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DIAGNOSTIC DATA-BASED SAFETY AND AVAILABILITY ENHANCEMENTS FOR AN ALTERNATIVE OF FEEDFORWARD CONTROL USING FOUNDATION FIELDBUS

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Abstract. *To enhance plant safety and production availability in case of transmitter failures for an alternative of Foundation Fieldbus (FF)-based feedforward control, this article proposes a practical technique for configuring control strategy using function block diagram concept. The proposed configuration technique is based on fault diagnostic data automatically accessed from FF transmitters to take actions for operating the studied FF-based control loop that utilizes a Bias/Gain (BG) function block to build feedforward summing function outside of a proportional-integral-derivative (PID) function block. The minor 'Uncertain' problem can be treated as severe 'Bad' problem to increase the safety of the control loop. On the other hand, the 'Uncertain' status can be configured to be treated as 'Good' status to improve the availability of the control loop. Six options for configuring function blocks to operate the temperature control performed at the DeltaV host system are described as a case study to demonstrate the workability of the proposed technique. Experimental results of the alternate feedforward control loop configured with different parameter options confirm that the diagnostic data provided by the transmitters used are very useful for implementing either the interested control loop with increased safety or the interested control loop with increased availability. Therefore, the user can strike a balance between safety and availability for the FF-based feedforward control utilizing BG function block.*
Keywords: Availability enhancement, Bias/Gain block, Diagnosis data, Feedforward control, Foundation Fieldbus, Safety enhancement

1. **Introduction.** Effective process automation systems depend on various types of field instruments, controllers, and field-level networks to provide single-loop and multi-loop controls. Unfortunately, all these control components used in industrial harsh environments can fail in a variety ways that allow not only problems to develop but also safety risks to happen. Reliable fault detection and diagnosis in process plants allow safety risks and failure costs to be minimized [1-3]. To maintain desired actions and avoid unwanted losses, several fault detection and diagnostic fuctions can be built for instrumentation such as digital sensors [4], wireless sensors [5], and actuators [6]. In addition, fault-state actions to shut down the basic controls when detecting the sensor/actuator failure as well as fault-recovery actions to return the configured operating mode after resolving the detected failure are particularly helpful to enhance safety for 4-20 mA-based basic control loops [7]. However, this safety improvement has been introduced for implementing the conventional proportional-integral-derivative (PID) loops with/without feedforward path in combination with/without actual actuator position signal. These studied basic controls consist

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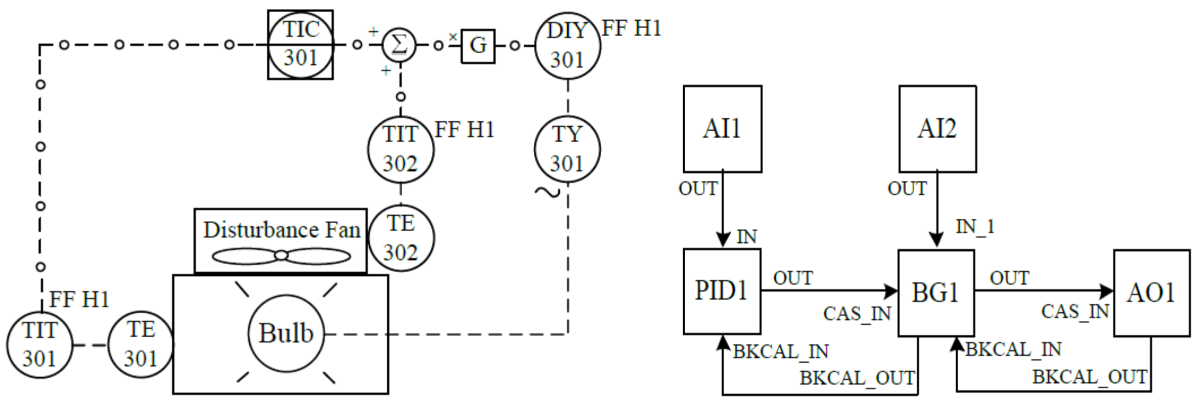
of field devices in standard current loops for data transmission at the field-level network and, as a result, the fault detection is based on the capability of analog input/output modules of a distributed control system (DCS) host used for configuring and running the control strategies. Recently, diagnostic functions built into intelligent field devices equipped with digital communication capability are useful for both operation and maintenance for process measurement and control applications [8]. The real-time process and diagnostic information from the intelligent instrument in a process plant can be accessed remotely over the digital wired or wireless network. Efforts and resources required for troubleshooting and maintenance tasks are low as in comparison to those of traditional analog instruments [9]. Moreover, reliability of measurements performed by self-validating transmitters is also essential for effective process control [10]. Based on Foundation Fieldbus (FF) H1 technology, which utilizes function block diagram language for creating control loops [11], the measurement status based on self-validation of the transmitter is stated as 'Good', 'Uncertain', or 'Bad'. The 'Bad' measurement status of the FF H1 transmitter used in the PID control can automatically enable the fault-state action to fail safely in the event of sensor failure [12]. Additionally, the 'Uncertain' measurement status can be treated as 'Good' or as 'Bad' for balancing two conflicting goals, safety and availability, on a loop-by-loop basis [13-16]. In case of instrument failures, the purpose of safety is to shut down the control loop, whereas the purpose of availability is to maintain the control. Analyzing safety and availability improvement of FF-based PID and cascade loops with control in the field concept by executing a PID function block in a final control element has been introduced [13]. In order to analyze possible cases for improving safety and availability of FF-based PID and cascade loops in two different strategies, control in the host and control in the field, details of function block configuration and actions of the interested loops in the presence of transmitter failures have been described [14]. In addition, details of function block configuration for enhancing safety and for improving availability of FF-based feedforward control loop using lead-lag (LL) function block for dynamic compensation have been proposed in [15] and [16], respectively. For the control loop using LL function block, the feedforward calculation is performed within the PID function block. Alternatively, the FF-based feedforward control loop can be also implemented by utilizing Bias/Gain (BG) function block to build the feedforward summing function outside the PID block for special requirements [17]. For this alternate implementation, segment macrocycle variations and control performance effects from assigning the PID and BG blocks to run in different devices have been suggested [18]. However, there is no practical guideline for using diagnostic data of transmitters to enhance the safety and availability of the alternate FF-based feedforward control loop employing BG block. Therefore, the aim of this article is to present a helpful technique for end users to understand how diagnostic data of transmitters can be utilized not only for improving the process safety but also for improving the production availability for the alternate implementation of the FF-based feedforward control. The user can take advantages of diagnostic data used by the alternative of implemented feedforward control to take special actions in case of 'Uncertain' and 'Bad' measurement statuses. Moreover, a configuration technique based on function block diagram concept for building the interested control strategies during engineering phase is also proposed. The feedforward temperature control of an FF H1 segment is used as a case study to demonstrate the performance of the proposed technique. Experimental results confirm that all possible configuration options give the user the ability to strike a balance between safety and availability for the feedforward control loop using BG block.

The remainder of this article is organized as follows. Section 2 details the case study used to confirm the workability of the proposed technique. Section 3 presents the control loop implementation by utilizing function block diagram and possible configuration options for safety and availability enhancement. Section 4 shows the experimental results obtained from experiments in 48 different scenarios. Section 5 provides the summary of the purpose, content, and significant results of this article as well as the possible future work.

2. **Interested FF-Based Feedforward Control Using BG Block.** Figures 1(a) and 1(b) show a piping and instrumentation (P&I) diagram for displaying interconnections of FF H1 devices and equipment used to control the temperature process and the function block diagram for displaying interconnections of five function blocks used to implement the interested control, respectively. The DeltaV is utilized as the host system for configuring and operating the studied FF-based control loop. From Figure 1(a), the TIT_301 and TIT_302 are the FF H1 temperature transmitters modeled Rosemount 3144P and Yokogawa YTA302, respectively. The TIT_301 transmitter and its TE_301 sensor are installed to measure the controlled variable, which is the temperature generated by a 100w bulb, whereas the TIT_302 transmitter and its TE_302 sensor are installed to measure the disturbance caused by a 5V fan operation. The TIC_301 controller as well as the summing and multiplying functions is operated by the DeltaV host controller. The DIY_301 is the FF H1 fieldbus-to-current converter modeled Smar FI302, which is connected to the TY_301 final control element for adjusting the bulb power supply. From Figure 1(b), the AI1 and AI2 analog input blocks for measurement functions are allocated to execute in the TIT_301 and TIT_302 transmitters, respectively. The PID1 block for control functions and the BG1 block for calculation functions are assigned to run in the host controller, whereas the AO1 analog output block for processing control output to be available for the TY_301 is placed to execute in the DIY_301 converter. The AI1 block output 'OUT' is connected to the PID1 block input 'IN', and the AI2 block output 'OUT' is connected to the BG1 block input 'IN_1'. The AI1 and AI2 blocks process measurements and convert them to be available for the PID1 and BG1 blocks, respectively. The PID1 block output 'OUT' becomes the BG1 block cascade input 'CAS_IN'. Based on algorithm execution of the BG1 block, the sum of the PID1 block 'OUT' and AI2 block 'OUT' is multiplied by the 'GAIN' value to give the BG1 block 'OUT', which is connected to the AO1 block 'CAS_IN'. To support the block initialization and interlock mechanisms, the BG1 block back-calculation output 'BKCAL_OUT' is connected backward to the PID1 block back-calculation input 'BKCAL_IN'. Similarly, the AO1 block 'BKCAL_OUT' is also connected backward to the BG1 block 'BKCAL_IN'.



(a) P&I diagram (b) Function block diagram

FIGURE 1. Interested FF-based feedforward temperature control

3. **Configuration Technique for Enhancing Safety and Availability.** Based on the DeltaV host system, the function block diagram created for implementing the interested FF-based feedforward control loop is illustrated in Figure 2. For each block, its input parameters are displayed on the left side, and its output parameters are displayed on

the right side. The forward connection for linking the output of the higher block to the input of the lower block is illustrated in solid line. On the other hand, the backward connection for linking the output of the lower block to the input of the higher block is illustrated in dash line. Table 1 gives the major function block parameters to configure the studied alternate feedforward control loop. The AI1, AI2, and AO1 function blocks have the transducer scale (XD_SCALE) parameter for the value on the input/output channel (CHANNEL). The scaling parameters including the process variable scale (PV_SCALE), output scale (OUT_SCALE), and output tracking scale (TRK_SCALE) are configured in percentages. The linearization type (L_TYPE) of the AI1 and AI2 blocks is 'Indirect' for converting the measurement value. Table 2 shows not only the permitted operating modes that are allowed target operating modes for each block and the normal operating mode that is expected to be in for normal operation for each block, but also the possible actual operating modes of each block. For actual mode of the function block, only one of the possible modes prevails at one time to reflect the operating mode that is able to achieve. In out of service (OOS) mode, the algorithm execution of the block is disabled, whereas in manual (Man) mode, the block output is directly set by the user through a process data interface tool. In automatic (Auto) mode, the algorithm execution determines the

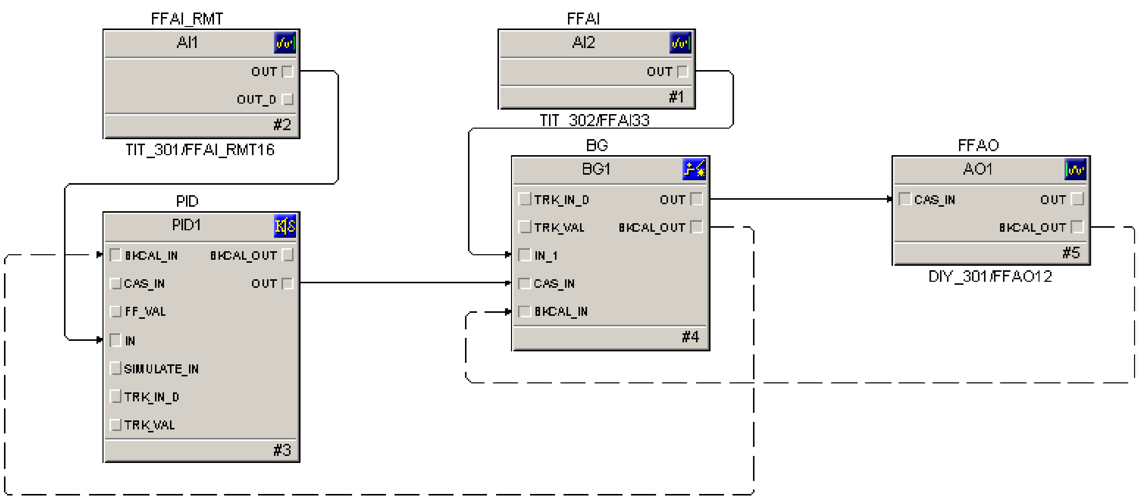


FIGURE 2. Function block diagram for implementing the interested control loop

TABLE 1. Major function block parameters for configuring in the interested control loop

Function block	Scaling		Processing	
	Parameter	Value	Parameter	Value
AI1	XD_SCALE	40-60°C	CHANNEL	1
	OUT_SCALE	0-100%	L_TYPE	Indirect
AI2	XD_SCALE	20-60°C	CHANNEL	1
	OUT_SCALE	0-100%	L_TYPE	Indirect
AO1	XD_SCALE	4-20 mA	CHANNEL	1
	PV_SCALE	0-100%	–	–
PID1	PV_SCALE	0-100%	GAIN	1.40
	TRK_SCALE	0-100%	RESET	99.2 s
	OUT_SCALE	−100%-100%	–	–
BG1	TRK_SCALE	0-100%	GAIN	0.1
	OUT_SCALE	0-100%	–	–

Table 2. Operating modes of function blocks in the interested control loop

Function block	Operating modes for configuration		Possible actual modes
	Permitted modes	Normal mode	
AI1, AI2	OOS, Man, Auto	Auto	OOS, Man, Auto
PID1	OOS, Man, Auto	Auto	OOS, IMan, Man, Auto
BG1	OOS, Man, Auto, Cas	Cas	OOS, IMan, Man, Auto, Cas
AO1	OOS, Man, Auto, Cas	Cas	OOS, LO, Man, Auto, Cas

Table 3. Major function block parameters for configuring the interested control loop

Block	Block parameter option	Possible configuration option					
		S1	S2	S3	S4	S5	A1
AI1, AI2	Bad if Limited	×	×	×	×	×	
	Uncertain if Limited						×
	Uncertain if Man mode	×	×	×	×	×	×
	Propagated Fault Forward	×	×	×	×	×	×
PID1	Target to Manual if BAD IN	×	×	×			
	Use Uncertain as Good						×
BG1	Target to Manual if BAD IN	×					
	Use Uncertain as Good						×
	IFS if BAD IN		×	×	×	×	
AO1	Fault State to value (FSTATE_VAL)		×	×	×	×	
	Target to Man if Fault State activated			×		×	

block output 'OUT' by using a local setpoint (SP) that may be set by the user through the interface tool. In cascade (Cas) mode, the SP value for executing the block algorithm is set by another higher function block through the CAS_IN parameter to determine the block output 'OUT'. The user cannot select the initialization manual (IMan) and local override (LO) modes as the target operating modes for function blocks. For the PID1 and BG1 blocks, if the IMan mode is activated by initialization and interlock mechanisms, the output 'OUT' will be set in response to the BKCAL_IN input. For the AO1 block, if the LO mode is activated by fault-state action, the CAS_IN input is frozen overridden by the fault-state value (FSTATE_VAL), which is set to 13% for the case study. Table 3 summarizes five cases (S1-S5) and one case (A1) for configuring the block parameter options for improving safety and availability, respectively, in the presence of transmitter failures. For the AI1 and AI2 blocks, the several status options can be configured in response to 'Uncertain' and 'Bad' measurement statuses from the TIT_301 and TIT_302 transmitters. The 'Bad if Limited' option is configured for safety enhancement, whereas the 'Uncertain if Limited' option is configured for availability enhancement. In addition, the 'Uncertain if Man mode' and 'Propagated Fault Forward' options are configured for all defined cases. The first is enabled to set the output status of the AI1 and AI2 blocks to be 'Uncertain', when their actual operating mode is Man. The latter is enabled to propagate the 'Bad' to the lower block without alarm generation. For the PID1 block, the 'Use Uncertain as Good' option is configured to treat the 'Uncertain' status of the AI1 block as 'Good' status for improving the availability. Otherwise, the 'Uncertain' status of the AI1 block is treated as 'Bad' status for improving the safety. Moreover, the 'Target to Manual if BAD IN' option is configured to bring the operation of the PID1 block to Man mode in the event of 'Bad' status of the AI1 block. Similarly, for the BG1 block, its operating mode becomes Man in the event of 'Bad' status of the AI2 block when enabling the 'Target to Manual if BAD IN' option. To enhance the availability, the 'Use Uncertain as Good' option for the BG1 block is configured to treat the 'Uncertain' status of the AI2 block as 'Good' status. On the other hand, to enhance the safety, the 'Uncertain' status of the AI2 block is treated as 'Bad' status when disabling the 'Use Uncertain as Good' option. In order to bring the control loop to a graceful shutdown by setting 'Initial Fault State' status in the BG1 block output 'OUT' in the event of 'Bad' status of the AI2 block, the 'IFS if BAD IN' option of the BG1 block as well as the 'Fault State to value of the AO1 block is enabled. If the 'Fault State to value' is activated, the AO1 block output 'OUT' will go to the preset FSTATE_VAL value for initiating the fault-state action. In addition, the 'Target to Man if Fault State activated' is configured to set the target operating mode of the AO1 block to Man when activating the fault-state action to enhance the safety.

4. **Experimental Results and Discussion.** Experiments in 48 different schemes as shown in Table 4 were performed to test the mode shedding of the function blocks used in the studied control loop in response to the 'Good', 'Uncertain', and 'Bad' statuses of the AI1 and AI2 block outputs when configuring the function block parameters by using six specified options from Table 3. For example, the 'S1d' and 'S1h' are the experiment schemes for the interested control loop with increased safety when setting the parameters with 'S1' option. The 'S1d' denotes the experiment that was performed in case of the failures to cause the 'Uncertain' status of the AI1 and AI2 block outputs, while the 'S1h' denotes the experiment that was performed in case of 'Bad' status of the AI1 and AI2 block outputs. Another example is that the 'A1g' is the experiment scheme for the interested control loop with increased availability when setting the block parameters with 'A1' option, and it denotes the experiment that was performed in the event of the 'Bad' and 'Uncertain' statuses of the AI1 and AI2 block outputs, respectively. From experimental results, the mode shedding in response to the transmitter failure occurring and transmitter failure disappearing for the PID1, BG1, and AO1 blocks are given in Table 5, where T and A denote for target mode and actual mode, respectively, and MA, IM, AU, and CA denote for the Man, IMan, Auto, and Cas modes of the block, respectively. For example (see the 'S4f' results), the PID1 block sheds to the actual Man mode, when the 'Bad' status of the AI1 block 'OUT' occurs, and the PID1 block returns to its target Auto mode when the AI1 block 'OUT' status becomes 'Good'. By comparing between the 'S4f' and 'S2f' schemes, it is safer for the S2-based control loop to remain in the Man mode when the failure disappears. In case of 'Good' and 'Uncertain' statuses of the AI1 block 'OUT' and AI2 block 'OUT', Figure 3 shows the interested control loop based on 'S5' configuration in online mode, whereas Figure 4 shows the interested control loop based on 'A1' configuration in online mode. The target and actual operating modes of the PID1,

Table 4. Schemes for testing the interested loop configured with different configurations

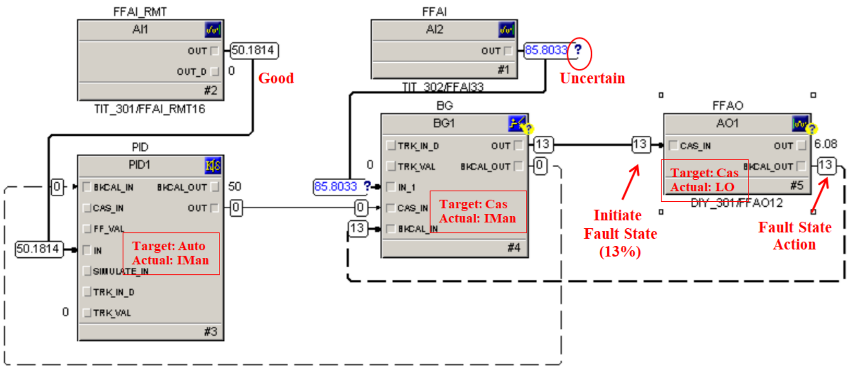
'OUT' status		Specified option for configuring block parameters					
AI1	AI2	S1	S2	S3	S4	S5	A1
Good	Uncertain	S1a	S2a	S3a	S4a	S5a	A1a
	Bad	S1b	S2b	S3b	S4b	S5b	A1b
Uncertain	Good	S1c	S2c	S3c	S4c	S5c	A1c
	Uncertain	S1d	S2d	S3d	S4d	S5d	A1d
	Bad	S1e	S2e	S3e	S4e	S5e	A1e
Bad	Good	S1f	S2f	S3f	S4f	S5f	A1f
	Uncertain	S1g	S2g	S3g	S4g	S5g	A1g
	Bad	S1h	S2h	S3h	S4h	S5h	A1h

Table 5. Mode shedding of the PID1, BG1, and AO1 blocks from experiment results

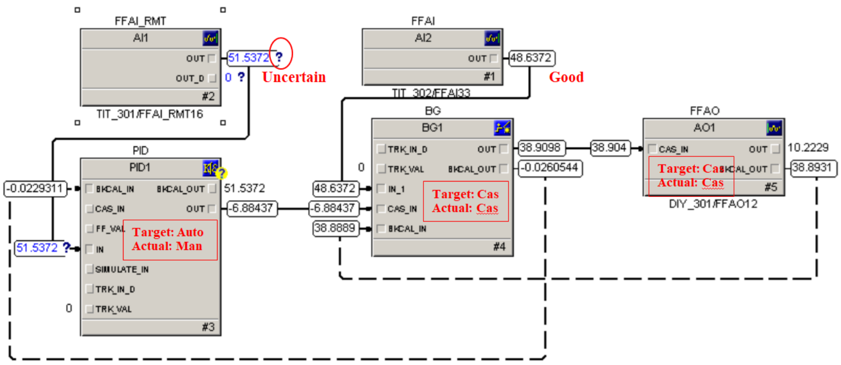
Schemes	Failure occurring						Failure disappearing					
	PID1		BG1		AO1		PID1		BG1		AO1	
	T	A	T	A	T	A	T	A	T	A	T	A
S1a, S1b	AU	IM	MA	MA	CA	CA	AU	IM	MA	MA	CA	CA
S1c, S1f, S2c, S2f, S3c, S3f	MA	MA	CA	CA	CA	CA	MA	MA	CA	CA	CA	CA
S1d, S1e, S1g, S1h	MA	IM	MA	MA	CA	CA	MA	IM	MA	MA	CA	CA
S2a, S2b	AU	IM	CA	IM	CA	LO	AU	AU	CA	CA	CA	CA
S2d, S2e, S2g, S2h	MA	IM	CA	IM	CA	LO	MA	MA	CA	CA	CA	CA
S3a, S3b	AU	IM	CA	IM	CA	LO	AU	IM	CA	IM	MA	MA
S3d, S3e, S3g, S3h	MA	IM	CA	IM	CA	LO	MA	IM	CA	IM	MA	MA
S4a, S4b, S4d, S4e, S4g, S4h	AU	IM	CA	IM	CA	LO	AU	AU	CA	CA	CA	CA
S4c, S4f, S5c, S5f	AU	MA	CA	CA	CA	CA	AU	AU	CA	CA	CA	CA
S5a, S5b, S5d, S5e, S5g, S5h	AU	IM	CA	IM	CA	LO	AU	IM	CA	IM	MA	MA
A1a, A1c, A1d	AU	AU	CA	CA	CA	CA	AU	AU	CA	CA	CA	CA
A1b, A1e, A1h	AU	IM	CA	MA	CA	CA	AU	AU	CA	CA	CA	CA
A1f, A1g	AU	MA	CA	CA	CA	CA	AU	AU	CA	CA	CA	CA

BG1, and AO1 blocks of Figures 3(a), 3(b), 4(a), and 4(b) are similar to the 'S5a', 'S5c', 'A1a', and 'A1c' results in Table 5, respectively, in case of failure occurring. It is seen that the actions of the S5-based control loop and that of the A1-based control loop are significant different, when the transmitter failures occur. Because the goal of the S5-based control loop is to enhance the plant safety by initiating the fault-state action for graceful shutdown, the goal of the A1-based control loop is to enhance the production availability by continuing the control functions even in the event of the transmitter failures. Thus, the proposed technique to configure the parameters of five function blocks can be used in the balance between safety and availability for the studied alternate FF-based feedforward control.

5. **Conclusions.** Based on graphical function block language, the alternate implementation of FF-based feedforward temperature control by employing the Bias/Gain block has been described. The configuration technique based on diagnosis in FF H1 transmitters during engineering phase to improve safety and availability of the interested control loop has been presented. How to act on the diagnostic measurement statuses to be selective for safety and availability enhancement in the presence of transmitter failures has been suggested. How different configuration options affect the function block mode shedding in response to 'Good', 'Uncertain', and 'Bad' statuses has been also discussed. Based on the possible configuration options, the interests of safety and availability can be balanced with

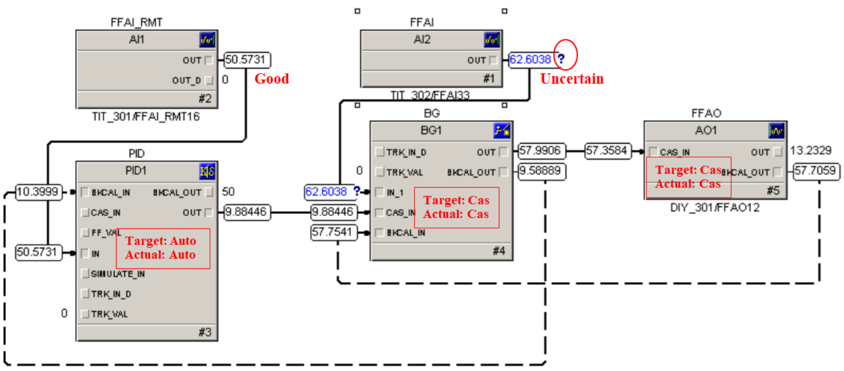


(a) ‘Good’ AI1 ‘OUT’ and ‘Uncertain’ AI2 ‘OUT’ statuses (‘S5a’ scheme)

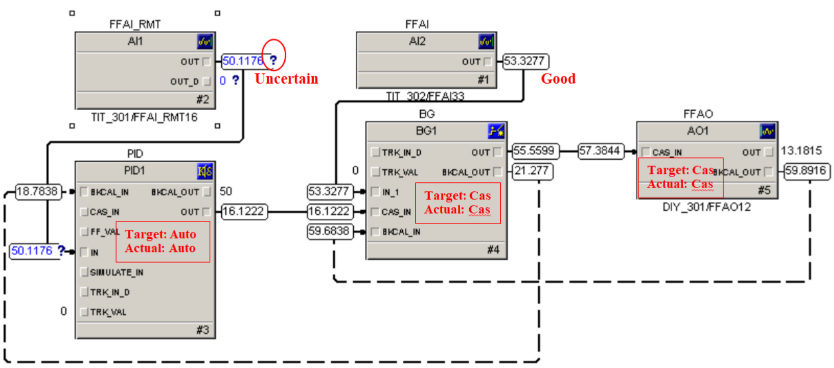


(b) ‘Uncertain’ AI1 ‘OUT’ and ‘Good’ AI2 ‘OUT’ statuses (‘S5c’ scheme)

FIGURE 3. Interested control loop based on ‘S5’ configuration in online mode



(a) ‘Good’ AI1 ‘OUT’ and ‘Uncertain’ AI2 ‘OUT’ statuses (‘A1a’ scheme)



(b) ‘Uncertain’ AI1 ‘OUT’ and ‘Good’ AI2 ‘OUT’ statuses (‘A1c’ scheme)

FIGURE 4. Interested control loop based on ‘A1’ configuration in online mode

respect to transmitter failures. A practical technique for improving safety and availability of basic process control systems using combined FF H1-HART solution is the future work.

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