ANALYSIS AND IMPROVEMENT OF INPUT CHANNEL SELECTION ALGORITHM FOR RELIABILITY OF CONTROL SYSTEMS IN NUCLEAR POWER PLANTS

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ABSTRACT

In most of non-safety NSSS (Nuclear Steam Supply System) control systems, a process input is composed of two channels for redundancy. In a normal situation, the average of both input channels is used in the control algorithm. If a failed channel is detected, the 'channel selection algorithm' chooses the remaining normal input channel. For a bumpless transition, many implemented control systems include the 'ramping rate' function, which makes it possible for the selected input to slowly approach the new input channel.

However, it recently turned out that this function adopted for positive effects may result in unintended consequences for the related control system and the plant in certain cases. Due to a process transient in the plant according to a significant event, any related sensor input signal can rapidly change and finally exceed the pre-defined range for detecting an out-of-range event in a short time. During the process of channel conversion due to a rapid transient in the plant, the processed input from the redundant channels can be distorted if the ramping rate function is not properly implemented. As a result, it can result in a plant shutdown because the control system fails to perform the critical function to mitigate a plant transient. To solve these potential problems, we analyzed the overall causes and derived a proposed algorithm for improving reliability and performance of the control systems.

Key Words: NCS, Ramping Rate, Reliability

1 INTRODUCTION

The NCS (NSSS Control System), which is classified as non-safety system in a nuclear power plant, is required to mitigate a transient due to a certain event as well as to maintain major process variables within proper range in normal operation. If a plant transient occurs as a result of a significant event such as 'load rejection' and 'loss of feedwater pump', the related NCS should detect this transient situation by observing a rapid change in the measured input signals. If necessary, the system should generate an appropriate output signal, which is needed to actuate a critical function for preventing worse situations resulting from subsequent effects. Through these prompt actions performed by the control system, the plant can recover from the unstable situation and resume normal operation in a steady state.

If actual situation in the plant is not properly reflected in the received input during a transient, the control system cannot perform the above functions as its control algorithm fails to detect a sudden change in sensor signals that indicate plant operating conditions. In that case, despite the urgent situation, prompt actions may not be taken by the control system. For this reason, other major process variables such as the pressurizer pressure and the steam generator level can exceed the pre-defined limit allowed for normal operation in a plant. Finally, it can cause a reactor trip by the 'Plant Protection System' that is classified as safety system.

Recently, it was revealed that in certain cases a minor problem hidden in signal processing of input channels can cause a serious situation such as the plant shutdown as described in the next section. To find an optimal means for solving these problems and thus improving the plant availability, we performed an analysis on many cases for identifying the root cause and finally derived a recommendable algorithm in the input stage of control systems.

2 ANALYSIS ON POTENTIAL PROBLEM IN CONTROL SYSTEMS

Fig. 1 shows the simplified functional block diagram applied in a part of NCS for suppressing a plant transient. In most of the NSSS control systems, the system input is designed to have redundant channels for reliability. For performing calculation of a control algorithm, it is necessary to select an appropriate input value from many input channels [1]. For this reason, an ICSM (Input Channel Selection Module) is generally included in the system as shown in Fig. 1. This block continuously monitors the diagnostic information of input channels to detect any trouble in each channel and thus determine whether to maintain the previous channel or change the channel selection mode to exclude the failed input channel.

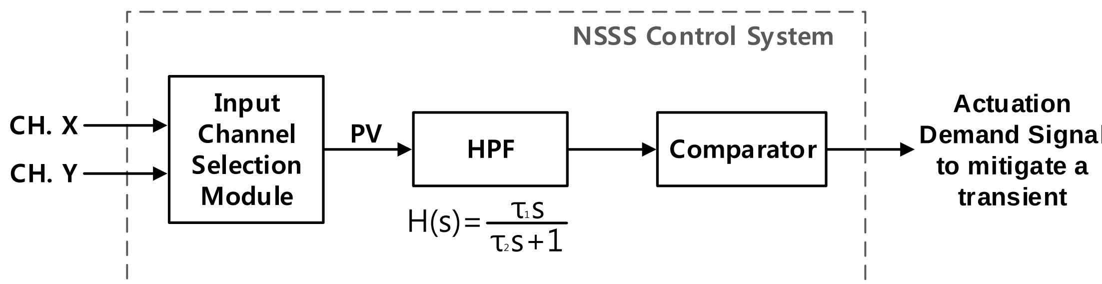


Figure 1. Simplified functional block diagram in NCS

The PV (Processed Variable), which is the output of the ICSM obtained by signal processing using several inputs from redundant channels, is used as an input to the HPF (High Pass Filter) to detect a sudden change in the selected input. Depending on the level of the transient, the control system should determine whether to generate an actuation demand signal to mitigate a transient or not. For this reason, if the output of the HPF is greater than or equal to a threshold, the comparator block generates 'TRUE (1)' as an output signal. In order for the control system's basic function to be performed successfully, each step in the functional block diagram has to be carried out properly.

As potential problems of the ICSM in many implemented systems were discovered, this block and its internal configuration need to be examined carefully as described in the following subsections. In this paper, it is assumed herein that the control system has two input channels, namely, 'CH X' and 'CH Y', for simple analysis. Therefore, there are three possible channel selection modes as follows: the 'CH X', the 'CH Y' and the 'AVG (Average)' mode.

In the ICSM, the transfer algorithm block is essentially included for selecting one of the three choices according to a certain condition. For this reason, we analyzed the transfer algorithm block first, prior to the analysis on the ICSM.

2.1 Transfer Algorithm Block

The transfer algorithm block is widely used in the functional block diagram of control systems for various purposes such as operation mode change, input channel selection, etc. As shown in Fig. 2, this block receives two different input signals, 'IN1' and 'IN2', and selects one of two inputs to generate an output depending on the binary value of the flag bit. The output will be equal to the input 'IN1' if the flag bit is 'FALSE (0)', and the input 'IN2' if the flag bit is 'TRUE (1)'.

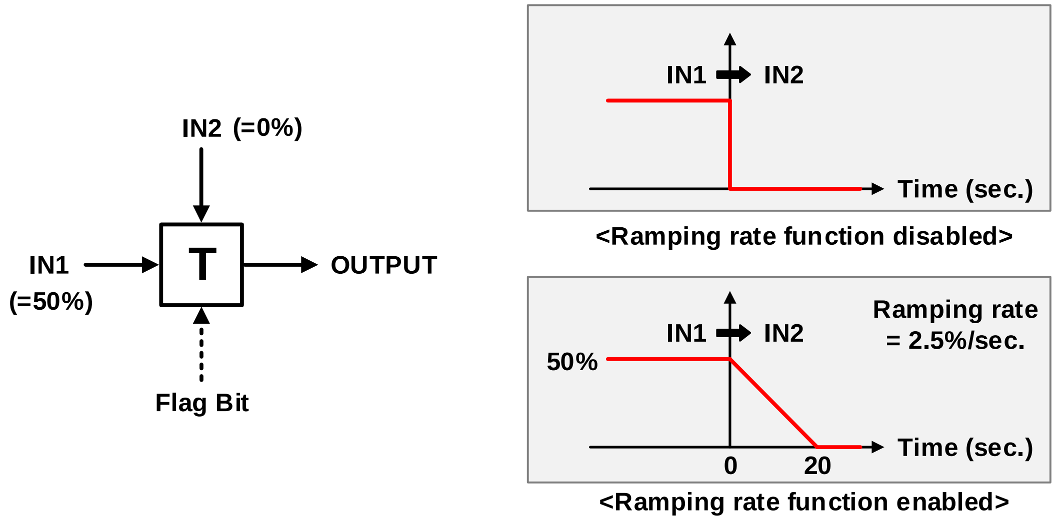


Figure 2. Transfer algorithm block and its ramping rate function

For a bumpless transfer between two input signals with different values, the 'ramping rate' function is generally applied to the transfer algorithm block. The role of this function is to make the output slowly approach the newly selected input from the previous input after the selection mode is reversed. It is attributed to the ramping rate at which the transfer algorithm block gradually reduces the deviation between the two inputs at the time the flag bit is changed. The ramping rate, being one of the internal properties of this block, can be adjusted. Fig. 2 shows the difference in the output according to the ramping rate function in the transfer algorithm block.

2.2 Input Channel Selection Module

We described the major principles of the transfer algorithm block in the above subsection. This block is necessary to configure the ICSM, because a process for selecting one from three choices is necessary to generate the PV which will be actually used in calculating the control algorithm.

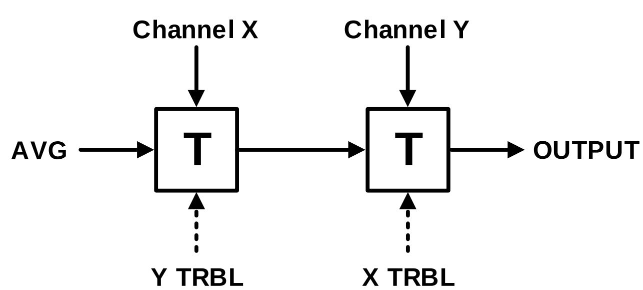


Figure 3. Basic configuration diagram for input channel selection module

Fig. 3 illustrates the basic configuration diagram for implementing the ICSM. Two transfer algorithm blocks are needed, as there are three input choices of X, Y and AVG for the control systems with two redundant input channels. The flag bits in this diagram, ‘X TRBL’ and ‘Y TRBL’, denote any channel trouble in the input channel X and Y, respectively. Therefore, if an input channel is considered to have any trouble such as sensor failure, input module failure, out-of-range event and so on, then the corresponding flag bit will be changed to ‘TRUE (1)’.

During normal situation with all of both input channels valid, the average of signals from two input channels should be calculated as the output of this module. If one of both input channels has trouble, the ICSM should select the other valid input channel. For example, when the input channel ‘Y’ is detected as failed, the channel selection mode should be changed to choose the channel ‘X’. For all cases of input channel’s conditions, the appropriate choice for channel selection is shown in Table I.

Table I. Logic table for input channel selection algorithm

X TRBL	Y TRBL	OUTPUT
0	0	AVG
0	1	CH X
1	0	CH Y
1	1	-

Due to channel uncertainty which is attributed to the corresponding sensor and analog input modules, the received input value in each channel is generally different from one another. Because there is an intrinsic error between input channels, the selected input value can be increased or decreased as a step change when the channel selection mode is altered by a certain event. A sudden change in the PV can adversely affect the corresponding control algorithm and thus finally can cause an unintended transient in the NSSS process. To prevent such a negative situation from occurring, a bumpless transfer is required [2]. Therefore, the ramping rate function of the transfer algorithm block is basically applied to the ICSM in many implemented systems.

2.3 Potential Problems in Control Systems

In most of normal cases, the ramping rate function in the ICSM performs its own correct role generally as shown in Fig. 2. Therefore, the implemented ramping rate function can be considered to be normal without any problem. However, in particular cases where a channel trouble in one of the two input channels is detected due to a plant transient, the potential problems attributed to incomplete implementation of the algorithm for the ramping rate function can be revealed.

An input channel trouble occurs by various causes including hardware failure in input channels [3]. In this paper, we considered an out-of-range event among many causes that result in an input channel conversion. Due to serious transient in the plant, the related input signal measured by each channel’s sensor can exceed the pre-defined range for detection of an out-of-range event which is slightly wider than the span of the transmitted input signal (e.g., 4~20mA). If the out-of-range event occurs, the corresponding input channel is considered to be failed even though there is no hardware failure in the input stage. For example, it was actually discovered that a large load rejection event in a nuclear power plant caused a measured input signal for steam flow to drop sharply below the low limit resulting in out-of-range.

To specifically describe the problems that will be caused by incomplete implementation of the ICSM, let’s assume that the measured input signals are declined rapidly in a unit cycle time (e.g., 100ms) as a result of significant transient in the plant as shown in Fig. 4. The input values from the two channels, X and Y, are shown to be decreased from the same value (50%) to zero (0) and certain minus value that is less than the low limit for out-of-range, respectively.

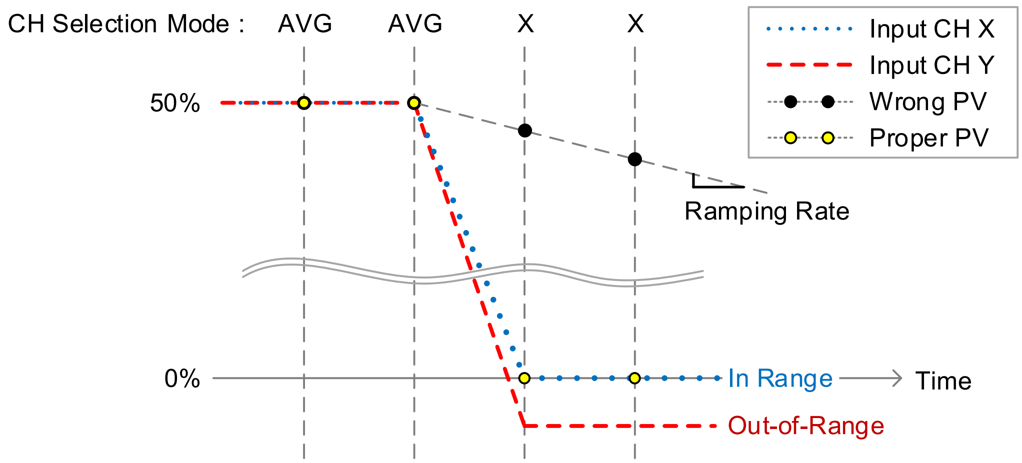
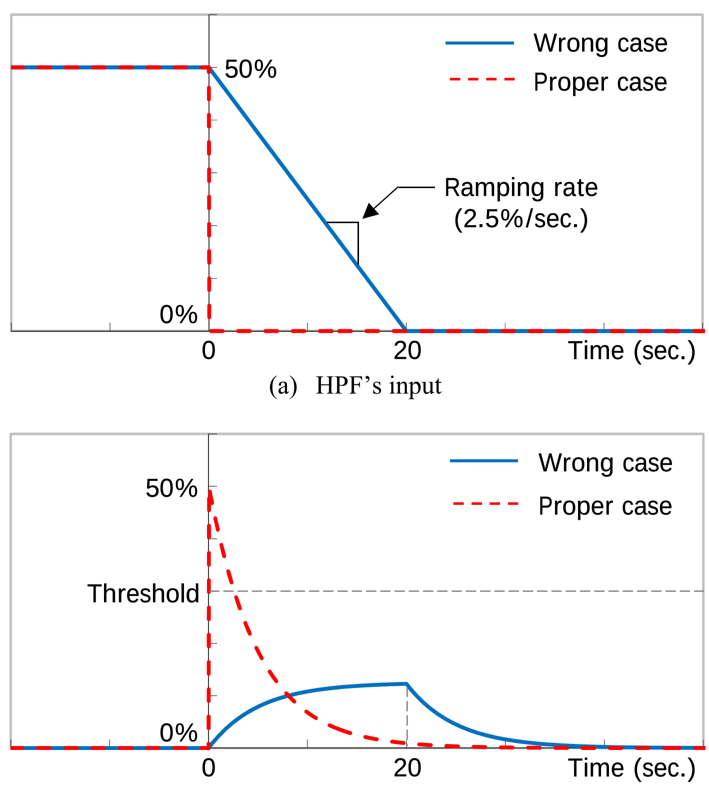


Figure 4. PVs obtained from input channel selection module for transient inputs



(a) HPF's input

(b) Absolute value of HPF's outputs

Figure 5. Inputs and outputs of HPF for two cases

For this reason, the channel selection mode is changed from the 'AVG' to the channel 'X' as the channel 'Y' is considered to have trouble. Although the measured signal in input channel 'X' is maintained to be 0% after a channel conversion, the output of the ICSM that is not properly implemented appears to be slowly decreased with a ramping rate from the previous output value (=50%) as shown with the black dots. Therefore, it will take a lot of time for the PV to approach the actual value in channel 'X'. This phenomenon is interpreted as significant distortion of a raw input signal reflecting real situation in the plant.

The appropriate PV for this case is demonstrated as the yellow dots. As there is no deviation between the 'AVG' and the channel 'X' just before the channel conversion occurs, the ramping rate function does not need to work. Even if the value of the selected channel falls sharply, the PV should track the measured value in channel 'X' reflecting this actual change. Therefore, the step change shown in the proper PV, which is attributed to the actual change in the selected channel, is not considered as a bump.

Fig. 5 shows the inputs and the outputs of the HPF according to the different PVs depicted in Fig. 4. The transfer function of the HPF is denoted as the following equation, where the parameters, τ_1 and τ_2, are assumed to be 5 seconds for simplicity.

$$H(s) = \frac{\tau_1 s}{\tau_2 s + 1} \quad (1)$$

The HPF's output is obtained by the equation Y(s) = H(s) • X(s), in which the X(s) and Y(s) are the Laplace transforms of the input and the output of the HPF, respectively. In addition, we assumed that the ramping rate is 2.5%/sec., at which the output in the wrong case is slowly decreased from 50% to 0% in 20 seconds since the channel selection mode was changed at time t=0.

As shown in Fig. 5, the HPF's output obtained using the proper PV meets the condition to generate an important actuation demand signal by the comparator block in the control system as it exceeds the pre-defined threshold, which is assumed to be 30% in this simulation. On the other hand, the HPF's output according to the distorted input due to wrong algorithm in the ICSM is less than the threshold. In this case, the control system will fail to take an essential action to mitigate the substantial transient.

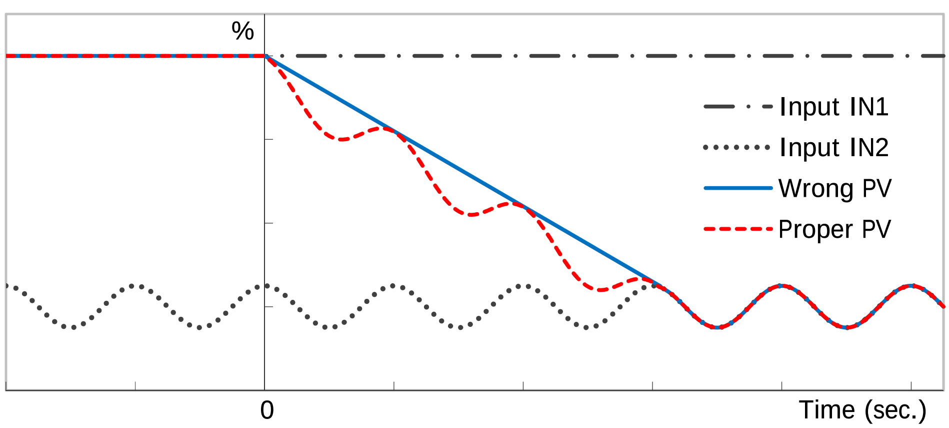


Figure 6. PVs obtained in case where selected input varies.

Let's assume the other case where the value of the selected input 'IN2' continuously varies since the channel selection mode was changed from 'IN1' to 'IN2' at time t=0 as shown in Fig. 6. Because the input channel was changed while there was a deviation between the two inputs, the PV should slowly approach the selected input channel by the ramping rate function for a bumpless transfer.

The solid blue line, which is considered as a wrong PV, is shown to be decreased with the constant change rate until its value becomes to be equal to the selected channel input. In this case, the dynamic change in the selected channel cannot be reflected in the PV during the transition. Moreover, it is not adequate to detect a transient state in the plant by using the PV signal that is monotonously changed with a constant slope. Recently, this phenomenon was also discovered in an implemented control system. On the other hand, the proper PV for the same condition is demonstrated as the dotted red line. It is shown that this line gradually reduces the deviation between the two channels while reflecting the selected channel's dynamic change.

3 PROPOSED ALGORITM FOR CHANNEL SELECTION

As described in the above section, we carefully analyzed the practical problems in the NCS for the two simple cases. To obtain the adequate PV in any cases of dynamic changes in the plant, many of the implemented input channel selection algorithms including the ramping rate function need to be improved to prevent the serious results.

Table II. Proposed algorithm for input channel selection

```
Switch (Selected_Channel) {

    Case 1 :
        temp = Out[n-1] + In1[n] - In1[n-1];
        If ( temp > In1[n] )
            Out[n] = max( In1[n], temp – RR * ΔT );
        Else
            Out[n] = min( In1[n], temp + RR * ΔT );
        break;

    Case 2 :
        temp = Out[n-1] + In2[n] - In2[n-1];
        If ( temp > In2[n] )
            Out[n] = max( In2[n], temp – RR * ΔT );
        Else
            Out[n] = min( In2[n], temp + RR * ΔT );
        break;
      ⋮

    Case N :
        temp = Out[n-1] + InN[n] - InN[n-1];
        If ( temp > InN[n] )
            Out[n] = max( InN[n], temp – RR * ΔT );
        Else
            Out[n] = min( InN[n], temp + RR * ΔT );
        break;
}
```

Through the specific analysis on the discovered problems, the proposed algorithm for the ICSM was derived as shown in Table II. In this algorithm, the 'Selected_Channel' is an integer value, which denotes the number of the corresponding channel chosen among N channels. In addition, 'InN[n]' and 'Out[n]' mean the current value at time t=n·ΔT, where 'ΔT' is a unit cycle time for discrete-time calculation in a CPU, for the Nth channel's input and the output, respectively. Therefore, the indication '[n-1]' in the variable names means its previous value. The parameter 'RR' denotes the ramping rate.

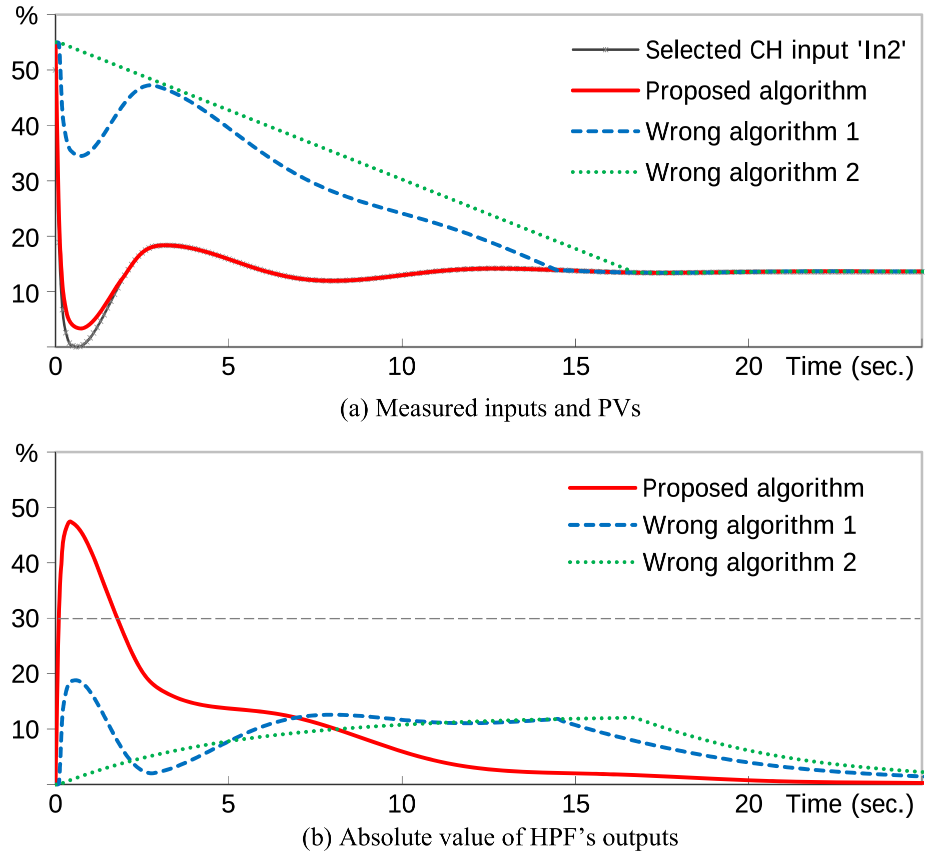


Figure 7. Simulation results according to various algorithms

To demonstrate the appropriateness of the proposed algorithm, a simulation was performed as shown in Fig. 7. Let's assume that, while the input signal in each channel was dropping rapidly due to a transient, a channel conversion from 'IN1' to 'IN2' occurred at time t=0, at which the input value of 'IN1' and 'IN2' was 55% and 50%, respectively. The selected channel input 'IN2' was assumed to reach a steady state after being decreased to a value near zero. All the parameters including the ramping rate and the threshold were assumed to be the same as those applied in the above section.

The two simulation results in Fig. 7 represent the PVs and the absolute value of the HPF's outputs according to different algorithms, respectively. In order for the control system to perform its critical functions properly in any cases, the change of the measured input signals from redundant channels should be adequately reflected to the PV while keeping the bumpless transfer characteristic based on the ramping rate. Unlike the wrong algorithms, the control system with the proposed algorithm is expected to generate the required actuation demand signal successfully, as its HPF's output is shown to exceed the threshold.

4 CONCLUSIONS

In this paper, it has been found that if the ramping rate function adopted for a good performance is not properly implemented in the control systems, it can unintentionally cause negative consequences under certain circumstances. Therefore, before applying a certain function to the control systems, it is necessary to thoroughly check if there are any potential problems in all possible cases. Through the specific analysis and the simulation results, it is concluded that the proposed algorithm for input channel selection meets the essential requirements to make it possible for the control system to generate an important actuation demand signal by detecting the fast changes in the PV while maintaining the bumpless transfer.

As a future work, we are considering applying this proposed algorithm to design of control systems in a SFR (Sodium Fast Reactor)-based nuclear power plant, in which stability is very important as major temperature variables should be maintained constant to minimize thermal fatigue of internal structures. In addition, we are also considering surveying the similar cases which are yet unveiled in the implemented control systems of many operating plants.

5 REFERENCES

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