of this paper is to explore some of the possibilities available to the SIS designer of an overpressure protection system for the logic solver and to show examples of straightforward system topologies and their associated *safety integrity level* (SIL) calculations.

A general step-by-step procedure to define and evaluate an SIS is suggested in the Appendix. The examples used in this paper illustrate how the procedure is applied in specific cases.

Overpressure Protection System

A *high integrity pressure protection system* (HIPPS) is an effective way to provide a barrier between high pressure and low pressure parts of an installation without the need to release fluid into or otherwise contaminate the environment. An example is in an offshore well platform where the source can occasionally present a harmful pressure surge in the pipeline. The HIPPS is designed to shut off the source before the design pressure of the downstream plant is exceeded, avoiding a rupture of a line or vessel. The normal system comprises pressure transmitters, a logic solver and fast-acting shut off valves. A HIPPS is a specific type of SIS that typically uses redundant elements to achieve the SIL specified for the application.

Factors Leading to the Choice of a Logic Solver

People can often assume the logic solver has to be a safety PLC. But in many cases a discrete logic device for each loop, which avoids the complications and expense of a programmable solution, is a sensible option. One of the objectives of functional safety is to engineer the protection layers so that the complexity of safety-related functionality is minimized. This includes designing the overall concept for the minimum number of safety instrumented loops, avoiding the unnecessary use of more complex technology and reducing interdependency between loops and keeping safety and non-safety functionality separate. IEC 61508-2[REF 2] and related standards demand a higher burden on the architectural design, which can often be avoided using less complex discrete logic solver technologies.

Apart from the obvious savings in cost from a simpler architecture, perhaps the biggest gains with this approach are unseen. Consider that this straightforward approach avoids the development cost of application programming (plus associated costs such as software maintenance, upgrades, configuration management and back-ups) and the need for specialist competence in operation and maintenance of the programmable platform. Installation, validation and commissioning of complex programmable systems also require specific competence and procedures, which can make the functional safety management (FSM) system more onerous to set up and maintain.

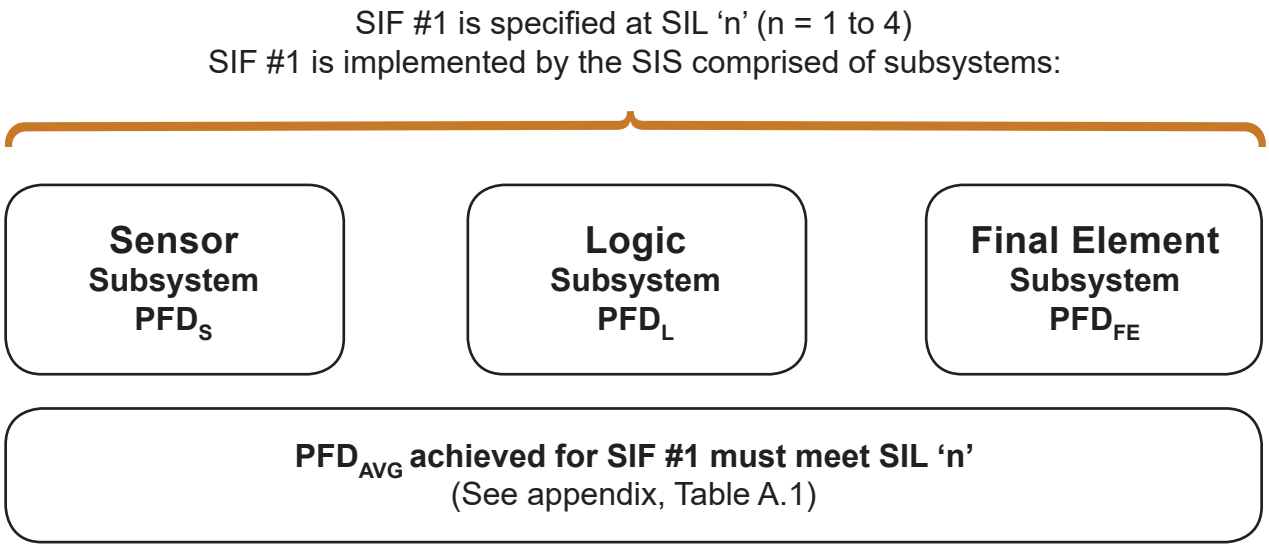
Logic Solvers for Overpressure Protection

Many safety-related applications in the process industry are ideally suited to one or more single loop logic solvers because they are small scale, isolated or located in remote areas. As mentioned, the simpler architectural demands using this approach can reduce the cost of hardware, software and procedural overheads.

The Safety Integrity Level

The performance of a SIF is defined by the *safety integrity level* (SIL 1 to SIL 4). All elements that form the SIS must be designed or selected in accordance with the IEC 61508 or IEC 61511 standards. In practice, each SIF in an SIS typically consists of three subsystems that include one or more sensor elements, logic solver elements and final control elements, as required to meet the (highest) target SIL for the function(s) being performed (Figure 1).

Figure 1. *Subsystems of a SIF.*



The three basic attributes of the SIS that require design consideration and evaluation in order to achieve the SIL are:

1) The **architectural constraints** for each subsystem are at least SIL 'n'

2) The **systematic capability** of each subsystem is at least SC 'n'

3) The **probability of failure on demand**, PFD_{AVG} is within (or <) the range for SIL 'n'

Each one of these attributes places requirements on the elements used in each subsystem.

Example Failure Data and Methodology

For the purposes of the examples in this paper, we shall assume that the elements included in these example SIFs have the following functional safety data available:

Table 1. SIF Device Safety Data.



Parameter	Pressure Transmitter	Safety Trip Alarm	Actuated Valve
Dangerous Detected Failure Rate, λ_{DD} (per hr)	3.4E-07	1.7E-07	5.6E-07
Dangerous Undetected Failure Rate, λ_{DU} (per hr)	3.4E-08	8.6E-08	2.8E-07
Safe Failure Rate, λ_S (per hour)	6.2E-07	6.6E-07	4.5E-07
Safe Failure Fraction, SFF	90% to <99%	90% to <99%	60% to <90%
Type, A/B	Type B	Type B	Type A
Systematic Capability, SC	SC3	SC3	SC2

NOTE: The failure rates (and hence SFF) in the table above are indicated for the failure mode of the element that affects the SIF (e.g., shut down of the pipeline if overpressure condition is detected). This is always a critical point for the system designer to note.

A simplified methodology to define and evaluate a SIS from element data that satisfies the three necessary attributes mentioned above is given in the Appendix of this paper, including the reference information needed from IEC 61508. (The reader might wish to study that first before looking at the examples of how it is implemented in the examples that follow).

NOTE: For the purposes of this paper, it shall be assumed that the system engineering from start to finish is performed in accordance with an appropriate functional safety management (FSM) system in accordance with [REF 4], clause 6.

SIL 2 HIPPS Example

Suppose the requirement is for a SIL 2 HIPPS. We shall follow the steps shown in the methodology in the Appendix for this example.

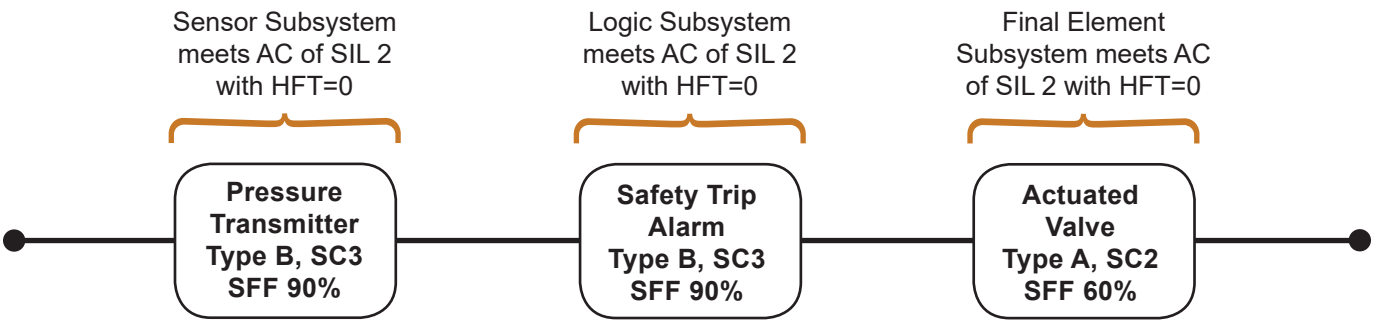
1. Architectural Constraints (AC)

Subsystem	Comments Regarding Element Failure Data Provided in Table 1
Sensor	The pressure transmitter is a Type B (due to the programmable features) and has SFF of 90-99%. With reference to Table A.2 in the Appendix, when used on its own (HFT = 0), the input subsystem has AC that meets SIL 2.
Logic	The STA logic solver is Type B and has SFF of 90 - 99%. With reference to Table A.2 in the Appendix, with HFT = 0, the logic subsystem has AC that meets SIL 2.
Final Element	The actuated valve is Type A and has SFF of 60-90%. With reference to Table A.2 in the Appendix, with HFT = 0, the output subsystem has AC that meets SIL 2.

2. Systematic Capabilities (SC)

Subsystem	Comments Regarding Element Failure Data Provided in Table 1
Sensor	The pressure transmitter is SC3 which meets (exceeds) the requirements for SIL 2 when used on its own.
Logic	The STA logic solver is SC3 which meets (exceeds) the requirements for SIL 2 when used on its own.
Final Element	The actuated valve is SC2 which meets the requirements for SIL 2 when used on its own.

Figure 2. Reliability Block Diagram for the SIF Showing the AC and SC for Each Element.



The outcome of steps 1 and 2 above mean that a SIL 2 architecture for the system can be achieved with a single element in each subsystem. This is reflected in the reliability block diagram (RBD) in Figure 2 for the system.

3. Probability of Failure on Demand (PFD_{AVG})

All three subsystems are based on a 1-out-of-1 (1oo1) voting architecture, for which the equation is:

$$PFD_{AVG} = (\lambda_{DU} + \lambda_{DD})\, t_{CE}$$

Where the channel equivalent down time (t_{CE}) which is given by:

$$t_{CE} = \frac{\lambda_{DU}}{\lambda_D}\left(\frac{T_1}{2} + MTTR\right) + \frac{\lambda_{DD}}{\lambda_D} MTTR$$

For this example we shall assume the following values:

Proof Test Interval, T_1 = 8,760 hrs (= 1 yr)	This must be confirmed by the operator and the PFD calculation re-performed if different from this assumption.
Mean time to repair, MTTR = 8 hrs	Also a user parameter, so the comment above applies.

Now we need to calculate the PFD_{AVG} for each subsystem by referring to the failure data in Table 1 (above), the assumptions listed above for T1 and MTTR and the equations in the Appendix.

Sensor Subsystem (Pressure Transmitter, 1oo1)

EQUATION	CALCULATION		RESULT
$\lambda_D = \lambda_{DD} + \lambda_{DU}$	3.4E-07 + 3.4E-08	=	3.74E-07
$t_{CE} = \frac{\lambda_{DU}}{\lambda_D}\left(\frac{T_1}{2} + MTTR\right) + \frac{\lambda_{DD}}{\lambda_D} MTTR$	(3.4E-08/3.74E-07)(8760/2+8)+(3.4E-07/3.74E-07)8	=	406
$PFD_{AVG} = (\lambda_{DU} + \lambda_{DD})\, t_{CE}$	(3.4E-08 + 3.4E-07)406	=	1.5E-04

Logic Subsystem (Safety Trip Alarm, 1oo1)

EQUATION	CALCULATION		RESULT
$\lambda_D = \lambda_{DD} + \lambda_{DU}$	1.7E-07 + 8.6E-08	=	2.6E-07
$t_{CE} = \frac{\lambda_{DU}}{\lambda_D}\left(\frac{T_1}{2} + MTTR\right) + \frac{\lambda_{DD}}{\lambda_D} MTTR$	(8.6E-08/2.6E-07)(8760/2+8)+(1.7E-07/2.6E-07)8	=	1457
$PFD_{AVG} = (\lambda_{DU} + \lambda_{DD})\, t_{CE}$	(8.6E-08 + 1.7E-07)1457	=	3.8E-04

Final Element Subsystem (Actuated Valve, 1oo1)

EQUATION	CALCULATION		RESULT
$\lambda_D = \lambda_{DD} + \lambda_{DU}$	5.6E-07 + 2.8E-07	=	8.4E-07
$t_{CE} = \frac{\lambda_{DU}}{\lambda_D}\left(\frac{T_1}{2} + MTTR\right) + \frac{\lambda_{DD}}{\lambda_D} MTTR$	(2.8E-07/8.4E-07)(8760/2+8)+(5.6E-07/8.4E-07)8	=	1468
$PFD_{AVG} = (\lambda_{DU} + \lambda_{DD})\, t_{CE}$	(2.8E-07 + 5.6E-07)1468	=	1.2E-03

As explained in the Appendix, the PFD_{AVG} for the system is calculated from the sum:

$$PFD_{SYSTEM} = PFD_S + PFD_L + PFD_{FE}$$
$$= 1.5E\text{-}04 + 3.8E\text{-}04 + 1.2E\text{-}03$$
$$= \mathbf{1.7E\text{-}03}$$

Referring to Table A.1 (Appendix) shows this is comfortably in the **SIL 2** range (10^{-3} to < 10^{-2}).

Note: That due to the relatively large uncertainties in the source values of component failure data, the results of failure analysis do not yield figures with high precision. Therefore, this means expressing results to more than two significant figures is of little value (and the implied precision could be misleading).

SIL 3 HIPPS Example

Now, suppose the requirement is for SIL 3. We will refer to the same element failure data and follow the same steps as above for the SIL 2 example and as given in the Appendix. For this example, we will also assume that the user requirements specification has an additional availability requirement that necessitates 2oo3 voting in the sensor subsystem (which is very typical for HIPPS).

1. Architectural Constraints

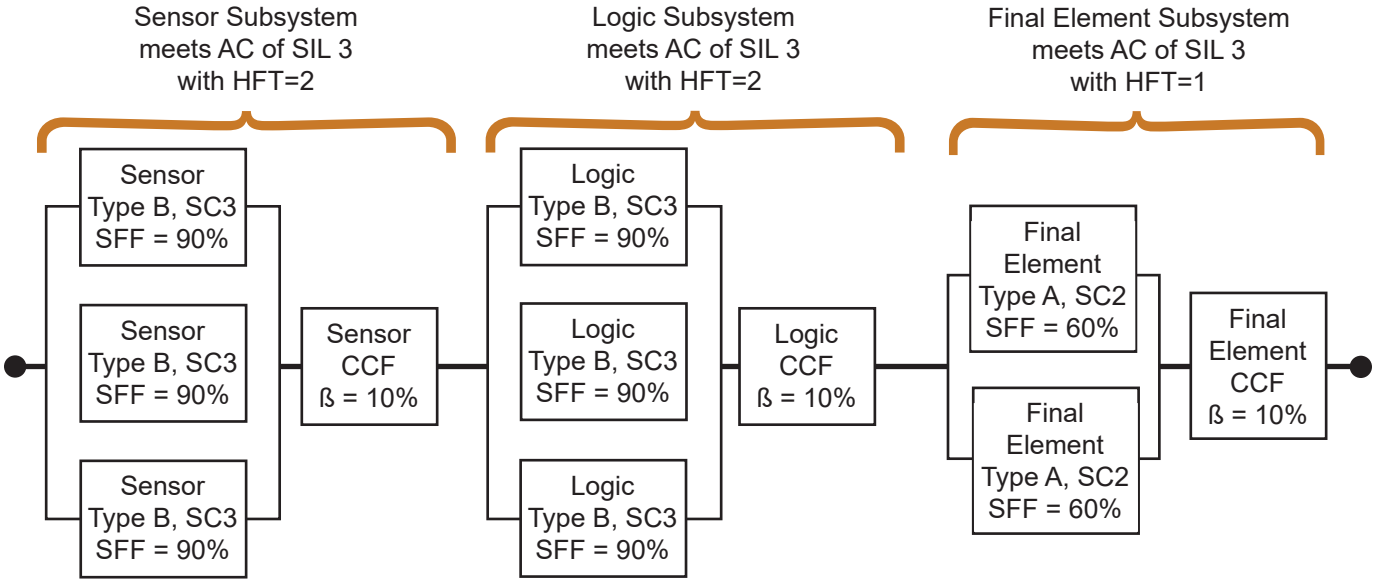
Subsystem	Comments Regarding Element Failure Data Provided in Table 1
Sensor	Because the pressure transmitter is Type B and has SFF of 90 - 99%, with reference to Table A.2 in the Appendix it needs to be used with HFT = 1 (minimum) to achieve AC of SIL 3. However, note that there is an additional requirement for 2oo3 voting due to availability reasons so HFT=2 will be used.
Logic	Because the STA logic solver is Type B and has SFF of 90 - 99%, with reference to Table A.2 in the Appendix it needs to be used with a HFT = 1 (minimum) to achieve AC of SIL 3. However, due to the additional requirement for 2oo3 voting on the sensors due to availability reasons, and because one STA is required for each sensor as they use 4-20mA loop, HFT=2 is also required for the STA. (The 2oo3 vote is then performed on the STA relay outputs).
Final Element	Because the actuated valve is Type A and has SFF of 60 - 90%, with reference to Table A.2 in the Appendix, it needs to be used with a HFT = 1 (minimum) to achieve AC of SIL 3.

2. Systematic Capability

Subsystem	Comments Regarding Element Failure Data Provided in Table 1
Sensor	The pressure transmitter is SC3 which meets the requirements for SIL 3.
Logic	The STA logic solver is SC3 which meets the requirements for SIL 3.
Final Element	The actuated valve is SC2. Using two elements in a 1oo2 configuration (HFT=1) will always introduce a possibility of some common cause failure (CCF) which needs to be assessed and justified with respect to the SIL involved. A detailed treatment of this subject is outside the scope of this paper, but in this case the assessment could consider the following design features or conditions of use: • Complexity is low (both are type A elements) • Both elements have SC2 (which is better than SC2 + SC1) • No software involved • Majority of CCF are fail safe (air lines, power supply, etc) • Independence can be improved by physical location, testing the two devices at different times, by different people, by different methods and by operating at slightly different profiles The outcome of such an assessment will support the choice of the “ß-factor” used in the SIL calculations that follow, but for the purposes of this paper we shall assume a worst case figure of 10%.

The outcome of Steps 1 and 2 above means that redundancy is required in all three subsystems to achieve a SIL 3 architecture for the system. With the additional requirements for availability, this is reflected in the reliability block diagram (RBD) in Figure 3 for the system.

Figure 3. Subsystem Systematic Capability.



3. Probability of Failure on Demand

All three subsystems use either 2oo3 or 1oo2 voted architecture, for which the equations are shown in the Appendix. For this example we will assume the following values:

Proof Test Interval, T_1 = 8,760 hrs (= 1 yr)	This must be confirmed by the operator and the PFD calculation re-performed if different from this assumption.
Mean time to repair, MTTR = 8 hrs	A user parameter - as comment above.
Common cause factor for undetected failures, ß = 10%	Typically this is in the range 3-10%. The strategies and justification are outside the scope of this paper (refer to IEC 61508 Part 2, clause 7.4.3.4 and 7.4.5.2d and Part 6 Annex D) hence a worst case of 10% is assumed for each instance in this example.
Common cause factor for detected failures, $ß_D$ = 10%	As comment above (a worst case figure is used).

As before, we need to calculate the PFD_{AVG} for each subsystem by referring to the failure data given in Table 1 (above), the assumptions listed above for T_1, MTTR, ß, $ß_D$ and the appropriate equation in the Appendix for the voting arrangement used.

Sensor Subsystem (Pressure Transmitter, 2oo3)

EQUATION		CALCULATION		RESULT
$\lambda_D = \lambda_{DD} + \lambda_{DU}$	=	3.4E-07 + 3.4E-08	=	3.74E-07
$t_{CE} = \frac{\lambda_{DU}}{\lambda_D}\left(\frac{T_1}{2} + MTTR\right) + \frac{\lambda_{DD}}{\lambda_D} MTTR$	=	(3.4E-08/3.74E-07)(8760/2+8)+(3.4E-07/3.74E-07)8	=	406
$t_{GE} = \frac{\lambda_{DU}}{\lambda_D}\left(\frac{T_1}{3} + MTTR\right) + \frac{\lambda_{DD}}{\lambda_D} MTTR$	=	(3.4E-08/3.74E-07)(8760/3+8)+(3.4E-07/3.74E-07)8	=	275
$PFD_{AVG} = 6((1-ß_D)\lambda_{DD} + (1-ß)\lambda_{DU})^2 t_{CE} t_{GE} + ß_D \lambda_{DD} MTTR + ßλ_{DU}(T_1/2+MTTR)$	=	6((0.9x3.4E-07)+(0.9x3.4E-08)^2 406x275 + (0.1x3.4E-07x8) + (0.1x3.4E-08)((8760/2)+8)	=	1.53E-05

Logic Subsystem (Safety Trip Alarm, 2oo3)

EQUATION		CALCULATION		RESULT
$\lambda_D = \lambda_{DD} + \lambda_{DU}$	=	1.7E-07 + 8.6E-08	=	2.6E-07
$t_{CE} = \frac{\lambda_{DU}}{\lambda_D}\left(\frac{T_1}{2} + MTTR\right) + \frac{\lambda_{DD}}{\lambda_D} MTTR$	=	(8.6E-08/2.6E-07)(8760/2+8)+(1.7E-07/2.6E-07)8	=	1480
$t_{GE} = \frac{\lambda_{DU}}{\lambda_D}\left(\frac{T_1}{3} + MTTR\right) + \frac{\lambda_{DD}}{\lambda_D} MTTR$	=	(8.6E-08/2.6E-07)(8760/3+8)+(1.7E-07/2.6E-07)8	=	992
$PFD_{AVG} = 6((1-ß_D)\lambda_{DD} + (1-ß)\lambda_{DU})^2 t_{CE} t_{GE} + ß_D \lambda_{DD} MTTR + ßλ_{DU}(T_1/2+MTTR)$	=	2((0.9x1.7E-07)+(0.9x8.6E-08)^2 1480x992 + (0.1x1.7E-07x8) + (0.1x8.6E-08)((8760/2)+8)	=	3.83E-05

Final Element Subsystem (Actuated Valve, 1oo2)

EQUATION		CALCULATION		RESULT
$\lambda_D = \lambda_{DD} + \lambda_{DU}$	=	5.6E-07 + 2.8E-07	=	8.4E-07
$t_{CE} = \frac{\lambda_{DU}}{\lambda_D}\left(\frac{T_1}{2} + MTTR\right) + \frac{\lambda_{DD}}{\lambda_D} MTTR$	=	(2.8E-07/8.4E-07)(8760/2+8)+(5.6E-07/8.4E-07)8	=	1468
$t_{GE} = \frac{\lambda_{DU}}{\lambda_D}\left(\frac{T_1}{3} + MTTR\right) + \frac{\lambda_{DD}}{\lambda_D} MTTR$	=	(2.8E-07/8.4E-07)(8760/3+8)+5.6E-07/8.4E-07)8	=	985
$PFD_{AVG} = 2((1-ß_D)\lambda_{DD} + (1-ß_{DU})^2 t_{CE}\, t_{GE} + ß_D \lambda_{DD} MTTR + ßλ_{DU}(T_1/2+MTTR)$	=	2((0.9x5.6E-07)+(0.9x2.8E-07)^2 1468x985 + (0.1x5.6E-07)+(0.1x2.8E-07)((8760/2)+8)	=	1.25E-04

The PFD_{AVG} for the system is calculated from the sum:

$$PFD_{SYSTEM} = PFD_S + PFD_L + PFD_{FE}$$

$$= 1.53E\text{-}05 + 3.83E\text{-}05 + 1.2E\text{-}04$$

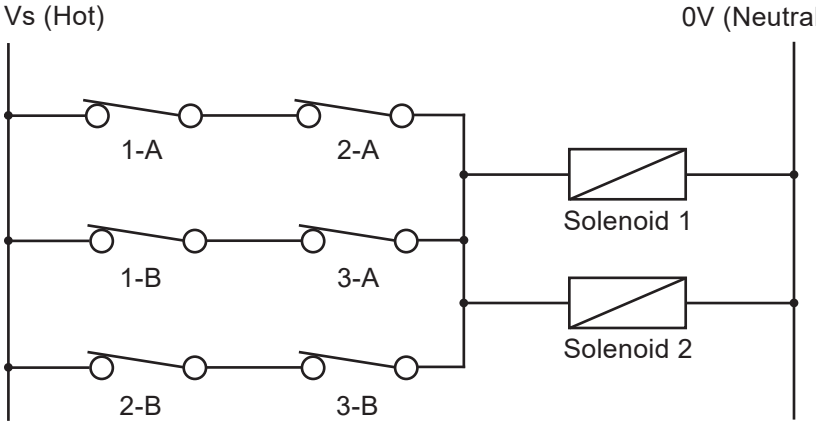
$$= \mathbf{1.8E\text{-}04}$$

Referring to Table A.1 (Appendix) shows this is comfortably in the **SIL 3** range (10^{-4} to < 10^{-3})

Design, Installation and Operational Considerations

In the case where redundant channels are used to support a voting configuration (2oo3 in the SIL3 HIPPS), the voting is implemented by using the appropriate connection scheme with the two relays (A and B) in each of the three STAs. A 2oo3 voting circuit is shown in Figure 4. By inspection it can be seen that the solenoids will be de-energized (by normally open relay contacts opening) if at least any 2 of the 3 STAs open their dual relay contacts (A and B relays on each STA are ganged).

Figure 4. 2oo3 STA Contact Wiring.



STA1	STA2	STA3	
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

Conclusion

While the safety PLC approach offers advantages for installations where there are a high number of field I/O safety loops, many plants have few such loops. (Keeping the number to a minimum is an objective of safety engineering.) The benefits of avoiding software programming and all the related support and competence aspects (at the highest safety function SIL on the site) have already been mentioned. For the majority of plants where the safety functions may be few and/or physically widespread, discrete logic solutions are advantageous (for example, savings in cable costs). The STA is easy to install with its wide range of power supply options and its small package that helps to keep it separate from non-safety instrumentation. In the event of maintenance due to transients or failure, it can be readily swapped out at low unit and operational cost without interfering with the other processes in the plant. Local indication gives reassurance that the status of safety loops is reported directly.

This paper shows that design of Safety Instrumented Systems does not necessarily have to be based on an expensive and complex safety PLC system. Discrete logic devices such as the STA offer flexible, low-cost and user-friendly advantages which will be welcomed by many plant operators. While Safety Instrumented Systems design is for competent practitioners, this paper shows a straightforward approach to selecting the most suitable devices and performing the analysis to demonstrate the achievement of the required safety integrity level.

References and Bibliography

[REF 1] IEC 61511-1:2003 Functional safety – safety-instrumented systems for the process sector – framework, definitions, system, hardware and software requirements

[REF 2] IEC 61508-2:2010 Functional safety of E/E/PE safety-related systems – system requirements

[REF 3] IEC 61508-6:2010 Functional safety of E/E/PE safety-related systems – Guidelines on the application of IEC 61508-2 and IEC 61508-3

[REF 4] IEC 61508-1:2010 Functional safety of E/E/PE safety-related systems – general requirements

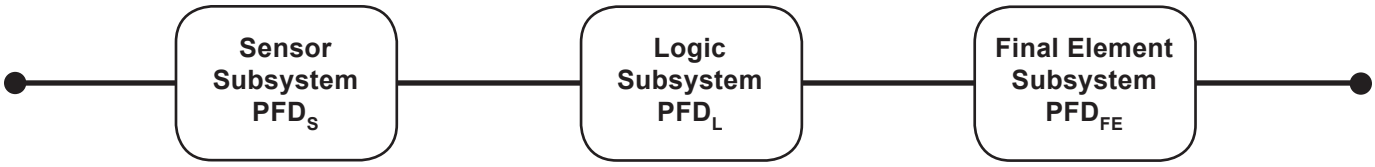
Useful Links

Moore Industries Website	http://www.miinet.com
Functional Safety Poster	http://www.miinet.com/SafetySeries
The STA Data Sheet	http://www.miinet.com/InterfaceSolutionDownloadCenter/PopularProducts.aspx
IEC Functional Safety Website	http://www.iec.ch/functionalsafety/

Appendix - A General Procedure to Define a Safety Instrumented System

This appendix is intended to offer a simple methodology to design a SIS for a specific application that uses safety functions in the low demand mode. For further information IEC 61508-6[REF 3] should be consulted.

Figure A.1. *SIS Subsystem Framework.*



The 3-stage subsystem framework for a SIS, as described in IEC 61508, is shown in Fig A.1 above.

This representation can also be seen as a *Reliability Block Diagram* (RBD) model. As the model consists of three series blocks, the simple rule can be applied that the PFD (or failure rate, for that matter) for each block can be summed to establish the relevant parameter (PFD or λ) for the system. Hence:

$$PFD_S + PFD_L + PFD_{FE} = PFD_{SYSTEM}$$

When there are redundant elements in a subsystem (depicted as parallel blocks in the RBD), things are more complicated and this is covered later in this procedure.

The average PFD of the system that performs the safety function is one of the key parameters that define the SIL for the safety function, as given in IEC 61508-1[REF 4] Table 2:

Table A.1. *SIL Ranges for Low Demand Safety Instrumented Functions.*

Safety Integrity Level (SIL)	Average Probability of Failure on Demand (PFD_{AVG}) for a Low Demand Safety Function
SIL 4	≥ 10^{-5} to <10^{-4}
SIL 3	≥ 10^{-4} to <10^{-3}
SIL 2	≥ 10^{-3} to <10^{-2}
SIL 1	≥ 10^{-2} to <10^{-1}

The system PFD_{AVG} will need to be divided between the three subsystems shown in Fig A.1. Although not in the Standard, a reasonable division that seems to be widely accepted is 35% : 15% : 50% to the sensor, logic and final element subsystems respectively. These provide realistic PFD targets for the subsystems to meet.

The other important reference information from the Standard that we shall need to refer to is the *architectural constraints* (IEC 61508-2 Tables 2 and 3):

Table A.2. *Architectural Constraints of Type A and B Elements or Subsystems.*

Safe Failure Fraction (SFF)	Type A Element or Subsystem (IEC 61508-2 Table 2)			Type B Element or Subsystem (IEC 61508-2 Table 3)		
	Hardware Fault Tolerance (HFT)			Hardware Fault Tolerance (HFT)		
	0	1	2	0	1	2
< 60%	SIL 1	SIL 2	SIL 3	NO SIL	SIL 1	SIL 2
60% - < 90%	SIL 2	SIL 3	SIL 4	SIL 1	SIL 2	SIL 3
90% - < 99%	SIL 3	SIL 4	SIL 4	SIL 2	SIL 3	SIL 4
≥ 99%	SIL 3	SIL 4	SIL 4	SIL 3	SIL 4	SIL 4

Unlike PFD, architectural constraints only apply to subsystems and elements (not systems); the SILs in the table are effectively the limit that the subsystem or element can be used in (unless further architectural measures are used).

Essentially, the procedure involves selecting elements from their failure modes and failure data that can be formed into the subsystems in the generic SIS shown in Figure A.1 above.

NOTE: For the purposes of this simplified procedure, we shall assume that:

-the elements being considered have already been preselected in terms of all their specifications to fulfill the functional, environmental and any other requirements of the system

-the Safety Requirements Specification (IEC 61508 Phase 9 - which derives system requirements from the hazard and risk studies for the specific application) is being implemented by the system designer

Each step in the approach relates to each of the three basic attributes of the SIS that were listed earlier on Page 2 of this paper.

1) First of all, consider the **architectural constraints** of each subsystem which need to meet the target SIL. Start by comparing the failure data of each element with the requirements in Table A.2 above for the target SIL with a HFT of 0 (i.e., the element on its own). If the type (A/B) and SFF indicate the target SIL is achieved, then no redundancy voting for that element is required. If it is not achieved, then redundancy/voting of the element will be needed (HFT = 1 or 2 columns apply). Use the results of this step to form a *reliability block diagram* (RBD) model of the SIS (in the form shown in IEC 61508-2 Fig 6). Remember that if redundancy is required (shown as parallel blocks in the RBD), a series block should be added to model the common cause failure (CCF).

2) Check the **systematic capability** number for each subsystem is at least the same as that of the target SIL. If this cannot be achieved using the single or redundant elements as selected in step 1, it will be necessary to use redundant elements in such a manner that they will not suffer from common cause systematic failures.

NOTE: From the two steps above, it should now be possible to determine the architecture of the SIS

3) Calculate the **PFD_{AVG}** of each subsystem from the dangerous failure rate of the element(s) to check it meets the proportion (35, 15 or 50%, as explained above) of the target SIL. This requires knowledge (or a conditional assumption at this stage) of the proof test interval (T_1) and the mean time to repair (MTTR) that will be used by the operator, both in hours. Here we shall use the PFD equations from IEC 61508-6[REF 3].

For the simple case where the subsystem is comprised of only one element (voting is 1oo1), the equation is:

$$PFD_{AVG} = (\lambda_{DU} + \lambda_{DD})\, t_{CE}$$

Where t_{CE} (the channel equivalent down time) is:

$$t_{CE} = \frac{\lambda_{DU}}{\lambda_D}\left(\frac{T_1}{2} + MTTR\right) + \frac{\lambda_{DD}}{\lambda_D} MTTR$$

For a 1oo2 voted architecture, where the safety function is performed if at least one of the channels indicates a dangerous state in the EUC, the equation to use is:

$$PFD_{AVG} = 2((1-ß_D)\lambda_{DD} + (1-ß)\lambda_{DU})^2\, t_{CE}\, t_{GE} + ß_D\, \lambda_{DD}\, MTTR + ß\lambda_{DU}\left(\frac{T_1}{2} + MTTR\right)$$

Where ß is the common cause factor (CCF) for dangerous undetected failures, $ß_D$ is the CCF for dangerous detected failures, t_{CE} is as defined above and t_{GE} (the group equivalent down time) is:

$$t_{GE} = \frac{\lambda_{DU}}{\lambda_D}\left(\frac{T_1}{3} + MTTR\right) + \frac{\lambda_{DD}}{\lambda_D} MTTR$$

For a 2oo3 voted architecture, where the safety function is only performed if at least two of the channels indicate a dangerous state in the EUC, the equation to use is:

$$PFD_{AVG} = 6((1-ß_D)\lambda_{DD} + (1-ß)\lambda_{DU})^2\, t_{CE}\, t_{GE} + ß_D\, \lambda_{DD}\, MTTR + ß\lambda_{DU}\left(\frac{T_1}{2} + MTTR\right)$$

Where ß, $ß_D$, t_{CE} and t_{GE} are as defined above.

Once the PFD_{AVG} quantities are established for each subsystem, the PFD_{AVG} for the system is calculated from the sum:

$$PFD_{SYSTEM} = PFD_S + PFD_L + PFD_{FE}$$

If the resultant PFD_{AVG} for the system does not meet the SIL, it may be possible to reduce the proof test interval until it does, assuming that this concludes with a realistic interval for the operator (otherwise further redundancy or diagnostics to produce lower failure rates and hence lower the PFD_{AVG} may be an option).

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MOORE INDUSTRIES

United States • info@miinet.com
Tel: (818) 894-7111 • FAX: (818) 891-2816

Belgium • info@mooreind.be
Tel: 03/448.10.18 • FAX: 03/440.17.97

China • sales@mooreind.sh.cn
Tel: 86-21-62491499 • FAX: 86-21-62490635

Australia • sales@mooreind.com.au
Tel: (02) 8536-7200 • FAX: (02) 9525-7296

The Netherlands • sales@mooreind.nl
Tel: (0)344-617971 • FAX: (0)344-615920

United Kingdom • sales@mooreind.com
Tel: 01293 514488 • FAX: 01293 536852