Proportional Pressure Reducing Valves with Intrinsic Fail Safe Function

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During the last two decades the aspect of functional safety has constantly gained more importance for all manufactures of mobile hydraulic machines or manufactures of subsystems used therein. Initiated by the IEC 61508 /1/ first issued in 1998 many divisions have deduced their own standards concerning functional safety with the goal to build control structures that are leading to fewer occurrence of dangerous situations during normal machine operation as well as in the case of a failing subsystem.

Looking into the failure modes assigned to a Proportional Pressure Reducing Valve (PPRV) within the ISO standard 13849 /2/ it was possible to integrate an intrinsic safety function into various types of pressure reducing valves. In the case of a stuck valve spool this fail safe function opens a second flow path from the control port to tank (Figure 1) resulting in a limited output pressure (Figure 2). For applications where this limited control pressure is in accordance with a safe situation this fail safe function is lowering the number of failure modes that are contributing to a dangerous situation and therefore is able to increase the diagnostic coverage of a subsystem build with such a fail safe valve. Depending on the working principle of the pressure reducing valve different types of fail safe designs are needed in order to realize this functionality.

Keywords: functional safety, pilot valve, PPRV, fail safe function, pressure control valves

1 Introduction

Proportional pressure reducing valves are very often used for 'forced actions' as called by the ISO standard 13849 in its 'fault and fault exclusion Table' in Annex C. An energized valve is meant to activate a hydraulic function, which is generally accompanied by movements of large heavy objects. A malfunction of the pilot valve can result in a dangerous or even life-threatening situation. This article describes special design features of such pressure reducing valves that are able to compensate the outcome of some common malfunctions keeping the machine function still in a safe state.

2 Functional principle of a PPRV

Direct operating pressure reducing valves are working as force balancing regulators. The magnetic force FM is always counterbalanced by the sum of the spring force FS and the hydraulic force acting on the valve spool PA (see Figure 1). Under normal operation conditions the spool is dithering at its metering edge resulting in a constant metering flow of hydraulic fluid from the pump port into the control port and back from the control port into the tank. As long as the force balance is maintained the pressure at the control port (PC) is proportional to the magnetic force FM and thus proportional to the electrical current through the solenoid.

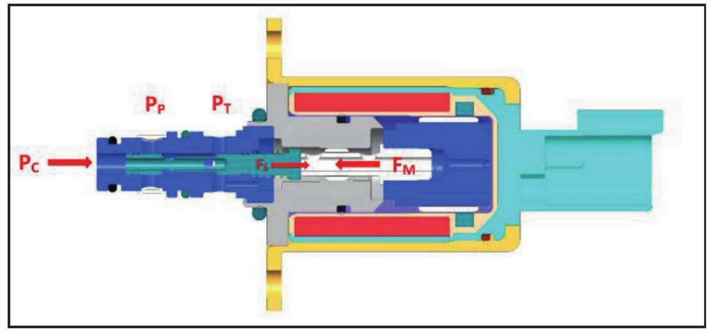

Figure 1: Force balance of a direct operating pressure reducing valve

Due to contamination or other mechanical influences it is possible that the spool gets stuck in its open position where the pump port is connected with the control port. In such a situation the control port pressure is rising within a short time to the level of the pump pressure and in standard application, where the PPRV is used as pilot valve, this is resulting in a fully actuated main stage (see figure 2). In mobile hydraulic applications such a scenario is mostly accompanied by a possible dangerous situation and has to be avoided by certain measures.

Depending on the strategy of the OEM there are different ways to avoid such uncontrolled movements. It is possible to use pilot valves that are extreme robust against a definite level of contamination and during normal operation the contamination level of the hydraulic fluid is always monitored and kept below a critical value. Other machine manufactures are implementing position sensors at the main spool of their sectional valves in order to detect actively an unmotivated actuation. In case of such an unwanted actuation the movement is stop by an on-off valve that shuts off the hydraulic supply to the sectional valve.

The following chapter will describe special design features that are able to keep the machine function still in a safe state although the pilot valves spool is stuck. This will be shown for two different valve types.

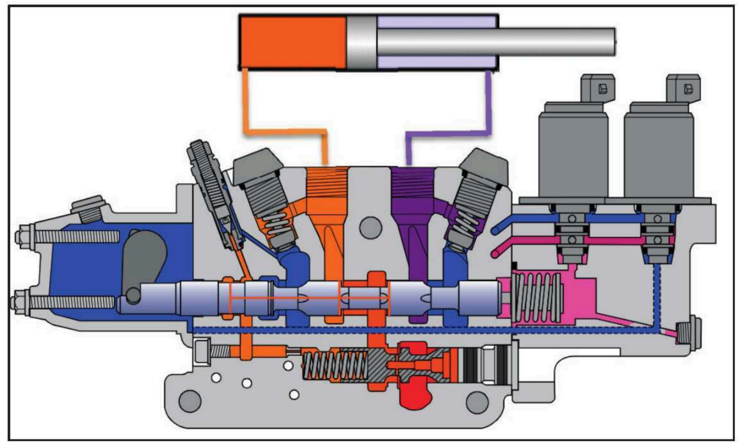

Figure 2: Sectional valve with two pilot valves. One energized and acting on a hydraulic cylinder.

3 Functional principle of the fail safe versions

In standard sectional valves the main spool always needs to travel a certain idle stroke until its metering edge comes into action. This is related to a certain minimum pressure at the control port of the pilot valve. Therefore not only a control port pressure of 0 bar is ensuring a not activated hydraulic function but also a pressure level significantly below that threshold pressure.

Figure 3 is describing how an additional flow path through the spool of a 25 bar valve is able to keep the control pressure below the critical value of – for example - 5 bar although the spool sticks at the metering edge. Under normal operation conditions the armature bar is closing the additional path with a sealing element. In the case of a stuck spool the armature bar retracts and opens the additional path to tank.

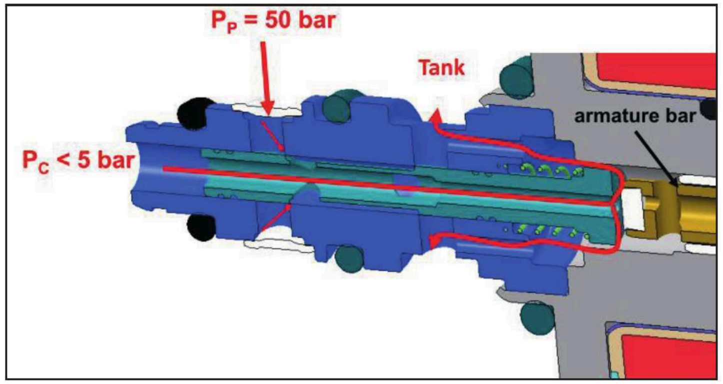

Figure 3: Functional principle of a fail safe valve. Basic type PPCD04 with nominal flow 4 l/min.

The residual pressure level in the control port depends on the flow restrictions of the different flow paths as well as on the supply pressure. The biggest influence has definitely the opening area that is created by the sticking spool at its P-metering edge. To be sure that the fail safe function is correctly and sufficiently working this opening area has to be limited.

Hence, a possible argumentation for the correct use of such a design feature as safety function must contain the exclusion of silting processes that are able to let the spool fully stuck open and additionally the particles that are causing the sticking spool have to be limited in size. The second condition is easy to ensure by the usage of filters meshes. A standard filter screen of a THOMAS PPRV has a mesh width of 125 µm. It is normally applied only to the pump port but if possible contamination with large particles through other ports cannot be excluded, additional filter elements at control and tank port are necessary. Figure 4 shows the pressure trace for a spool that got blocked during its retraction movement by a 125 µm thick wire and is therefore representative for the pressure situation of a particle of maximum size has entered the valve through from the pump port and blocked the spool.

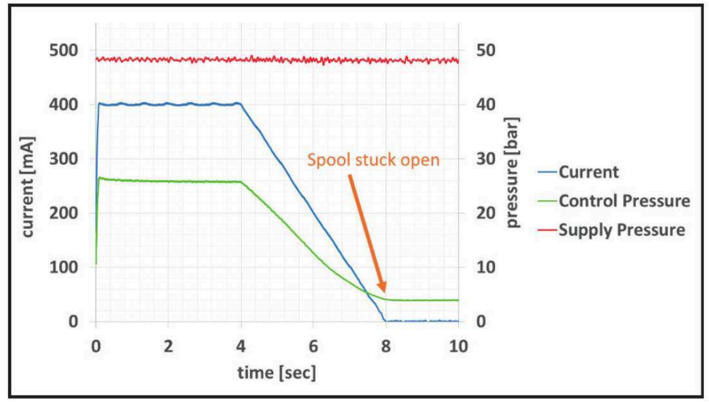

Figure 4: Pressure trace of an unenganged pilot valve with stuck open spool. 125µm thick wire opends the P-port.

The fail safe valve shown in figure 3 is a valve with a direct acting solenoid. The armature bar is applying the solenoid force directly to the spool. Due to the working principle of the balancing forces the spool diameter is limited and just as well is the flow capacity of such a valve restricted. Different valve types that are working with a pressure pin can compensate for this limitation – providing a higher flow capacity together with a normal reducing pressure range.

Figure 5 shows a cross section of such a PPCD06 valve. For this kind of pressure reducing valve it is also possible to open an additional flow path in the case that the spool is sticking right at the metering edge. The solution is realized by a spool, which is built out of two parts with two independent moving metering edges. During normal operation both parts are pressed together by the solenoid force on the one side and the hydraulic pressure in the control port on the other side. If the spool get stuck and the armature is retracted, the pressure pin opens an additional tank path and depressurizes the area behind the 'right' (see figure 5) part of the spool. Then the T-metering edge is opened and the flow from the pump port can be bypassed around the spool directly into tank resulting in a relatively low control pressure.

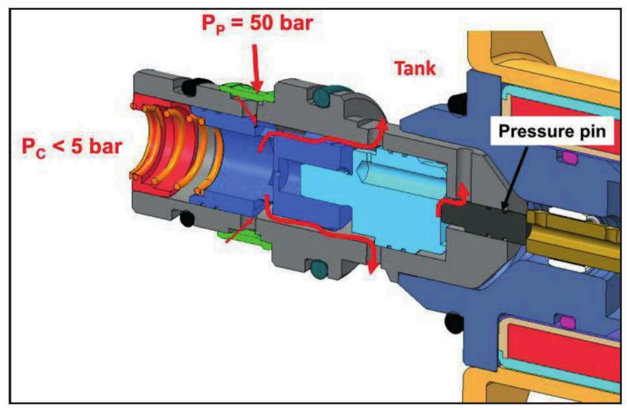

Figure 5: Functional principle of a fail safe valve. Basis type PPCD06 with nominal flow 16 l/min.

The biggest difference between the two fail safe features is their influence on the stability of the complete system. While the modified PPCD04 valve does not show any additional trend for instabilities the PPCD06 valve is more sensitive to instabilities due to the separately working metering edges. If such a valve is working against a closed control port and does not have to deliver any significant flow into the control port, no instabilities are visible (see figure 6a). As soon as the valve has to deliver some flow accompanied with a tendency for the spool to overshoot (see figure 6b) measures have to be taken in order to keep such instabilities under control. It is possible (see figure 7a) but the optimization between the overlap of the three metering edges (including the one at the pressure pin) and all possible dampening mechanisms inside the valve have to be precisely adapted to the valves load and overall stability over a large temperature range is extremely difficult to achieve. Especially fast commands (see figure 7b) have to be avoided or - to put it in other words – as long as the hydraulic system is not demanding a high dynamic behavior the fail safe valves can be used without large restrictions.

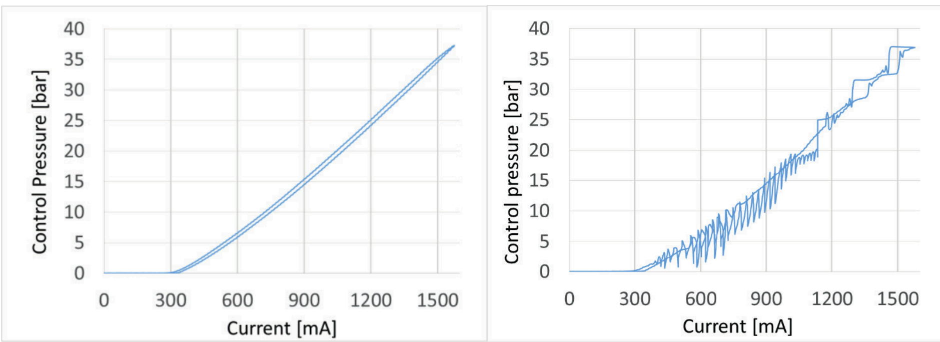

Figure 6: Left) PPCD06 fail safe working against a blocked port. Right) same valve working against a sectional valve.

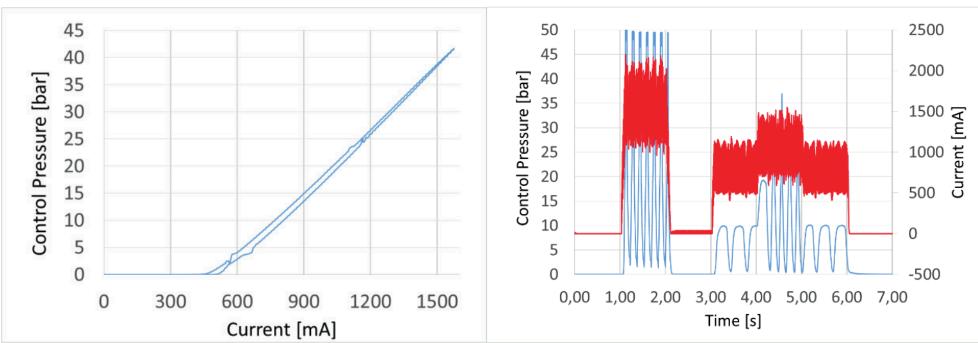

Figure 7: Left) Optimized PPCD06 valve working against a sectional valve. Right) Step response test with the same setup.

4 Limitations and restrictions

In the previous chapter it was discussed that the residual pressure of a valve with sticking spool is depending on the used pump pressure as well as the p-port opening given by the stuck spool. The graph in figure 8 shows the residual control pressure of a 25 bar fail safe PPRV where the metering edge is kept open by a metal wire simulating a large hard particle out of the initial contamination that are usually present in hydraulic systems. These measurements clearly reveal that the maximum size of the particle that can possibly cause the blockade has to be limited to 300 µm in order to use not more than 50% of the pilot valves pressure range for the idle stroke of the main section. In system where this cannot be assured and where silting effects as source for a sticking spool cannot be excluded the maximum residual pressure has to be limited by a general flow restriction from the pump port into the pilot valve.

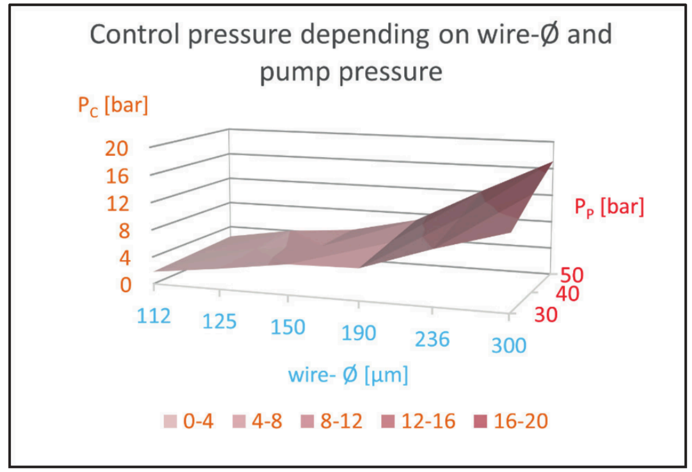

Figure 8: Residual control pressure of a PPCD04 Fail Safe valve with respect to the pump pressure and the opening area at the p-metering edge.

Figure 9 displays the residual control pressure of a 25 bar Fail Safe PPCD04 with a fully opened sticking spool and with different orifices implemented in the pump line. With such a general flow restriction it is possible to ensure a safe system situation independent from the actual clamping position but at the same time this goes along with a significant loss in dynamic behavior.

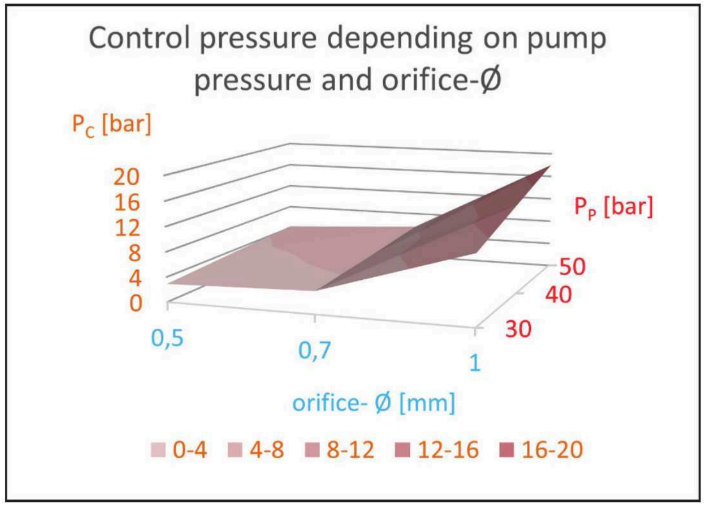

Figure 9: Residual control pressure of a PPCD04 Fail Safe valve with respect to the pump pressure and an additional orifice.

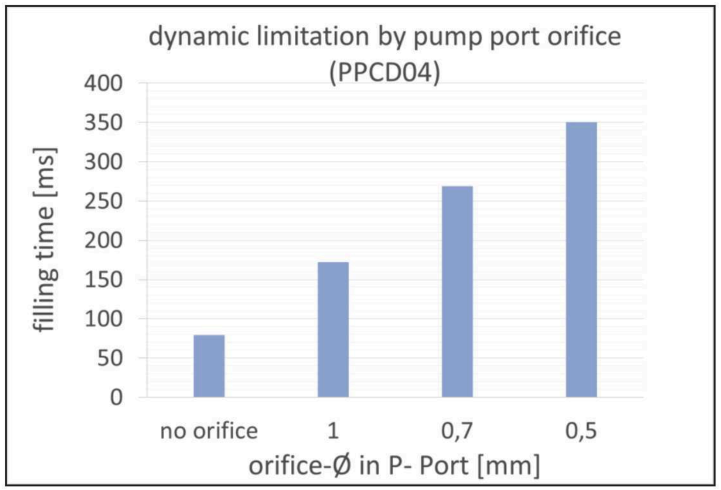

Figure 10: Dynamic limitation by an additional orifice.

In figure 10 the filling time of a spring loaded piston (complete suppressed volume = 6 ml) with a p-restricted Fail Safe valve is shown.

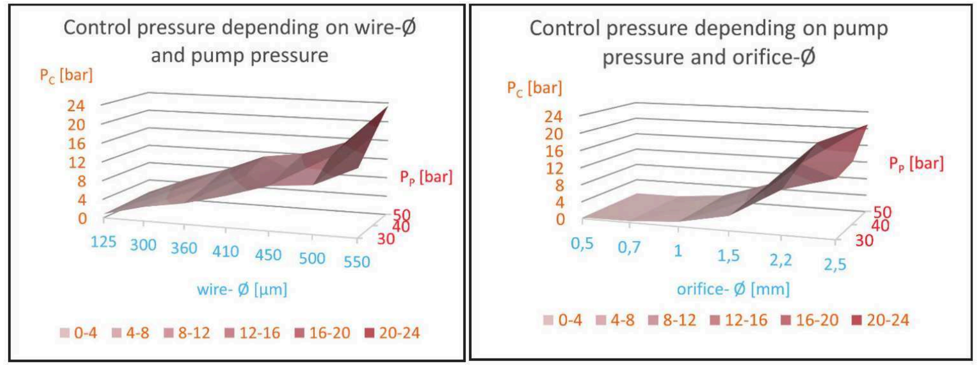

Figure 11: Residual pressure with and without additional orifice for a PPCD06 Fail Safe valve.

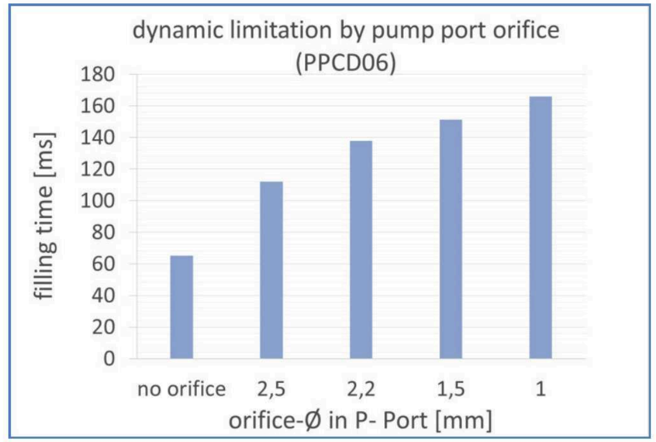

Figure 12: Dynamic performance of a PPCD06 Fail Safe valve with an additional flow restriction.

Figure 11 and 12 are displaying the results of identical measurements done with a 32 bar Fail Safe PPCD06.

For each individual system a compromise has to be found between the dynamic requirements and the allowed residual control pressure. Once such a compromise is found the rating of the complete system concerning its functional safety level can be improved significantly.

5 Influence on the functional safety rating

In general the rating of mechatronic systems with respect to the regulations of ISO 13489 are mainly determined by the influence of their hydraulic or pneumatic components. Electronic components normally do have reasonable large MTTFd values and it is relatively easy to implement diagnostic functions in order to accomplish a high diagnostic coverage (DC) value. Hydraulic and pneumatic components with their standard performance are generally those parts of a mechatronic system that are responsible for a low safety rating. The usage of Fail Safe PPRVs can significantly enlarge the DC value of a linear (not redundant) signal chain.

Taking as an example an electrohydraulic that is used as pilot system for a sectional valve actuator (see figure 13). Its main signal chain consisting of a CAN input signal, a microcontroller as CPU and field effect transistors to modulate PWM signals that are controlling the currents through the coils of the pilot valves. For such an electrohydraulic actuator a reasonable Safety Function in terms of ISO 13489 can be defined as 'Ensure a low enough pressure output at both working ports of the pilot valves if the input signal is indicating neutral position for the sectional valve'.

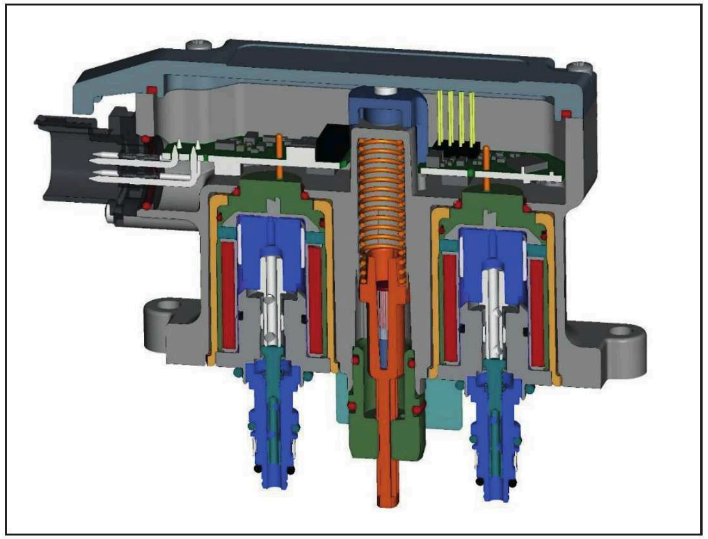

Figure 13: Cross section of the electrohydraulic actuator.

The single components of the active signal chain for that Safety Functions together with their assigned MTTFd and DC values are displayed in figure 14 and figure 15. The first figure shows the reliability model of a system with standard PPRVs as pilot valves while the second contains Fail Safe valves. In both cases the pilot valves are the components with the lowest MTTFd and DC values. The MTTFd value of 150 years is justified by the design rules for pressure valves given in table C1 and C2 of ISO 13849 and this value has to stay constant independent on the number of possible failure modes that are resulting in dangerous system situations. This argumentation is the reason for a constant MTTFd value of 29.1 years for both reliability models. The usage of Fail Safe PPRVs is not decreasing the probability for a safety relevant incident to happen but out of the three dangerous failure modes (Table C6 in ISO 13849) the number of detected and compensated failures is increased from one to two. This results in a significant larger diagnostic coverage value - for the signal component (33% -> 66%) as well as for the complete signal chain (71% -> 84%).

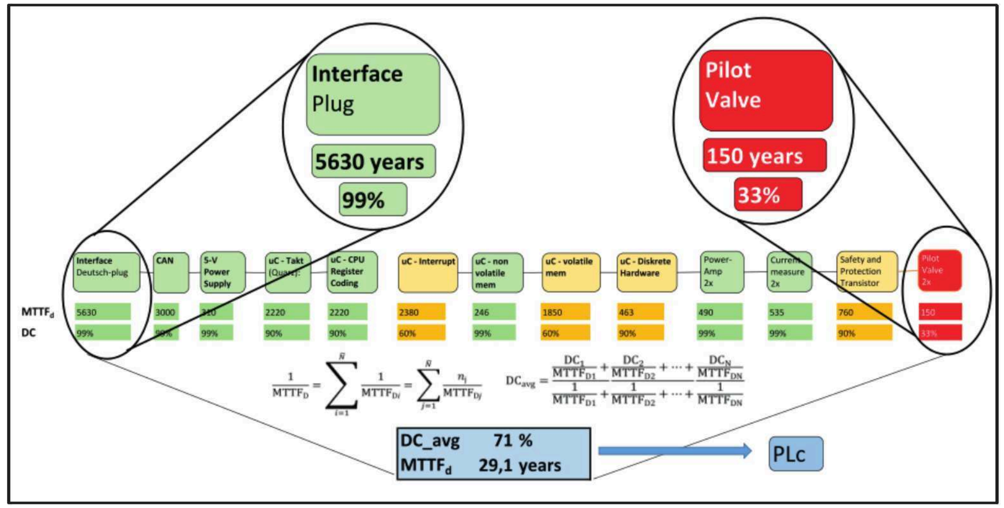

Figure 14: Reliability model of main signal chain for an electrohydraulic actuator with standard PPRVs.

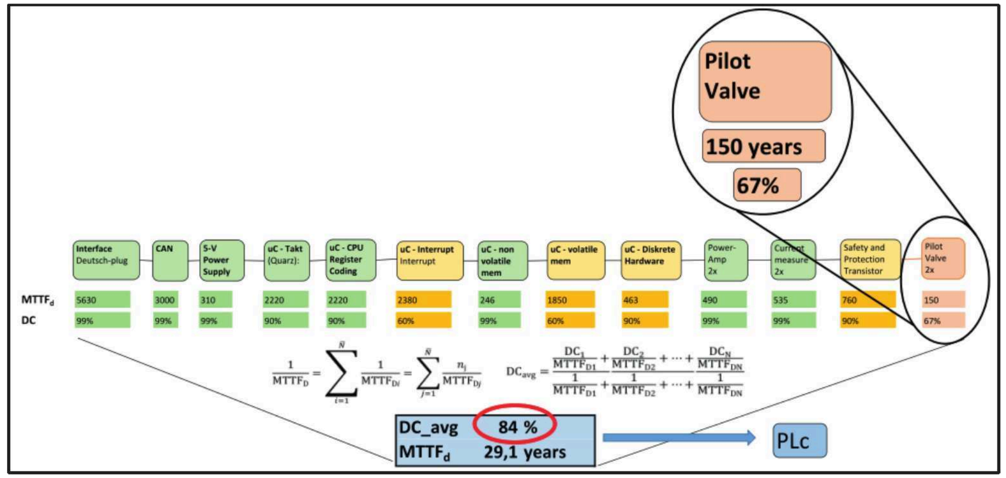

Figure 15: Reliability model of main signal chain for an electrohydraulic actuator with standard PPRVs.

In the given example the increased DC value does not lead to a change in the overall performance level of the product but this can be different depending on the systems structure and safety related characteristics of the other components of the signal chain.

In any case the usage of a Fail Safe PPRV is able to enlarge the safety level of a system that uses proportional pressure reducing valves as long as the safe situation is accompanied with an unengaged pilot valve.

References

/1/ IEC 61805: Functional safety of electrical/electronic/programmable electronic safety-related

/2/ ISO 13849: Safety of machinery - Safety-related parts of control systems