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In the process industry, the testing of safety instrumented systems is an inherent part of the safety approach. Usually, function tests are performed once a year on the entire instrumented system, consisting of sensor, logic solver, and final element. Further scheduled testing routines depend on local requirements and even involve removing valves from the plant and inspecting them in the workshop. These common procedures have not lost their importance even in view of the IEC 61508 and IEC 61511 standards. However, these standards require a quantitative analysis of safety equipment and SIL (Safety Integrity Level) ratings. The probability of failure for the safety loop and its individual components need to be calculated. The degree of coverage of the performed tests plays a key role. As a result, maintenance cycles can be planned more flexibly and even extended in some cases. This changed approach to safety is accompanied by the development of smart positioner diagnostics. This article discusses the opportunities of partial-stroke testing and the risks involved.

Keywords: IEC 61508/IEC 61511/final elements/process valves/partial stroke/maintenance cycle

1.Determining the SIL rating

The IEC 61508 and IEC 61511 standards focus on life cycle management. Specifications on the reliability of safety equipment are determined by performing a risk analysis of the plant that is to be operated ranging from SIL 1 to SIL 4. A combination of safety loop sizing and scheduled maintenance action is required to meet the specifications (Fig. 1).

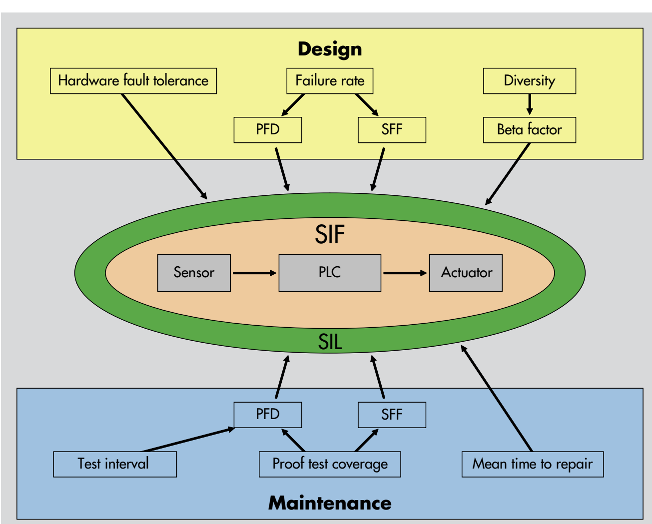

Fig. 1: Variables influencing the SIL rating

The design is steered by the decision for a one-channel or multi-channel version. The resulting Hardware Fault Tolerance (HFT) describes the safety equipment's ability to function when one or more faults occur. In the case of the multi-channel version, failures with a common source are to be observed which are described by the beta factor. This factor indicates the probability of failure due to systematic failures. As a result, diversified technologies are preferred, for example, various measuring principles for multi-channel pressure measurement. The failure rate (lambda) of the entire safety loop must be specified in a quantative form. Usually, this requires the rates of failure of individual devices. However, a SIL rating can only be determined when these three variables are combined with the intended maintenance strategy. An obligatory Probability of Failure on Demand (PFD) is derived in a simplified calculation [1] to comply with the standard.

$$PFD\ avg = \frac{1}{2}\lambda_d \cdot T$$

Lambda: Dangerous failure rate
T: Test interval

This model-type calculation is based on the assumption that the device functions properly after a test. This approach is, however, not always appropriate. If all failure mechanisms are not reliably covered by the test, i.e. the proper working condition cannot be proved sufficiently, the diagnostic coverage is used to describe it. Furthermore, any possible faults must be classified in safe and unsafe faults and the ratio between both of them is integrated as the Safe Failure Fraction (SFF) into the achievable SIL rating. Various sections of the standard contain tables that specifiy the consequences for the SIL rating for all six variables influencing the SIL rating.

2. Partial-stroke testing, test interval, and diagnostic coverage
Control valves in safety-related applications are subject to particular stress as they come directly into contact with the process medium. In cases where the valves are designed to function as mere shut-off valves, they are not activated in normal operation and can be stuck in the same position over months or years owing to the plant conditions. Consequently, control valves are usually regarded as the plant components with the lowest amount of availability [1]. It is therefore not surprising that the target involves meeting the conflicting demands of long plant life cycle as well as high availability of the safety equipment (low PFD) by increasing the test frequency in running operation, better known as partial-stroke tests. The valve is moved by approx. 10 to 15 % of its travel while the plant is running. It is still possible to prove that the valve moves while the operation of the plant is not impaired. It is immediately clear that partial-stroke testing enables the detection of some failure mechanisms such as seizure of the plug in the final position. Other failure mechanisms such as tight shutoff at the seat cannot be detected. The formula used to express this is [5,6]:

$$PFD_{(1oo1)} = DC \cdot \lambda_d \, TI_a/2 + (1\text{-}DC) \cdot \lambda_d \cdot (TI_m/2)$$

λ_d = Dangerous failure rate
TI_a = Partial-stroke test interval
Ti_m = Test interval for manual testing
DC = Diagnostic coverage factor

The formula is easily understood. The probability for non-detectable faults remains the same, while detectable faults are included in the entire PFD with the shortened testing time, resulting in a lower input. On the whole, a lower and better PFD arises as the achievable result depends on the diagnostic coverage and the selected test frequency.
It is difficult to precisely determine the quantative diagnostic coverage. Indiscriminate specifications on the effects of a partial-stroke test are often publicized: 13,000 years MTBF achievable. Such a general statement is, however, inappropriate since the characteristics of the equipment used and the process involved are also decisive. The FMEDA must be regarded as the initial step of a quantative assessment. An FMEDA is a possible way to list the individual failure sources for equipment, to describe their frequency of occurrence in figures, and to categorize them as safe or unsafe as stipulated by IEC 61508. The results are usually presented in tables, individual failures are listed and their effects on the PFD described. This can be extended by including the detectablity using partial-stroke testing and may be upgraded by adding special features of faults that allow faults to be pinpointed (Table 1).

Table 1: Example of a FMEDA with diagnostics acc. to [2]

Components Actuator	**Faults**	**Safe /unsafe**	**Diagnostics possible using partial-stroke test**	**Tool**
Piston sealing	Leakage	Safe	Yes	Transit time or valve position
Spring broken	Actuator cannot move	Unsafe	Yes	Observing deflection
Piston stem	Stuck	Unsafe	Yes	Transit time, dead time, friction test
Solenoid valve				
Coil	Short-circuit	Safe		Transit time
Spring broken	Unable to vent	Unsafe	Only if solenoid valve is included in test	Transit time or valve position
Piston	Stuck	Unsafe	Only if solenoid valve is included in test	Transit time or valve position
Mechanical attachment				
Actuator/valve linkage	Mechanical play	Unsafe	Yes	Analysis of travel/time graph
Pneumatic connection	Leakage	Safe	Yes	Transit time or valve position
Valve				
Ball	Stuck	Unsafe	Yes	Transit time, friction test
Ball	Foreign body in seat	Unsafe	Full stroke test	Valve position, zero point shift
Seal	Leakage	Unsafe	Partly by performing a full stroke test	Valve position, zero point shift

The SIL rating is always based on a Safety Instrumented Function (SIF). The entire control loop is taken into account and not just the valve on its own. A control loop for safeguarding against excessive temperature, for example, consists of a temperature sensor, PLC, and valve together with all connecting lines and fittings. The valve itself in a safety loop comprises the actual final control element, the pneumatic actuator, solenoid valve to trigger emergency shutdown, and the limit switch (Fig. 2). The mechanical and electric connections as well as the pneumatic piping play a key role, particularly in the failure analysis as operational experience with control valves has shown. The way the valve is mounted is of major importance, e.g. integral attachment, assembly of components, or whether the pneumatic components are flange connected or hooked up.

In any case, the results achieved by theoretical and calculated analysis need to be critically assessed and compared with past plant experiences by process engineers. For instance, [7] shows that a diagnostic coverage greater than 70 % cannot be achieved. This conclusion is based on quantative data from the OREDA manual and refers to the conditions in offshore plants. Another example is illustrated by the procedure in the chemical industry which stipulates the use of two-channel instruments in the VDI 2180 standard and the NAMUR recommendation NE 31 in the risk area II covering higher risk. This kind of procedure proven in practice should not be just abandoned in favor of purely calculated results.

The reliablity of the diagnostics must be looked at more closely. In case of partial-stroke testing, the evidence that the test has actually been implemented is important, and not just the test procedure itself. Software-generated artifacts such as the feedback of obsolete data or even the incorrect display of a valve actuation that never actually took place, must be reliably prevented. After such evidence on the actual implementation of the test has been produced, the logging of parameters that bring more information can be beneficial. A whole range of modern diagnostic options in a positioner are available [2]. For example:

Fig. 2: Typical shut-off valve with actuator, solenoid valve, proximity switches

- Valve transit time
- Dead time
- Rise time
- Measured friction
- The use of supplementary sensors, for example, to measure the structure-borne noise to detect leakage

Other practices or parameters can also be used depending on the situation.

3 Implementation and integration in the plant

The article [7] describes the options for performing a partial-stroke test. The manual procedure is most common, where the valve stroke is limited by a mechanical device or by a groove/pin arrangement. The connected solenoid valve is triggered on site by service staff who also monitor the test procedure and document the results. Automatic partial-stroke testing procedures include:

- Control over the safety-related control loop where the solenoid valve is controlled either directly or by pulsing
- Use of a positioner with the option of moving the valve to a certain set point within the valve's operating range. This positioner can be used in addition to a solenoid valve or instead of a solenoid valve.

The second procedure (positioner) is the best option as the question involving real-time signal transmission is not significant because fast movements can be recorded directly at the valve and the diagnostic parameters transmitted locally thanks to the features of modern digital positioners [2]. Furthermore, the full function range of modern devices can be completely used. In safety loops, a limit switch is usually used in addition to the positioner with diagnostics and the solenoid valve. Position feedback is useful for more detailed monitoring. In case a positioner similar to Fig. 3 is used, all components are contained in one housing, which minimizes mechanical, electrical, and pneumatic connections in a particularly rugged design. The integration of all components into one housing is enhanced by the integral attachment of the positioner, minimizing the number of necessary connections to the actuator and valve, which makes them very robust and protects moving parts (Fig. 4).

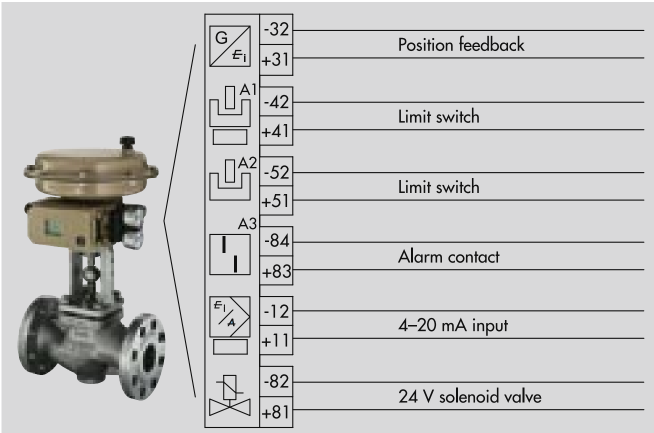

Fig. 3: Positioner with integrated limit switch and solenoid valve

In addition to the selected arrangement and design of individual components, which play a key role in the availability (PFD), the diagnostic method and the achievable results are determined by it to a great extent as well. The FMEDA explained in section 2 must therefore be based on the whole function block consisting of valve, actuator, accessories, the selected attachment, and the operating conditions in the intended process. Realistic ratings for the degree of diagnostic coverage can be achieved by including the diagnostics of the selected equipment in this special combination of devices and the particular environment. However, observing the components individually and adding up the individual results, even possibly based on laboratory investigations, is not regarded to be representational.

A partial-stroke test can be triggered either on site or over HART protocol. Alternatively, the test can be triggered automatically according to a time schedule. The necessary validation of the partial-stroke test, i.e. whether the test has actually been performed and the point in time when it took place, can be implemented particularly effectively when the described combination of devices is connected to a customary safety-related PLC. The limit switch in the positioner that functions independently from the microprocessor is set to the target value required to trigger the partial-stroke test. Its signal is logged, time-stamped, and stored by the safety-related PLC. This signal chain using exclusively certified components (limit switch, standard input of the safety-related PLC, PLC software) guarantees a reliable result (Fig. 5).

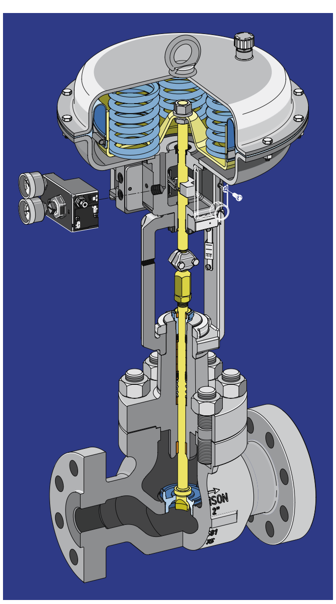

Fig. 4: Integral positioner attachment

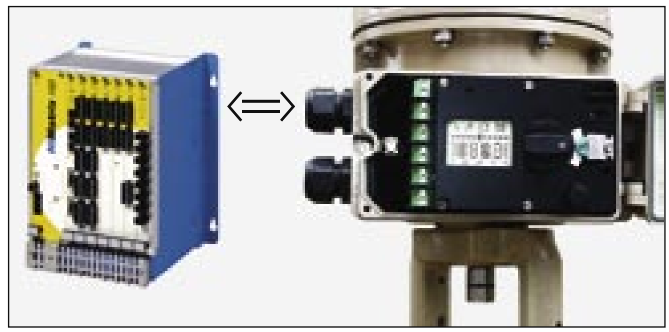

Fig. 5: Positioner with safety-related PLC to log the partial-stroke test

This instrumentation is particularly beneficial as only tested components available on the market are used which have already been proven in practice and whose reliablity has been verified. The use of specially developed instruments is avoided.

Integration into an existing automation plant needs to take into account any already existing structures. A valve in the safety loop that is capable of performing a partial-stroke test must be integrated in two ways. The safety function is triggered by the safety-related PLC, with solenoid valve being wired correspondingly. Similarly, the limit switch signal needs to be registered at this point. The integration into a standard asset management system, as part of the process control system, is particularly suitable for extensive diagnostics and analysis of the data logged in the positioner. Fig. 6 shows a corresponding set-up.

Fig. 7 demonstrates a possible set-up when shut-off valves and control valves are condensed into one unit. In this case, the control valve is constantly in action, requiring no additional triggering or, at the most, a very small impulse that does not affect the control process. The fundamental principle of prolonging test intervals through online diagnostics is still effective in this case.

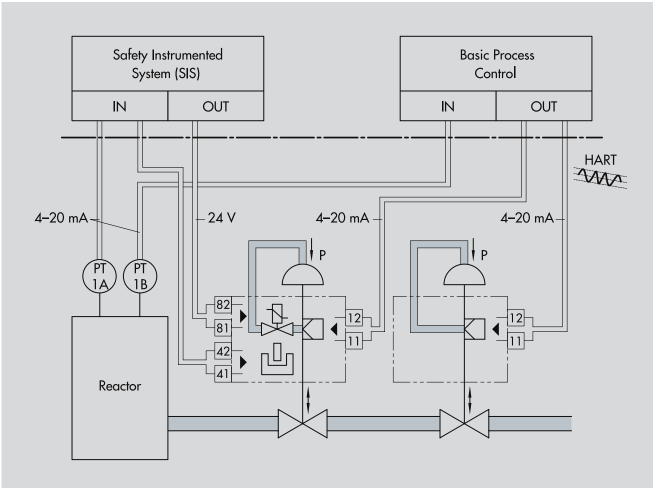

Fig. 6: Positioner set-up

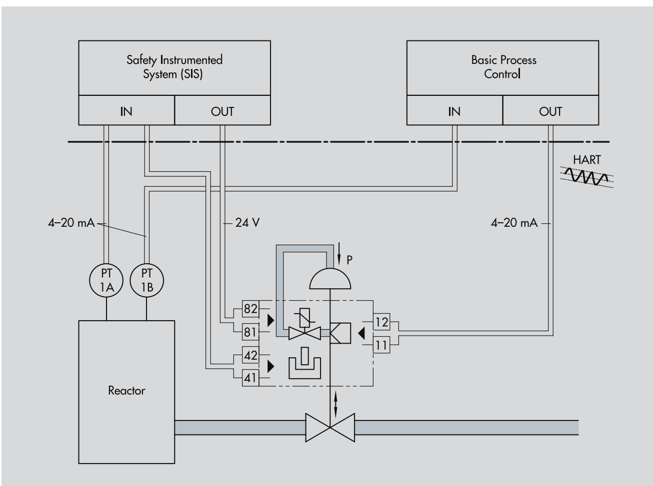

Fig. 7: Positioner 2 set-up

The solenoid valve is not needed if the positioner is certified similar to a solenoid valve for emergency shutdown, i.e. it switches off the power supply and reliably vents the pneumatic output. In place of the solenoid valve, the 4-20 mA input signal of the positioner is connected to the safety-related PLC. For this purpose, customary printed circuit boards for the PLC are available. Integration into the asset management system of the process control system to trigger the partial-stroke test and to transmit diagnostic data is performed exclusively over HART protocol in this case.

4. Extended options

As already described, the use of partial-stroke testing on a shut-off valve requires the attachment of a positioner, which replaces or upgrades the previously used solenoid valve. Due to this higher amount of investment, it makes sense to make full use of the available functions of this equipment.

As complete test coverage using online procedure such as partial-stroke testing is only possible in rare cases, the demand for complete testing of the shut-off valve remains. The selected method must fulfill the principle stipulated in IEC 61511, i.e. the functionality must be guaranteed after completion of the test. In theory, the failure rate for activation directly after the test must be zero. This kind of thorough testing is usually associated with plant shutdown. In practice, the safety loops are activated, partly even the leakage across the valve is measured, even removing the valves to examine them and to perform maintenance work in the workshop is common practice. Quantitative analysis, e.g. in the scope of an FMEDA, to determine which action is necessary to achieve complete test coverage, would be more appropriate.

Extended instrumentation with a positioner instead of a solenoid valve can be used to reduce cost of ownership. The essential objective must be to simplify testing also for offline tests using automation, where possible, while increasing the scope of the test statements. The prime objective is to avoid removing the valve from the pipeline as well as to shorten the test intervals for on-site tests, to automize the tests, and to simplify the necessary documentation procedures. Possible approaches are described below:

- Recording operating times, operating modes, the number of valve activations, and the strokes performed can help to predict wear and maintenance requirements. At the same time, these data can be used to make statements on the operational proof of the equipment.
- The operating conditions of valves can be monitored for exceeding permissible limits, for example, temperature or supply pressure, etc.
- Operating modes that accelerate wear can be avoided. For example, rigorous strokes at high speed to the final position can be avoided by appropriate damping.
- Activation of a normally open valve or a solenoid valve in the final position at regular intervals prevents seizure due to corrosion or material diffusion.

The precise way to proceed can only be determined when the process conditions are known as well as relying on operating experience. An analytic method similar to FMEDA would be recommendable in this case, providing a detailed comparison with the manufacturer’s experiences concerning general failure mechanisms and diagnostics.

5. Summary

Where field instruments are concerned, the selection of reliable components is of major importance, both in safety loops and in other applications [3]. Based on this, modern diagnostics can be used to reduce costs. Online tests can be used to prolong test intervals. The successful application of diagnostics requires a precise analysis of possible sources of failure and the exact comparison with available diagnostic methods. To fulfill these requirements, a process similar to an FMEDA is proposed, performed together by the plant operator and manufacturer. The tests can be validated using customary components available on the market. The method concerned and the applied diagnostics can also be used for inspection during plant shutdown.

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