International Journal of Innovative Computing, Information and Control
Volume **16**, Number **2**, April **2020**

ICIC International ©2020 ISSN 1349-4198
pp. **621–630**

PROCESS SAFETY ENHANCEMENT OF FEEDFORWARD CONTROL USING FOUNDATION FIELDBUS

Amphawan Julsereewong and Sart Kummool

Faculty of Engineering
King Mongkut's Institute of Technology Ladkrabang
Ladkrabang, Bangkok 10520, Thailand
amphawan.ju@kmitl.ac.th; sartkmm@gmail.com

Received August 2019; revised December 2019

Abstract. *This paper presents a practical technique in engineering phase for enhancing safety of Foundation Fieldbus (FF)-based feedforward control through propagation of measurement validity and status information in the loop using function block language to prevent hazards in the presence of a transmitter failure. The proposed technique is based on fault diagnosis of FF devices to increase the safety beyond that found in basic control loops using traditional technologies. For hybrid architecture by assigning basic and advanced function blocks to execute in H1 field instruments and H1 interface module, respectively, all possible cases for configuring parameter options not only to shut the loop down when the failure occurs but also to resume the loop to normal when the failure disappears are described. The feedforward on temperature control of H1 segment configured and operated on the DeltaV integrated host is used for experimentally testing the correctness of the defined parameter options to provide function block interlocks and failsafe actions as well as fault recovery mechanisms. In addition, the Petri net model to represent the control loop behaviors for comparing the process safety enhancement in different scenarios from five cases of parameter configurations is also included.*

Keywords: Failsafe action, Fault diagnosis, Feedforward control, Foundation Fieldbus, Function block, Measurement validity, Safety enhancement

1. **Introduction.** Safety is a crucial factor for designing process control systems to achieve various benefits including industrial accident minimization [1]. The closed-loop control system using invalid or untrue inputs from measuring device failures is safety hazard [2,3]. To provide the safety in case of abnormal conditions, affected loops must be shut down for stopping the process and then placed in fault state [4]. Nowadays, information from self-checking and self-validating capabilities of field devices based on Foundation Fieldbus (FF) technology can be utilized to improve safety and availability of basic control systems that need no safety-related functions [5-8]. This industrial communication technology has standardized methods without any custom programming to disseminate diagnostic parameters through the process control loop using function block language in comparison with the conventional analog system, which does not access device diagnostic features [5]. Contrarily, operator personnel can access all H1 field instruments on the site from a single operator/engineering workstation at any time. The health of any H1 field device installed in the plant can be easily investigated without requirement of manual probing in the field by utilizing a handheld configurator. The FF self-diagnostic information for detecting device failures is updated dynamically as the quality part in the status element of every measured and processed parameter. The status indicates on the validity of the process value, and indication of invalid process variable measurements

---

DOI: 10.24507/ijicic.16.02.621

can then be employed by the control strategy for shutdown interlocks and failsafe actions for safety purpose [6]. The loops with increased safety are forced to bring the system to shut down in the event of transmitter failure, because the control cannot continue with invalid input. However, the method proposed in [6] emphasizes on balancing the interests of safety versus availability of Proportional-Integral-Derivative (PID) and cascade control schemes using FF only with control-in-the-field concept. In order to suggest more details about safety and availability enhancement of the FF-based PID and cascade control strategies, the Petri net model for representing the logical behaviors of the interested loops with both control-in-the-field and control-in-the-host concepts has been introduced [7], and the comparative analysis between these two concepts for building the basic control loops has also been presented [8]. Recently, the FF-based hybrid architecture to build a feedforward control with ability of anticipating an influence of disturbance has been proposed [9]. Its hybrid architecture is based on assigning basic function blocks to run in H1 field instruments and advanced function block for lead-lag compensation to run in an integrated host controller. Alternatively, calculation and control function blocks can be allocated to execute in an H1 interface module of integrated host with special feature to maintain the synchronization between function block executions and scheduled data communications at the input/output module level [10,11]. However, there is no suggestion for safety enhancement of the FF-based feedforward control in the open literature. The aim of this paper is to propose a workable technique during engineering phase to improve the process safety of FF-based feedforward control with hybrid architecture by placing basic function blocks including PID block to execute in H1 field instruments and advanced lead-lag function block to execute in H1 interface module. The proposed technique offers powerful advantages in the utilization of diagnostic capabilities provided by FF technology to detect and act upon transmitter failures, which are not detected by traditional means. Based on propagation of parameter status, there are five possible cases for configuring status and input/output options of function blocks not only to bring the control loop to safe states when detecting the transmitter failure but also to resume the control loop by using different fault recovery mechanisms after fixing the failure. Correctness of all specified cases of the proposed technique is verified by experimental results from using the DeltaV integrated host to configure and operate the studied H1 segment for feedforward on temperature control. For ease of comparison of safety enhancement results from five different parameter configurations, the Petri net model is created to show the behaviors of the control loop.

The remainder of this paper is organized as follows. The studied feedforward on temperature control using FF technology and the proposed technique for enhancing process safety are described in Section 2 and Section 3, respectively. Experimental and comparison results are discussed in Section 4. Finally, conclusions and possible future work are detailed in Section 5.

2. **Studied FF-Based Feedforward Control.**

To demonstrate the proposed technique, the H1 segment connected with the DeltaV host for feedforward on temperature control as illustrated in Figure 1 is employed as a case study [9,10]. The temperature generated by a lamp is defined as a controlled variable in range of 40-60°C, while the temperature caused by the fan operation is defined as a disturbance variable in range of 20-60°C. The TIT_301 temperature transmitter (modeled Rosemount 3144P) and TIT_302 temperature transmitter (modeled Yokogawa YTA320) are connected for primary and disturbance measurements, respectively. The DIY_301 fieldbus-to-current converter (modeled Smar FI302) is installed for converting the FF H1 signal to the 4-20 mA signal, and this converted current is then applied to the TY_301 power regulator (modeled Sangi Electric

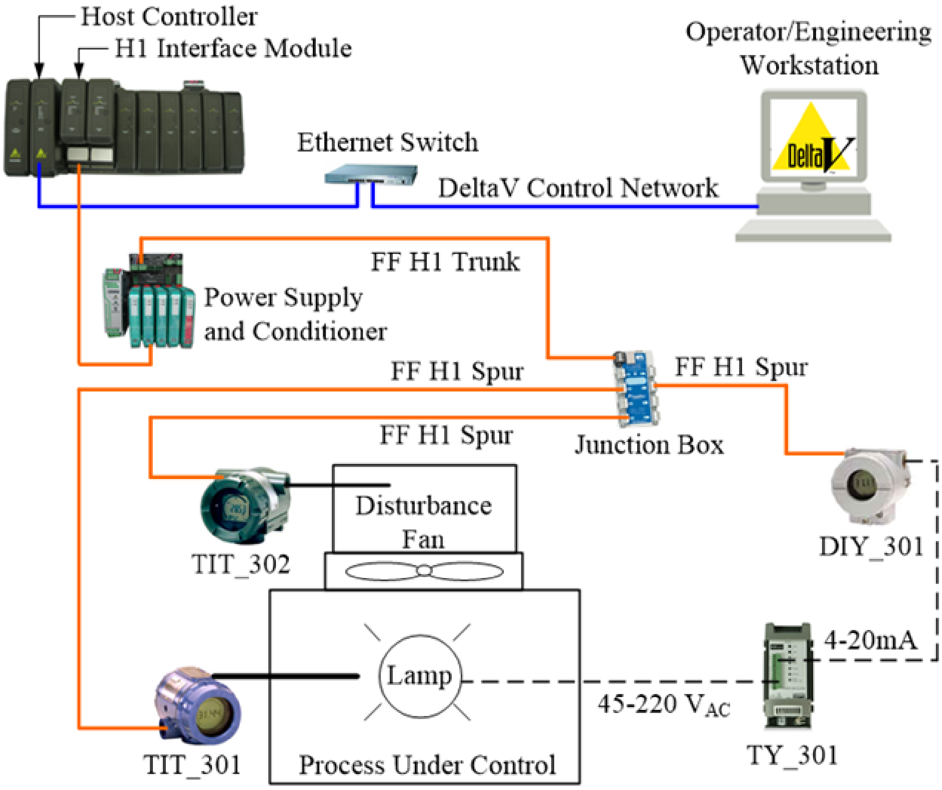

Figure 1. Studied H1 segment for feedforward temperature control

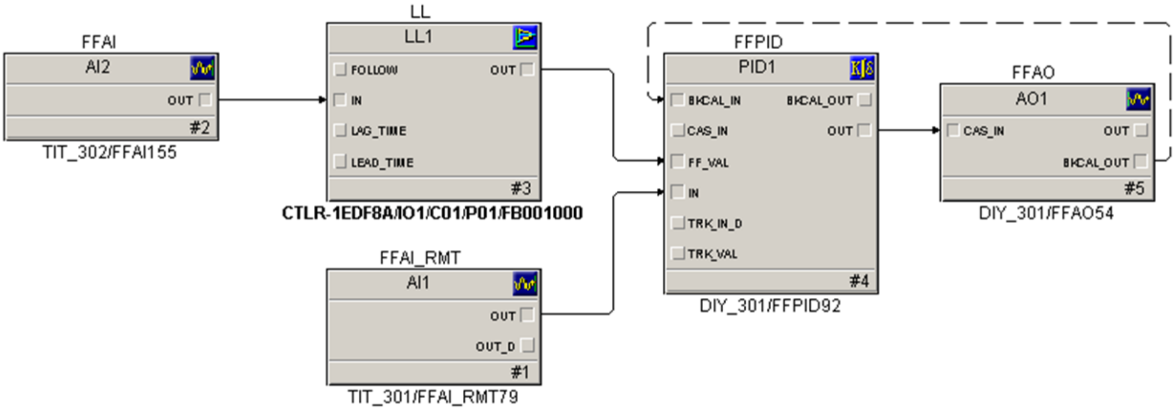

Figure 2. Preferred function block assignment for building feedforward control loop

SCR-1A030) for adjusting the lamp supply voltage to change the controlled temperature. The feedforward control applied in combination with feedback control is created by a set of function blocks connected together as shown in a diagram of Figure 2. Based on the capabilities of H1 field devices and H1 interface module, the function block assignment providing minimum number of scheduled data transfers is preferred [10]. The AI1 and AI2 analog input blocks are placed in the TIT_301 transmitter for measuring controlled variable and the TIT_302 transmitter for measuring disturbance input, respectively. The LL1 lead-lag block is assigned into the H1 interface module for compensating a change in measured disturbance in feedforward path. The PID1 control block is allocated to the DIY_301 converter for maintaining the controlled variable at the setpoint, where the feedforward summing function is performed inside this control block [9]. The AO1 analog output block is also placed in the DIY_301 converter for generating the control signal of the TY_301 regulator.

3. **Proposed Safety Enhancement.** During control strategy configuration, FF function blocks allow the user to set desired behaviors by utilizing parameter options on the loop-by-loop basis. The proposed technique is based on fault diagnosis provided in H1 instruments to automatically initiate safe loop actions in the event of invalid measurements. Input and output parameters in FF function blocks have the status associated with the value for indicating additional validity and diagnostic information. The quality that is one of three portions in the parameter status for showing general validity of the value can be 'Good', 'Uncertain', or 'Bad'. The 'Good' indicates that the value may be used for control, whereas the 'Bad' indicates that the value should not be used for control. The 'Uncertain' indicates that the value is doubtful and may be incorrect. Usually, the 'Uncertain' should be treated as 'Bad' for primary safety concern [4]. From Figure 2, each data flow between two function blocks, such as from the 'OUT' parameter of the AI1 block to the 'IN' parameter of the PID1 block, is identified by configured wire connection from output parameter of the source to input parameter of the destination, where the solid and dashed lines represent the forward and backward links, respectively. The status information can be propagated throughout the control loop to inform whether the associated value is suitable to control. To enhance process safety, the parameter status should not only be informed to the plant operator but also be involved in the safe loop actions. Table 1 illustrates the interested status options (STATUS_OPTS) and input/output options (IO_OPTS) of FF function blocks that are assigned to execute in H1 field devices for safety improvement of the studied control. The 'Uncertain' and 'Bad' statuses of the AI1 and AI2 blocks from the validity of measurements are determined

Table 1. Interested parameter options in function blocks assigned to H1 field devices

Parameter	Option	Description
STATUS_OPTS (AI1 and AI2)	Uncertain if Man mode	If the actual block mode is manual, set the status of 'OUT' to be 'Uncertain'.
	Bad if Limited	If the sensor is at a low or high limit, set the status of 'OUT' to be 'Bad'.
	Propagated Fault Forward	If the status from the sensor is 'Bad' or the sensor (or device) failure occurs, propagate the 'Bad' status to 'OUT' without generating an alarm.
STATUS_OPTS (PID1)	Target to Man if Bad IN	If the status of 'IN' is 'Bad', set the target of block mode to be manual.
	IFS if Bad IN	If the status of 'IN' is 'Bad', set the 'Initiate Fault State' status on 'OUT'.
IO_OPTS (AO1)	Fault State to value	If the fault occurs, set 'OUT' to be the predetermined safe value.
	Tgt to Man if Fault St Act	If 'Initiate Fault State' is activated, set the target of block mode to be manual.

Table 2. Five possible cases of parameter configurations for safety enhancement

Block	Parameter Option	Case 1	Case 2	Case 3	Case 4	Case 5
AI1, AI2	Uncertain if Man mode	√	√	√	√	√
	Bad if Limited	√	√	√	√	√
	Propagated Fault Forward	√	√	√	√	√
PID1	Target to Man if Bad IN	√	√	√		
	IFS if Bad IN		√	√	√	√
AO1	Fault State to value		√	√	√	√
	Tgt to Man if Fault St Act			√	√	

for automatic initiation of the shutdown interlocks, failsafe actions, and fault recovery mechanisms. There are five possible cases as shown in Table 2 to configure the interested parameter options in the PID1 and AO1 blocks for providing different actions in case of transmitter failures. The LL1 block can propagate the status information from its 'IN' parameter to its 'OUT' parameter without configuration requirements. The normal operating modes of the PID1 and AO1 blocks are automatic (Auto) and cascade (Cas) modes, respectively. The purpose of enabling 'Propagated Fault Forward' option for the AI1 and AI2 blocks is to report the fault to the PID1 block during the transmitter failure without generating the block alarm. In case of TIT_302 failure, the 'Bad' status of the AI2 block is propagated throughout the intermediate LL1 block. With the 'Bad' status of the 'IN' primary input, the PID1 block will generate the alarm as a substitute for the AI1 block in the event of TIT_301 failure. That is, only one of the function blocks generates the transmitter failure alarm to offer ease of monitoring by focusing on a single block rather than on an entire loop. By its default, the PID1 block does not propagate the status from upstream to downstream blocks. This means that the 'Bad' primary input of the PID1 block from the AI1 block does not become the 'Bad' output. During the 'Bad' primary input, the actual operating mode of the PID1 block automatically changes to the manual (Man) mode without operator intervention by mode shedding, and then the 'OUT' of the AO1 block freezes in the last value. Alternatively, the PID1 block can also be configured to set a fault state status on its 'OUT' parameter in the event of the 'Bad' primary input by enabling the 'IFS if Bad IN' option. In combination with setting 'Fault State to value' option, the 'Initiate Fault State' status will initiate the failsafe action to occur in the AO1 block, and its 'OUT' goes to the preset safe value for taking the control loop to be graceful shutdown. In addition to the interlocks between function blocks and the failsafe actions to fail safely in the presence of failure, the fault recovery mechanisms in safety purpose are also focused. In general, the function block immediately returns to the desired operating target mode once the failure has been fixed. However, the control loop should remain in the 'Man' mode rather than return to the operating target mode to provide greater safety. Enabling the 'Target to Man if Bad IN' safer option allows the PID1 block to remain in the 'Man' mode after the 'Bad' status of the 'IN' has cleared. Similarly, setting the 'Tgt to Man if Fault St Act' option allows that the target mode of the AO1 block becomes the 'Man' mode when the 'Initiate Fault State' is activated. The actual operating mode of the AO1 block remains in the 'Man' mode after the failure has been solved, until its target mode is changed by the operator.

4. **Experimental and Comparison Results.** In order to confirm the failsafe actions and fault recoveries for increasing the safety of the feedforward control loop of Figure 2 in various scenarios, experiments in 40 schemes were performed by configuring the parameter options in the function blocks as well as emulating the failures to cause the 'Uncertain' and

TABLE 3. Schemes of parameter configurations and transmitter failures for experiments

AI1 'OUT' Status	AI2 'OUT' Status	Parameter Configurations				
		Case 1	Case 2	Case 3	Case 4	Case 5
Good	Uncertain	1a	2a	3a	4a	5a
Good	Bad	1b	2b	3b	4b	5b
Uncertain	Good	1c	2c	3c	4c	5c
Uncertain	Uncertain	1d	2d	3d	4d	5d
Uncertain	Bad	1e	2e	3e	4e	5e
Bad	Good	1f	2f	3f	4f	5f
Bad	Uncertain	1g	2g	3g	4g	5g
Bad	Bad	1h	2h	3h	4h	5h

TABLE 4. Failure mode shedding of the PID1 and AO1 blocks from experimental results

Schemes	When the failure occurs				When the failure disappears			
	Mode of PID1		Mode of AO1		Mode of PID1		Mode of AO1	
	Target	Actual	Target	Actual	Target	Actual	Target	Actual
1a, 1b, 2a, 2b, 3a, 3b, 4a, 4b, 5a, 5b	Auto	Auto	Cas	Cas	Auto	Auto	Cas	Cas
1c, 1d, 1e, 1f, 1g, 1h	Man	Man	Cas	Cas	Man	Man	Cas	Cas
2c, 2d, 2e, 2f, 2g, 2h	Man	IMan	Cas	LO	Man	Man	Cas	Cas
3c, 3d, 3e, 3f, 3g, 3h	Man	IMan	Cas	LO	Man	IMan	Man	Man
4c, 4d, 4e, 4f, 4g, 4h	Auto	IMan	Cas	LO	Auto	IMan	Man	Man
5c, 5d, 5e, 5f, 5g, 5h	Auto	IMan	Cas	LO	Auto	Auto	Cas	Cas

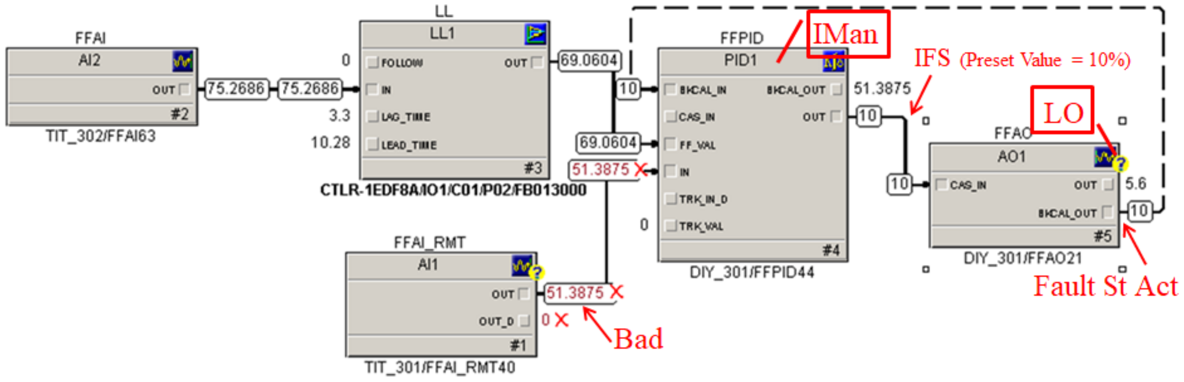

FIGURE 3. Control loop in online mode during the experiment of '3f' scheme

'Bad' statuses of the AI1 and AI2 block outputs as summarized in Table 3. The propagation of parameter status through the loop and the automatic change of actual operating mode for the PID1 and AO1 blocks for failsafe actions were investigated. The operations of PID1 and AO1 blocks for fault recovery mechanisms were also determined. Table 4 gives the failure mode shedding patterns in the PID1 and AO1 blocks from experimental results. The results from '1a-5a' and '1b-5b' schemes show that the 'Uncertain' and 'Bad' statuses of the AI2 'OUT' have no effect on the operation of the control loop. The PID1 and AO1 blocks still function in their normal operating modes when the status of the AI1 'OUT' is 'Good'. To increase the safety in the event of instrument failure, 'Uncertain' is treated as 'Bad' for the AI1 'OUT' status to automatically bring the control loop to manual (see the results from '1c-1h') or shut the control loop down (see the results from

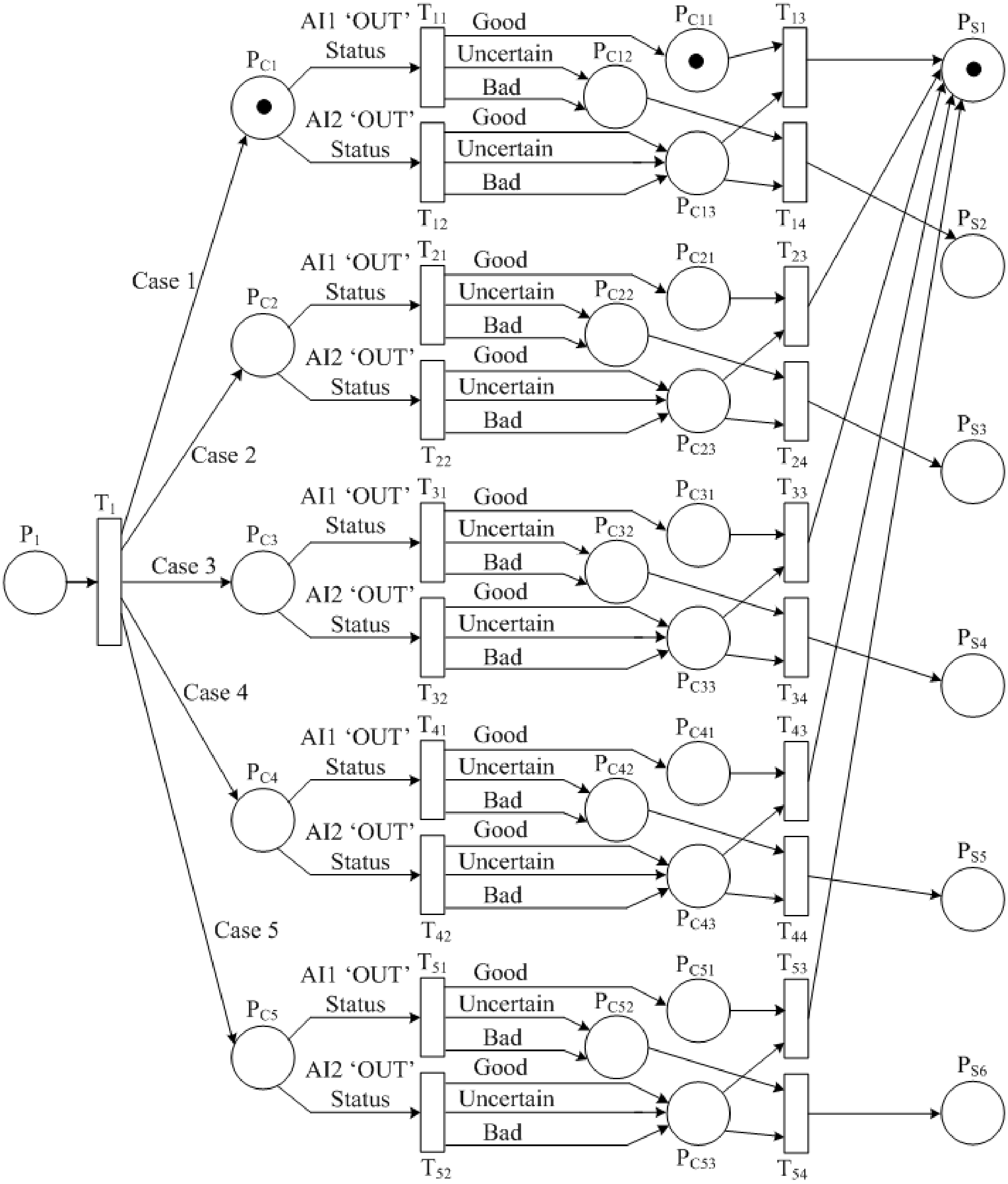

FIGURE 4. Petri net model of the feedforward loop in the proposed safety improvement

'2c-2h', '3c-3h', '4c-4h', and '5c-5h'). The mode shedding patterns of the PID1 and AO1 blocks for both fault state and fault recovery are dependent on the enabled parameter options. By enabling 'IFS if Bad IN' and 'Fault State to value' options in the PID1 and AO1 blocks, respectively, the Local Override (LO) mode activated in the failsafe action in the AO1 block overrides the defined target mode. This block setpoint is also overridden by the predetermined safe value (e.g., the preset value = 10%) during the 'Uncertain' and 'Bad' statuses of the AI1 'OUT'. The fault state that is active in the AO1 block is passed back to report the PID1 block; thus, the actual operating mode of the PID1 block is changed to be initialization manual (IMan) mode for shutdown interlocking between function blocks. Moreover, the operator is required to intervene for bringing the control back to normal operation when enabling 'Tgt to Man if Fault St Act' in the AO1 block. In this case, the control loop remains shutdown state after the failure has been cleared (see the results from '3c-3h' and '4c-4h'). Similarly, the target mode of the PID1 block remains in manual until it is changed by the operator when setting the 'Target to Man if Bad IN' option (see the results from '1c-1h', '2c-2h', and '3c-3h'). Figure 3 shows the

Table 5. Place and transition descriptions of the created model of Figure 4

Item	Description
P_1	The feedforward control loop of Figure 2 is created.
T_1	If the control loop is configured with options in Case i (where $i = 1, 2, 3, 4$, or 5) then P_{Ci}.
P_{Ci}	The safety of the control loop is improved by using the options in Case i.
T_{i1}	If P_{Ci} is true and the status of AI1 'OUT' is 'Good' then P_{Ci1}. If P_{Ci} is true and the status of AI1 'OUT' is 'Uncertain' or 'Bad' then P_{Ci2}.
T_{i2}	If P_{Ci} is true and the status of AI2 'OUT' is 'Good', 'Uncertain', or 'Bad' then P_{Ci3}.
P_{Ci1}	The loop is configured with options in Case i, and the status of AI1 'OUT' is 'Good'.
P_{Ci2}	The loop is configured with options in Case i, and the status of AI1 'OUT' is 'Uncertain' or 'Bad'.
P_{Ci3}	The loop is configured with options in Case i, and the status of AI2 'OUT' is 'Good', 'Uncertain', or 'Bad'.
T_{i3}	If both P_{Ci1} and P_{Ci3} are true, then the failsafe action and fault recovery can be P_{S1}.
T_{i4}	If both P_{Ci2} and P_{Ci3} are true and $i = 1, 2, 3, 4$, or 5, then the failsafe action and fault recovery can be P_{S2}, P_{S3}, P_{S4}, P_{S5}, or P_{S6}, respectively.
P_{S1}	The loop can normally maintain the controlled variable.
P_{S2}	In the event of transmitter failure, the loop is changed to be manually controlled, and the AO1 block output is set to freeze in the last value. The PID1 block continues in the manual mode for fault recovery.
P_{S3}	In the event of transmitter failure, the fault state is active in the AO1 block. The PID1 block continues in the manual mode for fault recovery.
P_{S4}	In the event of transmitter failure, the fault state is active in the AO1 block. Both the PID1 and AO1 blocks remain in the manual mode for fault recovery.
P_{S5}	In the event of transmitter failure, the fault state is active in the AO1 block. The AO1 block remains in the manual mode for fault recovery.
P_{S6}	In the event of transmitter failure, the fault state is active in the AO1 block. The control loop can resume immediately for fault recovery.

control loop operation in online mode during the experiment of '3f' scheme as an example for investigating the status propagation between the function blocks and the effect in the control loop operation during invalid measurement in the AI1 block as well as for examining the mode shedding patterns of the PID1 and AO1 blocks. It is seen that the failsafe action is initiated in the AO1 block in the event of 'Bad' primary input (IN) of the PID1 block. Figure 4 illustrates the Petri net model for representing the behaviors of the feedforward control loop with increased safety by differently configuring parameter options in response to the 'OUT' statuses of the AI1 and AI2 blocks. The place (P) and transition (T) details of the model are summarized in Table 5. It is seen that the configuration options in Case 1 and Case 3 provide the lowest and highest levels for safety enhancement of the studied feedforward control, respectively. The fault diagnosis in H1 field devices can then be utilized to increase the safety of process control system by detecting and acting upon failures, which are not detected by conventional means. The 'Uncertain' and 'Bad' statuses are not only displayed to the operator but also used as an integral part of function block interlocks and failsafe actions in case of instrument failure.

5. **Conclusions.** The practical technique during control strategy configuration in engineering phase for safety improvement of FF-based feedforward control with hybrid architecture by acting on device diagnostic information on various scenarios has been presented in this paper. Based on parameter status propagation throughout the control loop utilizing function block language, the validity of measurements can automatically switch the loop to operate in manual mode or gracefully shut the loop down by setting the manipulated variable to be predetermined safe value in the case of primary transmitter failure. Moreover, a technique for availability improvement of the FF-based feedforward control through diagnostic information to minimize process downtime is the future work.

Acknowledgment. The authors would like to thank the FieldComm Group Thai Association for helpful supports of the experiments. The authors are also grateful to the reviewers for their valuable suggestions to improve this manuscript.

REFERENCES

[1] W. M. Goble, *Control Systems Safety Evaluation and Reliability*, ISA Press, USA, 2010.

[2] B. G. Liptak, *Instrument Engineers' Handbook: Process Control and Optimization*, CRC Press in Cooperation with ISA Press, USA, 2006.

[3] L. Sun, X. Liu and A. Sano, Model structure identification and parameter estimation for unstable process in closed-loop, *ICIC Express Letters*, vol.13, no.7, pp.625-633, 2019.

[4] J. Berge, *Fieldbuses for Process Control: Engineering, Operation and Maintenance*, ISA Press, USA, 2004.

[5] N. Khochasin, T. Trisuwannawat, P. Julsereewong and A. Julsereewong, Comparative study on cascade control configuration in engineering phase for analog system and FF system, *Proc. of IEEE/SICE International Symposium on System Integration*, Sapporo, Japan, pp.881-886, 2016.

[6] T. Sangsuwan, T. Thepmanee and A. Julsereewong, Safety and availability of basic process control using Foundation Fieldbus with control in the field – An experimental analysis, *International Journal of Intelligent Engineering & Systems*, vol.10, no.4, pp.135-146, 2017.

[7] T. Sangsuwan, N. Whatphat, J. Chanwutitum, T. Thepmanee and A. Julsereewong, Petri net modeling for performance analysis of FF-based process control in terms of safety and availability enhancement, *Proc. of International Conference on Control, Automation and Systems*, Jeju, Korea, pp.631-636, 2017.

[8] A. Julsereewong, N. Whatphat, T. Sangsuwan, J. Chanwuttitum and T. Thepmanee, Comparative analysis between control in the host and control in the field in terms of safety and availability for Foundation Fieldbus-based process control, *International Journal of Innovative Computing, Information and Control*, vol.14, no.2, pp.737-745, 2018.

[9] P. Pannil, S. Jaroenla, A. Julsereewong and S. Kummool, Feedforward hybrid control using Foundation Fieldbus: A case study of temperature control with DeltaV system, *Proc. of International Conference on Control and Robotics Engineering*, Nagoya, Japan, pp.104-108, 2018.

[10] S. Jaroenla and A. Julsereewong, Analysis of FF H1 segment macrocycles for feedforward control with hybrid architecture, *Proc. of the 15th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology*, Chiang Rai, Thailand, pp.513-516, 2018.

[11] A. Julsereewong and P. Pannil, Analysis of macrocycle schedules for an alternative of FF-based feedforward control, *International Journal of Innovative Computing, Information and Control*, vol.15, no.2, pp.793-801, 2019.