International Journal of Occupational Safety and Ergonomics (*JOSE*) 2006, Vol. 12, No. 1, 105–115

NOTES

Safety Studies on Hydraulic Proportional Valves With Electrical Position Feedback

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The authors analysed a proportional valve with electrical position feedback for its failure behaviour. Several failures were introduced into the feedback loop, especially into the 2 solenoids and the inductive position transducer. The behaviour of the valve for square and ramp reference signals was recorded and systematically analysed. It was shown that failures could be detected by monitoring the residual signal from the equipment under control or the residual signal from the sensor. It was possible to achieve the safe position within twice the normal response time of the valve by switching off the current of both solenoids. The application of these results for a new generation of safe proportional valves is discussed. The use of the results of these investigations obviates the need for redundancy of the electrical position monitoring arrangement in a safe proportional valve.

proportional value electrical position feedback failure behaviour
hydraulic safety fault detection

1. INTRODUCTION

Proportional valves are currently permitted in safety applications only if both solenoids are switched off during a safety-related operation (e.g., the opening of a movable safety guard) [1, 2]. The safety function of a valve is thus the stopping of a movement or the avoidance of an unintended start-up by virtue of its closed position. For certain applications (e.g., in robotics), a safe proportional valve position is desirable for assurance of a safe reduced velocity. In this case, the hydraulics must be switched to a conventionally generated safe flow, which leads to additional costs. Most proportional valves employ position monitoring by means of a linear variable differential transducer in a closed-loop control. A key question is whether faults in the position monitoring unit can be detected sufficiently early to switch off both solenoids of the valve and place it in the off position using the integrated spring.

The authors wish to thank the Japanese Government for financing the stay of Tetsuya Kimura at the BG Institute for Occupational Safety and Health (BGIA).

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Standard No. EN 954-1:1996 [3] requires, for category 3 electronic control systems, that the requirements of category B be fulfilled, that well-tried principles be used, that a single fault should not lead to the loss of the safety function [2, 3, 4], and that whenever reasonably practicable individual faults must be detected during or before the next demand on the safety function. Faults in the digital PID (proportional integral derivative) controller or in the position transducer can simulate an incorrect valve position (faulty monitoring) or insufficient control of the valve position (faulty PID loop). The present paper simulates these faults in the form of a worst-case scenario. It was demonstrated that all faults in the worst-case scenario could be detected during or before the next demand on the safety function with the use of additional hardware or software. A proposal for low-cost, efficient changes to commercially distributed valves will be given in the final section of this paper. The response time of the hydraulic system was measured and constitutes the limit for safety applications, e.g., in robotics, where a safe proportional valve position is necessary. A new generation of proportional valves with a safe proportional valve position can be developed on the basis of these results.

2. EXPERIMENTAL SET-UP

The authors used the commercially available 4WRE 6E16-2X/G24K4V 4/3 proportional directional valve (nominal flow 4.23 GPM), directly controlled, with electrical feedback, from Mannesmann Rexroth (Germany) together with a VT-VRPD PID controller to introduce worst-case faults into the monitoring system and solenoids under laboratory conditions and in the absence of load differences. Valve behaviour was analysed.

The hydraulic valve [5] was connected to a mobile hydraulic system operated at a pressure of 100 bar. During the experiment, the pressure was varied between 50 and 200 bar in order to detect a possible influence of the response time with both solenoids switched off. No failures were introduced into the hydraulic circuit.

The two solenoids and the inductive position transducers were connected to the VT-VRPD-2-1X/Y0/0 digital amplifier [6]. The digital amplifier was programmed through an RS 485 serial interface by means of the BODIV PC program (user interface for digital amplifiers) [7]. As shown in Figure 1, we monitored voltage on solenoid A using channel 1 (CH1) of a Tektronix (USA) TDS 3014B four-channel digital oscilloscope [8], solenoid B on channel 2 (CH2), the valve actual position on channel 3 (CH3) and the valve reference position on channel 4 (CH4).

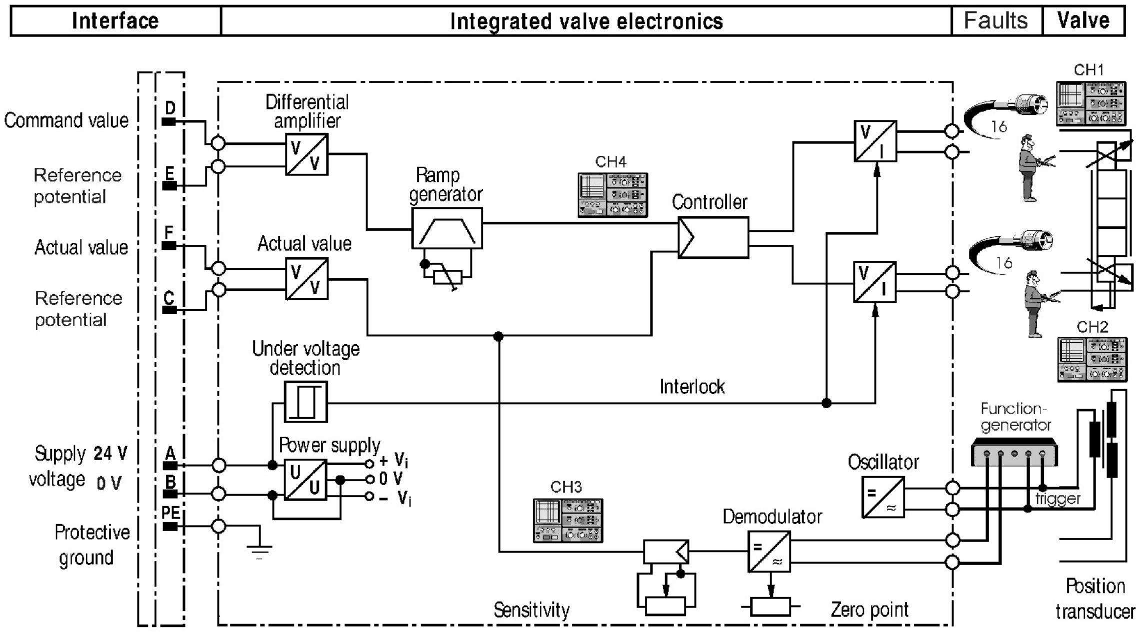

Figure 1. Schematics of the experimental set-up. *Notes.* CH—channel.

TABLE 1. Overview of the Experiments

Case	Pressure (bar)	Reference Signal	Failure	Rod Response	Comment (Trigger in Time)
1	100	0% constant	Modify position to +100%	1-way rightward motion, maximum speed	Begins rightward motion and continues, maximum speed
2	100	0% constant	Modify position to –100%	1-way leftward motion, maximum speed	Begins leftward motion and continues, maximum speed
3	150	0% constant	Solenoid B cut-off	No motion (no response)	Triggered at –15% manually, 150 bar
4	100	0% constant	Solenoid A cut off	No motion (no response)	Triggered at -20% manually
5	100	0% constant	Modify position to 0%	1-way slow motion	Stops and waits, then starts rightwards very slowly and accelerates
12	100	±25% ramp, 1 s	Modify position to 0%	Strong reversing movement	
13	100	±25% ramp, 1 s	Modify position to +50%	1-way rightward motion, maximum speed	
15	150	±25% ramp, 1 s	Solenoid B cut-off	Stop	Failure at –40%, triggered manually
16	100	±25% ramp, 1 s	Solenoid A cut-off	Stop	Failure at –5%, triggered manually
17	150	±25% ramp, 1 s	Add resistor (15.9 Ω) to solenoid B	Continued motion without change	Failure at –25%, triggered manually
18	150	±25% ramp, 1 s	Add resistor (15.9 Ω) to solenoid A	Continued motion without change	Failure at 0%, triggered manually
19	150	±25% ramp, 1 s	Add resistor (15.9 Ω) to solenoid A, 16.2 Ω to B	Continued motion without change	Not triggered
22	100	±25% square, 1 s	Modify position to 0%	Strong reversing motion	
23	100	±25% square, 1 s	Modify position to +50%	1-way rightward motion, maximum speed	
24	100	±25% square, 1 s	Modify position to –50%	1-way leftward motion, maximum speed	
25	150	±25% square, 1 s	Solenoid B cut-off	Drifts to right with stop-start	Failure at –25%, triggered manually
26	100	±25% square, 1 s	Solenoid A cut-off	Drifts to left with stop-start	Failure at –25%, triggered manually
27	150	±25% square, 1 s	Add resistor (15.9 Ω) to solenoid B	Continued motion without change	Failure at –30%, triggered manually
28	150	±25% square, 1 s	Add resistor (15.9 Ω) to solenoid A	Continued motion without change	Failure at –30%, triggered manually
29	150	±25% square, 1 s	Add resistor (15.9 Ω) to solenoid A, 16.2 Ω to B	Continued motion without change	Not triggered
30	150	±25% square, 1 s	No failure		Normal movement
41	100	±100% ramp, 1 s	Solenoid A, B cut-off	Stop	Cut off at approximately –40%
43	200	±100% ramp, 1 s	Solenoid A, B cut-off	Stop, 22 ms for 7.7 V = 77% (0.35 V/ms=3.5%/ms)	Cut off at approximately –80% triggered manually
45	50	±100% ramp, 1 s	Solenoid A, B cut-off	Stop, 24 ms for 8.3 V = 83% (0.35 V/ms = 3.5%/ms)	Cut off at approximately 70% triggered manually

Several failures were introduced for study of the closed-loop system's failure behaviour. To simulate solenoid faults, resistors of 16 Ω (normal resistance: between 2 and 3 Ω) were inserted between the solenoid and *z*2 and/or *z*6 of the digital amplifier (see [6]). One or both solenoids' connection to the control was broken in some experiments. To simulate incorrect positions or a faulty feedback, a frequency generator (function generator in Figure 1) was connected between *z*16 and *z*14 [6] and its frequency triggered with the oscillator of the digital amplifier. We adjusted the frequency manually at *z*16 and *z*14 to the oscillator frequency (see Figure 1). The valve reference position was modified with changes to the voltage bias at *z*14 or a phase shift between oscillator and demodulator frequency.

This experimental set-up enabled us to simulate uncontrolled command and control behaviour [2, 3, 4]) on the directional control valve. The influence of purely hydraulic faults on electronic signal processing, such as failure to switch or incomplete switching, was also simulated with modification of the valve reference position to a static signal. This is electrically equivalent to a fault in the valve's moving component. In the same way, it was possible to simulate an automatic change in the initial switching position of the moving component. Changes in the voltage of current converters were simulated by changing coil impedances. In particular, electrical and mechanical faults in the position transducer were introduced by manipulating the valve reference position. Worst-case faults such as breaks in coil conductors or in the position transducer were also introduced. The behaviour of the system was fully recorded with four oscilloscope channels.

Table 1 provides an overview of the experiments executed. The reference signal was kept constant: a ±25% ramp of 1 s or a ±25% square signal was generated by connecting a personal computer to the RS 485 interface. To investigate the functional limits in the event of a failure, ramps with 100% amplitude were also introduced. The step response was recorded by changing the reference signal to +100% and –100%.

Table 1 shows only the experiments with the worst-case behaviour. In most of them, the digital amplifier detected the fault (error 11) and switched off within 100–500 ms. When studying the control system's behaviour in the event of a fault, the latter cases were not analysed further.

3. ANALYSIS OF FAILURE BEHAVIOUR

Figure 2 shows the control signals for the digital amplifier with no faults inserted (Case 30 in Table 1). For the two solenoids, the coil current is pulse-width modulated. In order to facilitate easy interpretation of these signals in the following figures, we will show the integrated data (integration by trapezoid rule with $\Delta t = 100\ \mu s$) of both signals. The information on actual and reference positions will also be shown as the difference between the two signals. The diagram shown in Figure 2a provides information over the full time span of the experiment shown in Figure 2b. The expansion in Figure 2a was necessary in order to show the pulse-width modulation of the two solenoids.

Careful study of Figure 2b shows that the difference between the integrals of coil currents is a measure for the movement of the rod. Further, we analyse some experiments with introduced faults to show whether the two items of information in Figure 2b could be used to detect faults. Figures 3a and b show the diagrams of Case 5, in which the actual position was forced to 0 at 0 s and of Case 1, in which the actual position was forced to 100% at 0 s.

The two cases represent the worst-case failure during avoidance of unintended start-up. The position transducer or the electronic processing arrangement of the actual position signal is faulty. In Figure 3a, it cannot change any longer and in Figure 3b, it jumps to the maximum position and forces the valve to follow, which initiates rod movement at maximum velocity. The response of the rod in Case 5 is to stop temporarily and then to start to move rightwards, at low velocity and accelerating. This is exactly what can be seen in the lower diagram of Figure 3a. The response in Case 1 is for the rod to begin rightward movement at maximum velocity. Due to the fact that Figure 3b shows only one tenth of the time interval given in Figure 3a, the lower diagram depicts the movement

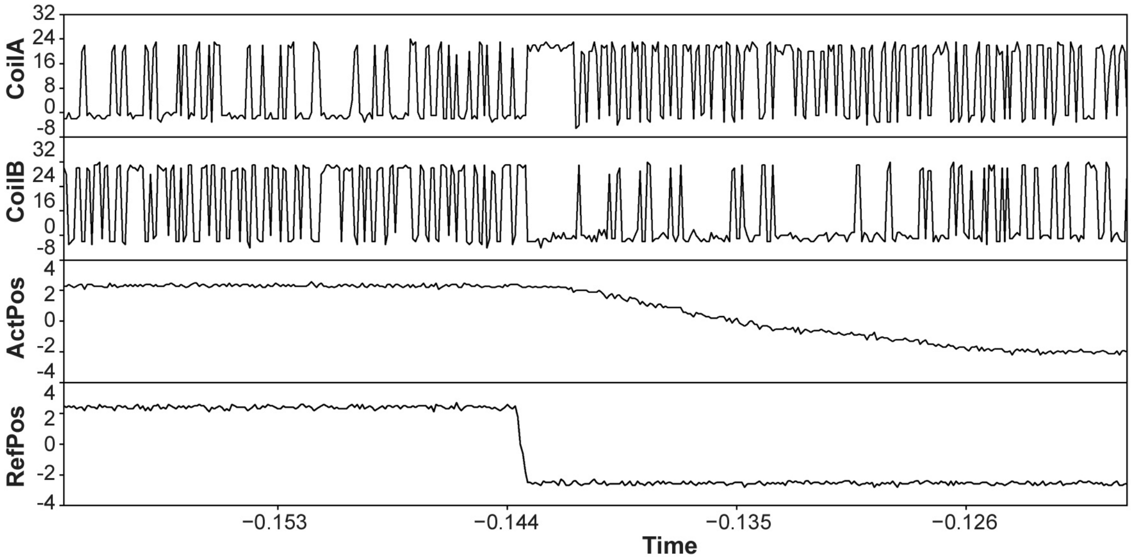

Figure 2a. Diagram (raw data) for fault-free operation of the valve (time in s, voltage in V). *Notes.* CoilA, CoilB—currents of solenoids; RefPos—reference position, ActPos—measured actual position.

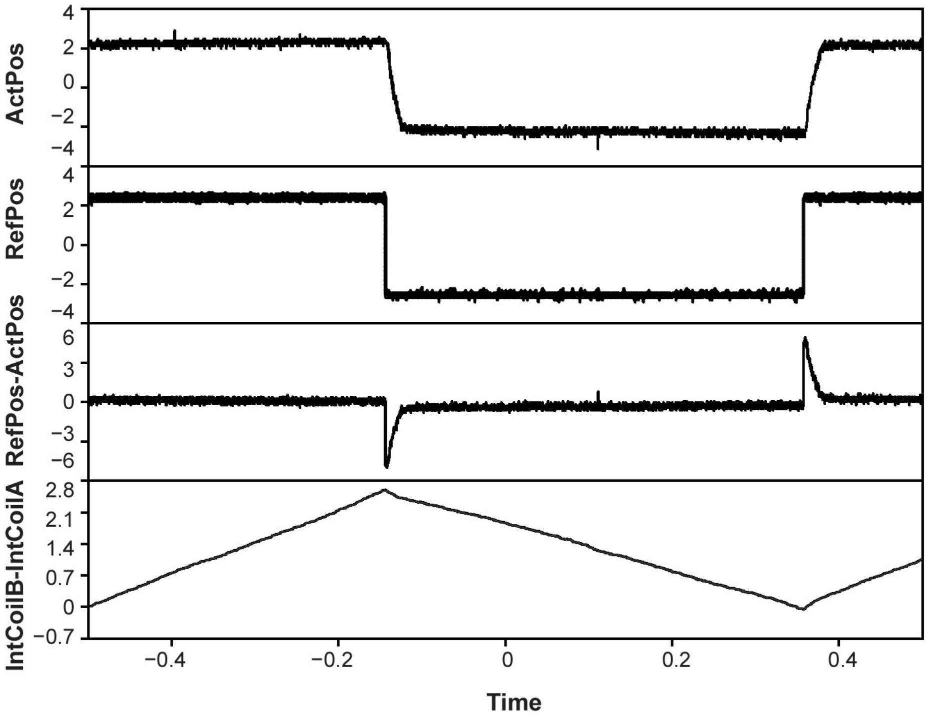

Figure 2b. Diagram (integrated data) for fault-free operation of the valve (time in s, voltages in V). *Notes.* RefPos—reference position, ActPos—measured actual position; IntCoilA, IntCoilB—integrals of measured coil signals.

of the rod. It appears that failures in the position transducer or its signal processing arrangement can be detected by monitoring the difference between the integrals of the signals on the two coils of the valve. Figure 2 also suggests that the difference between the integrals is a measure for the changes in the hydraulic flow created by the valve. In the case of a changing reference position, we expect a change in the difference between the integrals. Given a constant reference position, a change in the difference between the integrals is an indicator of failure of signal processing of the actual position.

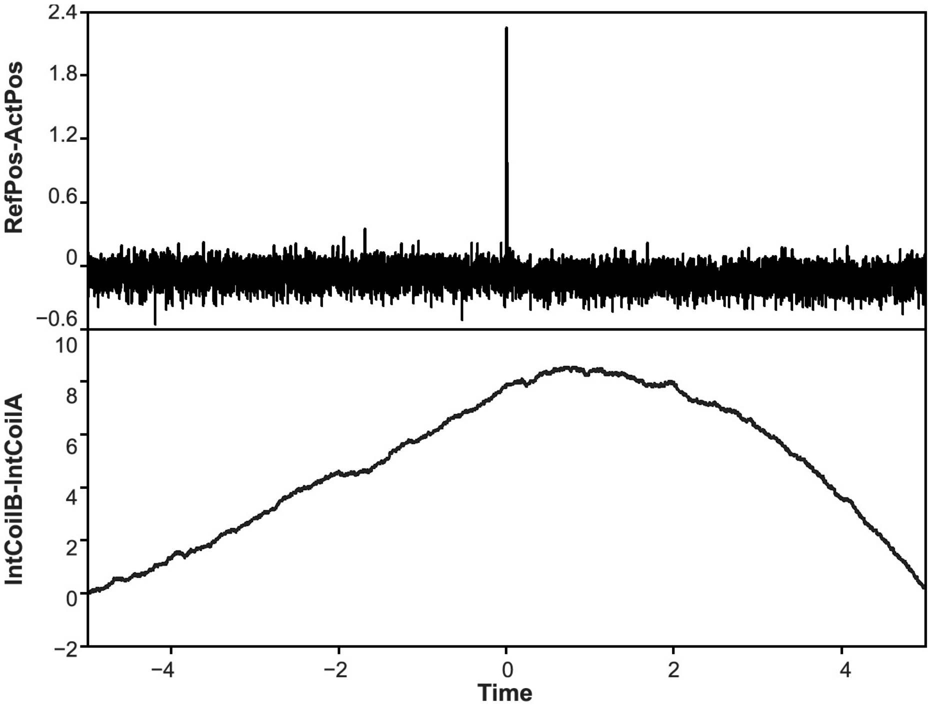

Figure 3a. Actual position forced to 0. *Notes*. RefPos—reference position, ActPos—measured actual position; IntCoilA, IntCoilB—integrals of measured coil signals.

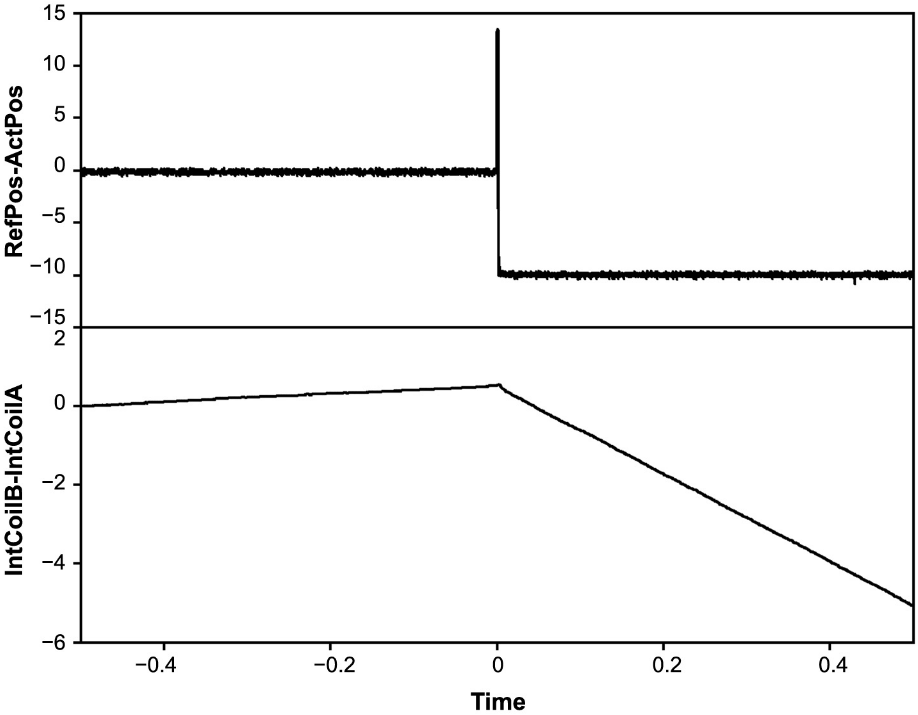

Figure 3b. Actual position forced to 100%. *Notes*. RefPos—reference position, ActPos—measured actual position; IntCoilA, IntCoilB—integrals of measured coil signals.

In Figure 4, we modified the control of the solenoids (see Cases 16 and 18). In the first case (Figure 4a) we interrupted the connection to solenoid A, and in the second case, inserted a resistance of 16 Ω into the connection of the coil. The observed response of the rod was to stop in Case 16 and unchanged continuation of movement in Case 18 (Figure 4b). In both cases, changes can be observed in the actual position (and also in the difference between reference and actual positions)

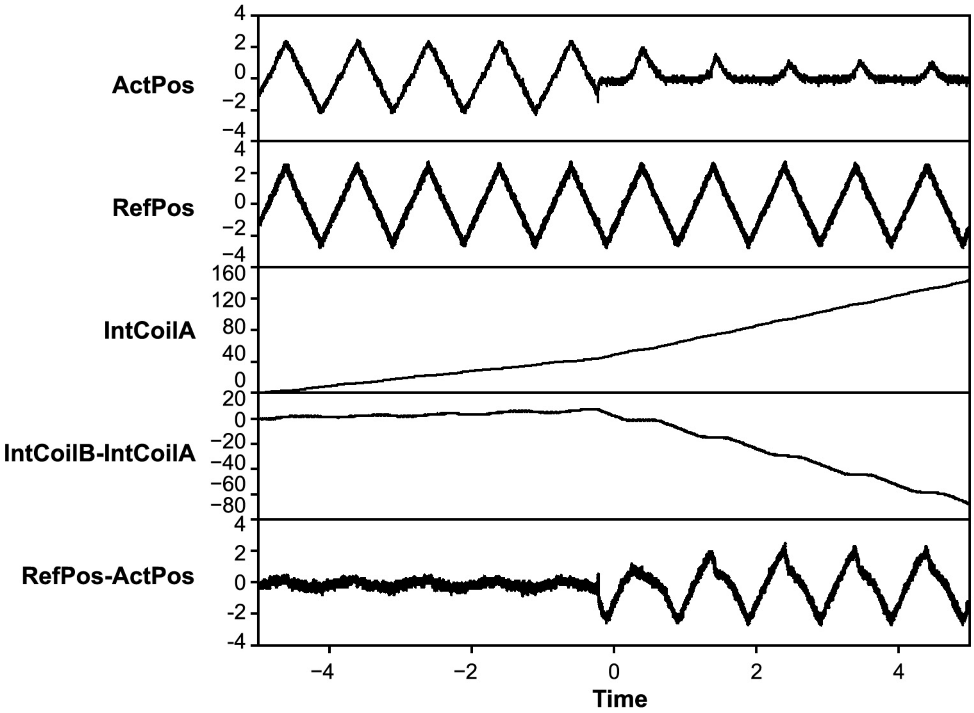

Figure 4a. Solenoid A current cut at –0.2 s. *Notes*. RefPos—reference position, ActPos—measured actual position; IntCoilA, IntCoilB—integrals of measured coil signals.

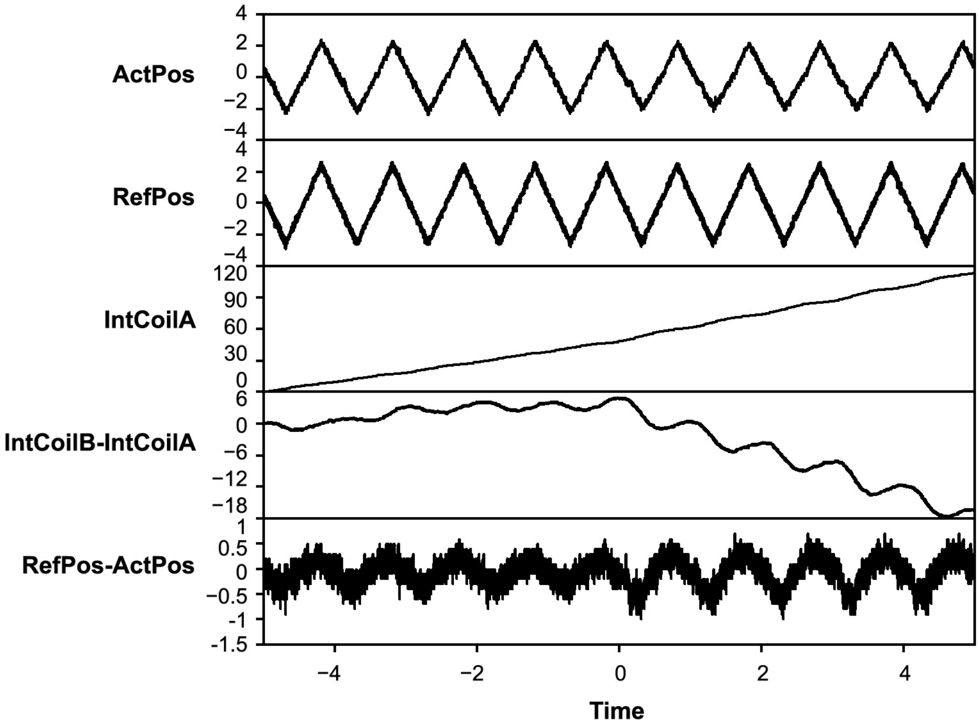

Figure 4b. Solenoid A 16 Ω at 0 s. *Notes*. RefPos—reference position, ActPos—measured actual position; IntCoilA, IntCoilB—integrals of measured coil signals.

and in the difference between the integrals. Likewise in Case 18, in which a change in the movement of the rod is not easy to observe, the difference between reference and actual positions and between the integrals indicates a failure in the solenoid or its signal processing. The same was observed for a modification of the current to both coils.

The final investigation necessary was measurement of the response of the valve in a case in which the current to both solenoids is cut off in the event of failure. We expected a response time of 30 ms for a 100% amplitude at the coils (worst case) based upon the data sheet.

In Figure 5 the response time at different pressures was measured. This is 24 ms for Case 43 and 28 ms for Case 45. The current to both solenoids was cut off at a relatively high reference position, resulting in an amplitude of between 76 and 81%. Careful investigation of the experiment depicted in Figure 2 shows the step response time of the valve for a 25% amplitude to be 20 ms. According to the data sheet, approximately 27 ms is expected for an amplitude of 100%. This is the worst-case time required for detecting a fault from the difference between reference and actual positions. Together with the response time determined in Figure 5, a safe state can be achieved within twice the response time of the valve.

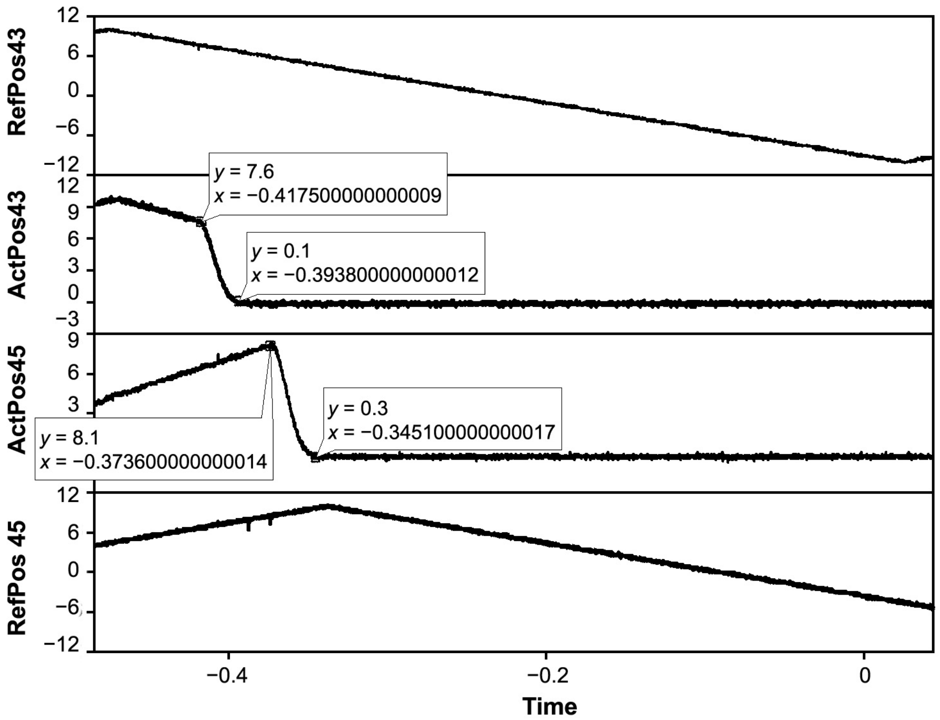

Figure 5. Response time in the event of failure for 200 bar (Case 43) and 50 bar (Case 45). *Notes.* RefPos—reference position, ActPos—measured actual position.

4. DISCUSSION

Figure 6 shows the feedback structure of the system, where the sub-systems are

- P: equipment under control (EUC) = valve,
- C: controller = digital amplifier,
- S: sensor = position transducer,

and the signals are

- *r*: reference position = RefPos,
- *u*: control input to EUC (difference of currents or voltages for the two solenoids) = CoilB – CoilA,
- *y*: true actual position, which is proportional to the motion of the rod,
- *z*: measured actual position = ActPos,
- *e*: error = RefPos – ActPos,

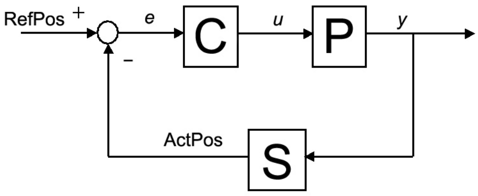

Figure 6. Schematic control diagram of the proportional valve control loop. *Notes.* C—controller, P—equipment under control, S—sensor; RefPos—reference position, ActPos—measured actual position; *e*—error, *u*—control input, *y*—true actual position.

and the signal relationships become

$$r \to y\colon y = \frac{\mathrm{PC}}{(1+\mathrm{PCS})}\,r, \text{ and}$$
$$r \to u\colon u = \frac{\mathrm{C}}{1+(\mathrm{PCS})}\,r.$$

Here we assume, in a normal situation, a gain of C >> 1 (the controller is highly sensitive to the error signal *e*) and that S = 1 (sensor signal *z* is the same as *y*).

This implies that 1 + PCS is nearly equal to PCS (C >> 1). Thus in a normal situation

$$\begin{aligned} r \to y\colon y &= \frac{\mathrm{PC}}{(1+\mathrm{PCS})}\,r = \frac{\mathrm{PC}}{(\mathrm{PCS})}\,r \\ &= \frac{\mathrm{PC}}{(\mathrm{PC})}\,r = r, \text{ and} \\ r \to u\colon u &= \frac{\mathrm{C}}{(1+\mathrm{PCS})}\,r = \frac{\mathrm{C}}{(\mathrm{PCS})}\,r \\ &= \frac{\mathrm{C}}{(\mathrm{PC})}\,r = \frac{1}{\mathrm{P}}\,r. \end{aligned} \tag{1}$$

We now distinguish the failure cases: fault in S, fault in P and fault in C.

When a part of the sensor is subject to failure, e.g., S becomes S':

$$\begin{aligned} r \to y\colon y &= \frac{\mathrm{PC}}{(1+\mathrm{PCS'})}\,r = \frac{\mathrm{PC}}{(\mathrm{PCS'})}\,r \\ &= \frac{\mathrm{PC}}{(\mathrm{PCS'})}\,r = \frac{1}{\mathrm{S'}}\,r, \text{ and} \\ r \to u\colon u &= \frac{\mathrm{C}}{(1+\mathrm{PCS'})}\,r = \frac{\mathrm{C}}{(\mathrm{PCS'})}\,r \\ &= \frac{\mathrm{C}}{(\mathrm{PCS'})}\,r = \frac{1}{(\mathrm{PS'})}\,r. \end{aligned}$$

In this sensor failure case, both $r \to y$, $r \to u$ relationships are changed.

The residual signal could therefore be

$$\begin{aligned} \mathrm{R_S} &= u - \frac{1}{(\mathrm{PS'})}\,r, \\ \mathrm{R_S} &= y - \frac{1}{\mathrm{S'}}\,r. \end{aligned} \tag{2a}$$

Since we did not measure *y*, we substitute *y* with

$$\begin{aligned} &\frac{1}{\mathrm{S'}}\,z\colon\ \mathrm{R_S} = \frac{1}{\mathrm{S'}}\,(z-r), \text{ or} \\ &\mathrm{R_S} = -\frac{1}{\mathrm{S'}}\,e = -\frac{1}{\mathrm{S'}}(\text{RefPos} - \text{ActPos}). \end{aligned} \tag{2b}$$

When a part of the EUC is subject to failure, e.g., P becomes P':

$$\begin{aligned} r \to y\colon y &= \frac{\mathrm{P'C}}{(1+\mathrm{P'CS})}\,r = \frac{\mathrm{P'C}}{(\mathrm{P'CS})}\,r \\ &= \frac{\mathrm{P'C}}{(\mathrm{P'C})}\,r = r, \text{ and} \\ r \to u\colon u &= \frac{\mathrm{C}}{(1+\mathrm{P'CS})}\,r = \frac{\mathrm{C}}{(\mathrm{P'CS})}\,r \\ &= \frac{\mathrm{C}}{(\mathrm{P'C})}\,r = \frac{1}{\mathrm{P'}}\,r. \end{aligned}$$

Consequently, in the event of a failure in the EUC, the $r \to y$ relationship is not changed, but the $r \to u$ relation changes from $\frac{1}{\mathrm{P}} \to \frac{1}{\mathrm{P'}}$ The signal which represents the difference between the normal and the failure situation (residual signal) is thus

$$\mathrm{R_P} = u - \frac{1}{\mathrm{P'}}\,r. \tag{3}$$

In the case in which C is faulty, e.g., C becomes C', $r \to y$: $y = r$ and $r \to u$: $u = r$ owing to Equation 1, and C' is in both cases present in both denominator and numerator.

The examples in the previous chapter have shown that the difference between the integrals is very sensitive to sensor faults (see Figure 3). Because of the pulse-width modulation, we propose to take the integral of the measured coil signals and use the difference between the integrals for *u*, which is IntCoilB – IntCoilA in Figures 2 to 5. The changes in *u* must be placed in relationship to the reference signal, since a change in the reference signal also modifies the difference between the integrals, as proven by Figure 2. This interpretation of Equation 2a is in line with the results in Figure 3. In the absence of a change in the reference position, we do not anticipate changes in *u* for a fault-free system. The difference between *u* and

r is therefore a measure of the sensor failure. As Figure 2 shows, the response time must be taken into consideration in order for this difference to be determined. In parallel, the difference between reference and actual positions is an indicator for faults in S (see Equation 2b). This is in line with Figure 3b.

Interpreting Equation 3, where $\frac{1}{P'}$ is a constant, a fault may be detected in the valve or its solenoids by monitoring the difference between the integrals IntCoilB and IntCoilA against the reference signal (see Figure 4, especially 4b), which is in line with Equation 3. As already stated, in this case the response time must be taken into consideration when monitoring the difference.

Further investigations are necessary into the dependence of the difference between the integrals IntCoilB and IntCoilA upon the load. For directly controlled valves we expect a dependence of coil currents upon the load. Investigations into the data recorded at different pressures (see Table 1) show that the dependence is not as strong as the influence of the failures induced on the coils. Otherwise, particularly for failures induced in the signal chain of the position transducer, only small differences between the integrals can be seen (see Figure 3a). An algorithm to detect these failures may be sensitive to load changes, which will decrease the reliability of the valve.

5. FUTURE APPLICATION

The commercially distributed Mannesmann Rexroth proportional directional valve which we examined implements most of the digital amplifier functions by means of embedded software [6]: the PID controller and control logic are implemented in a small controller. This means that the demodulator signal, which is dependent upon the actual position, and the reference signal are actually processed in the controller. Only the output signals to the solenoids are not processed by the controller. Owing to the pulse-width modulation, only two digital inputs are needed to record these signals and to perform a simple software integration of the two signals. The monitoring the difference between reference and actual positions will detect failures where this difference is higher than a limit value for longer than the response time of the valve. The difference between the integrals of the currents to the coils should also be monitored at the same time, to detect failures near the zero position of the valve (see Figure 3a). A significant change here will also detect failures in the closed loop. The load dependence of this signal must be studied in order for the correct limit value to be established. If necessary, the pressure difference in the hydraulic systems must be considered in order to distinguish load changes from real failures. At present, control logic triggers an error relay which could be used to switch off the two solenoids. This output could be used to react to detected failures by monitoring the difference of reference and actual positions and the integrals of the coil signals. A watchdog should also be connected to this output, such that failures in the program flow will switch the valve into the safe position.

Analogous to the highly dynamic sensors for numerical control and power drive systems for machining centres [9] for Category 3 applications, no specific processor tests [10] are necessary, owing to the highly dynamic signal processing.

With a minor hardware change and small software changes, all electrical failures listed in BIA Report 6/97e [2], Standard No. EN 954-1:1996 [3], and Standard No. EN 954-2:2000 [4] in control logic and the position transducer could be detected and the safe position, namely the closed position for the valve, could be reached within twice the response time of the valve (see Figure 5) using Equations 2 and 3. Even some of the purely hydraulic failures can be detected by this mechanism. It should be mentioned that the valve must fulfil the hydraulic requirements listed in PE-BIA-M01 [11] in order to be certified as a safety valve by virtue of the measures described.

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