International Journal of Recent Technology and Engineering (IJRTE)
ISSN: 2277-3878, Volume-8 Issue-1S3, June 2019

Dynamic Compensation and fault Detection and Isolation in Thermocouples

N. Divya, Y.Vidyasagar

Abstract*: For the safe and efficient operation of the many industries where temperature measurement is required such as power generation, cement etc., it is important to use temperature as the feedback signal in the control systems. As temperature measurement is done with thermocouples in most of the industries including power generation, Response time of thermocouple has to be measured periodically. In order to avoid the human intervention, and the errors associated with it, It is always preferred to be done online i.e., while the plant is in operation. To suggest a solution to this problem a scheme aiming at the Dynamic compensation of thermocouple in order to improve time response characteristics and to reduce the noise in the output signal and also fault detection and isolation of thermocouple to handle the degradations is presented in this paper. In this scheme as a part of the dynamic compensation, the Kalman filter formulation in linear time-invariant system framework for the thermocouples is used to assess and regenerate the input temperature to a thermocouple. The model of K and E type thermocouples are used for the demonstration of the results and by using these models the filter parameters are tuned appropriately to achieve the desired response. Generalized likelihood ratio (GLR) method is used in the Fault detection and isolation algorithm to identify the magnitude of fault in the thermocouples. The correction in the thermocouple output to compensate for the slow response and unwanted abrupt jumps is found to be extremely satisfactory.

Index Terms: ***Dynamic Compensation, Fault Detection and Isolation, Kalman Filter, Response Time, Thermocouple.***

I. INTRODUCTION

A Thermocouple which is an electrical device consisting of two dissimilar electrical conductors forming junctions at different temperatures, produce a temperature dependent voltage as a result of thermo electric effect. This property of thermocouples can be used to measure temperatures of the industries. Depending upon the range of temperature measurement many variantssuch as J,K, T and E type thermocouples can be neededwhich are most widely used. The Noble metal thermocouples such as type R, S and B which are used for high-temperature applications can also be realized.

Thermocouples are used in many industrial, scientific and OEM applications such as power generation, Oil/Gas, Pharmaceutical, Bio Tech, Cement, Paper and Pulp etc. Thermocouples are also used in every day appliances such as stoves, furnaces and Toasters. Totally the problems that are associated with a thermocouple are conduction, convection and radiation, Grounding issues and short circuits especially when placed on metal surfaces, high response time and noise in the output that comprises of both process noise and measurement noise.Process noise is the uncertainty in the system model and measurement noise is the uncertainty in the measurements of thermocouple. These noises are assumed to be zero mean, independent of each other and white.However, physical properties like tip diameter, wire length etc., and fluid properties like Reynolds number, Nusselt number etc. limit the band width of thermocouples. The protective sheaths onthe thermocouple assemblies also make them respond slowly.

In order to ensure the safe and efficient operation of critical systems the thermocouples Dynamic response characteristics play an important role The time constant which represents the fast response to the variations in the parameters of the process is analyzed by using the response time of thermocouple. To deal with a few of the above problems associated with thermocouples, Arun Prasad et.al [1]attempted to compensate the slow response of the thermocouples dynamically through Kalman filter-based technique using the linear time-invariant model of the thermocouples. They tested their method on – and – type thermocouples and could compensate for the slow response quite satisfactorily. However, their method doesn't include Fault Detection and Isolation (FDI),that generates features corresponding to normal operation and compares them with the actual behavior of thethermocouple, so that faults present in the thermocouples are recognized. In this paper, the similar mathematical model as used by Arun Prasad et al [1] is used to address the major issues in thermocouples such as compensation for the slow response, reduction of noise in the output, detection of faults and correction in the output to eliminate the effect of the faults. Performing FDI, the celebrated Generalized Likelihood ratio test[2] is used as in Yellapu et.al[2].The models of K and E type thermocouples are used and the results obtained with the proposed method are presented. Process noise is the uncertainty in the system model and measurement noise is the uncertainty in the measurements of thermocouple. These noises are assumed to be zero mean, independent of each other and white. By tuning the filter parameters the noise in the output signal of the thermocouple can be reduced.

In addition to the above, thermocouples sometimes also undergo faults which are some unpermitted deviations in one or more characteristic properties of the thermocouples from the normal operation.. Faults can either incipient or abrupt faults. If these faults are not detected and diagnosed they may lead to reduce the system reliability, may cause operational upsets and also reduce the safety margins.

Rest of the paper is organized as follows: Section II presents Dynamic compensation with Kalman filter, Section III describes Tuning of Filter parameters, Section IV describes Generalized likelihood ratio test, Section V gives the results and discussion. Finally, Section VI gives the important conclusions.

.Dynamic compensation with kalman filter

Dynamic Compensation which is the improvement of time response characteristics of the thermocouple by using different effective algorithms without using any external hardware,is required to ensure safe, fast and efficient temperature measurement. Dynamic compensation reduces not only the time constant of thermocouple but also the noise in the output signal. There are different compensation techniques for the response time improvement of thermocouples, such as direct inversion method, the dominant-pole Tustin[5] method and Kalman filtering Technique[4].In this section, the dynamic compensation with Kalman filter is briefly discussed.

Kalman filter is a set of mathematical equations that can recursively estimate the state of .the process such that mean-square error in the state estimate is minimized. Kalman filter which works on the principle of 'correction of prediction' supports the estimations of past, present and even future states of the process, even if the precise nature of the system is unknown. The regular Kalman filter is based on the linear Time-Invariant system framework. According to linear system theory, any linear discrete system is represented as

$$x_{k+1} = Fx_k + w_k \qquad (1)$$

$$y_k = Hx_k + v_k \qquad (2)$$

Where x_k is the state estimate,y_k is the output of the state, w_k and v_k are process noise and measurement noise respectively which are assumed to be independent with zero mean, as seen from

$$\mathrm{E}\left(\begin{bmatrix} w_k \\ v_k \end{bmatrix}\begin{bmatrix} w_k \\ v_k \end{bmatrix}^T\right) = \begin{bmatrix} Q_k & 0 \\ 0 & R_k \end{bmatrix}\delta_{kl} \qquad (3)$$

Here Q_k and R_k are the covariance matrices of process and measurement noises respectively, which are assumed to be stationary.

The equations representing the Kalman filter for the estimation of the state in the form of 'correction of prediction' are:

$$\hat{x}_k^- = F\hat{x}_{k-1}^+ \qquad (4)$$

$$P_k^- = F\hat{x}_k P_{k-1}^- F^T + \mathrm{Q} \qquad (5)$$

$$K_k = P_k^- H^T (\mathrm{H}P_k^- H^T + R)^{-1} \qquad (6)$$

$$\varepsilon_k = y_k - H\hat{x}_k^- \qquad (7)$$

$$\hat{x}_k^+ = \hat{x}_k^- + K_k\varepsilon_k \qquad (8)$$

$$P_k^+ = (E - K_k H)P_k^- \qquad (9)$$

In the first step, model parametersF_{k-1},H_k,Q_{k-1},R_k,T are determined. In the second step, the initial state estimate $\hat{x}_0$ and Intial state covariance P_0 are determined. In the third step a priori estimate $\hat{x}_k^-$ and priori error covariance P_k^- are computed using the estimate from the previous step. In the next step Kalman gain K_k and innovation ε_k are computed. Using this Kalman gain and innovation a posteriori estimate $\hat{x}_k^+$ and a posteriori error covariance P_k^+ are computed. And this process repeats. The innovation ε_k in (7) represents the difference between the predicted measurement $H\hat{x}_k^-$and the actual measurementy_k.

In order to go for the dynamic compensation of thermocouple, the linear model of thermocouple has to be known. The first order equation of a thermocouple is given by

$$T_g(\mathrm{t}) = T(t) + \tau\frac{dT(t)}{dt} \qquad (10)$$

Here τ is the time constant. T andT_g are the thermocouple temperature and input temperature respectively. The time constant τ represents the response of thermocouple to the variations in the parameters of the process. It can be determined by[1].

$$\tau = \frac{\rho c d^2}{4N_u k}$$

Where ρ isthe density of sensor, $c$represents specific heat of materials used, d represents tip diameter of thermocouple, k is the thermal conductivity,N_u is the Nusselt number. Time constant can also be determined experimentally by plunge test.

Equation (10) is discretized at a sampling interval T_s with zero order hold as

$$T(k) = \mathrm{a}\,T(k-1) + (1-a)\,T_g(\mathrm{k}\text{-}1) \qquad (11)$$

Where a=exp($\frac{-T_s}{\tau}$). The equation (11) is assumed to be a model of thermocouple which is known as given in [1], whereas the input model that is to be assessed is

$$T_g(\mathrm{k}) = T_g(\mathrm{k}\text{-}1) \qquad (12)$$

The state space model of thermocouple can then be obtained by combining the equations (11) and (12) as

$$\begin{bmatrix} T(k) \\ T_g(\mathrm{k}) \end{bmatrix} = \begin{bmatrix} a & 1-a \\ 0 & 1 \end{bmatrix}\begin{bmatrix} T(k-1) \\ T_g(\mathrm{k}-1) \end{bmatrix} + \mathrm{w(k\text{-}1)} \qquad (13)$$

$$T(k) = [1 \quad 0]\begin{bmatrix} T(k) \\ T_g(\mathrm{k}) \end{bmatrix} + \mathrm{v(k)} \qquad (14)$$

Q and R are the covariance matrices of process noise w(k) and measurement noise v(k) respectively, are

$$\mathrm{Q} = \begin{bmatrix} \sigma_1^2 & 0 \\ 0 & \sigma_2^2 \end{bmatrix}; \qquad \mathrm{R} = \sigma_s^2 \qquad (15)$$

Rcan also be estimated from the measurements of $T(k)$. In the covariance matrix Q, $\sigma_1^2$is the uncertainty in the process model.$\sigma_2^2$is the variance in the noise assumed on the input of the sensor . The estimated states are

$$\hat{x}(k) = [\hat{T}(\mathrm{k}) \quad \hat{T}_g(\mathrm{k})]^T \qquad (16)$$

Where $\hat{T}$(k) is the assessed input temperature. By selecting the filter parameters appropriately, the input temperature $\hat{T}_g$(k) nearly follows the actual input T_g(k).

The values of F and H in equations (5) and (6) are computed by comparing the thermocouple model with linear model. Thus by comparing the equations (13) and (14) with (1) and (2), the values of F and H are

$$\mathrm{F} = \begin{bmatrix} a & 1-a \\ 0 & 1 \end{bmatrix} \text{ and } \mathrm{H} = [1 \quad 0] \qquad (17)$$

Thus by knowing the value of the time constant τ value of a can be computed. The values of F and H can be determined from equation (17).

II. TUNING OF FILTER PARAMETERS

In the model of thermocouple given by equations (13),(14) and (15) σ_1^2 is small in value when compared with the σ_2^2 .which decides the accuracy of measurement..The uncertainty in the process modelσ_2^2 is to be chosen carefully because of a high value of σ_2^2 allows the filter to follow the fast changes of input to the sensor and also the output signal noise is amplified strongly.

III. GENERALIZED LIKELIHOOD RATIO TEST

Fault detection and isolation for step or abrupt faults have gained much significance in the recent years whereas incipient faults also seen regurarly. The main goal of Fault detection and isolation algorithm is to identifythe time of occurrence of fault, identify the location of the fault and estimate the magnitude of the fault and correction of the signal to compensate for the effect of fault. The FDI

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

algorithm compares the actual behavior of the system with the normal operation of the system and recognizes the anomalies responsible for deviations[4]. .

The FDI technique chosen in this paper is Generalized Likelihood Ratio method which is a innovation based detection system which performs statistical tests on the innovations sequence of a Kalman filter state estimator. The outcomes of GLR method will be the time of occurrence of fault and magnitude of fault. The signal can be corrected accordingly to compensate for the effect of fault.

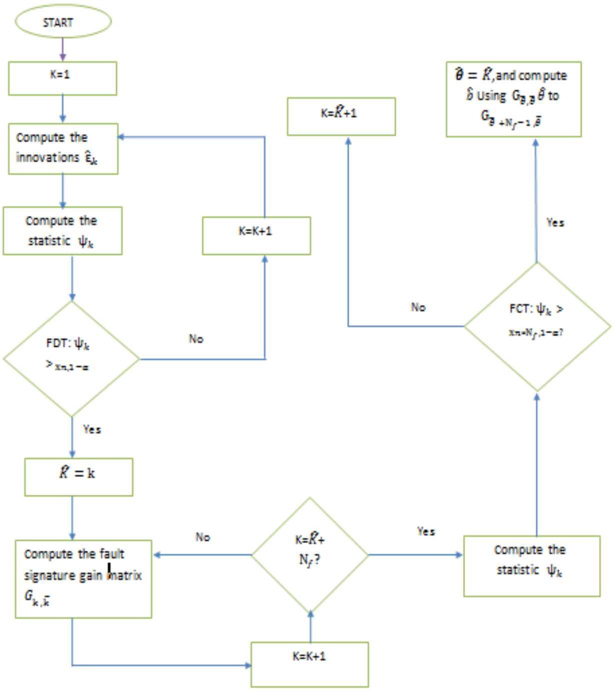


Fig. 1 Flow chart of GLR method for FDI

The flow chart od GLRT is as shown in Fig.1. Initially, at an instant k=1,the innovations obtained from the Kalman filter are used to compute the FDT statistic ψ_k. If ψ_k is greater than the threshold imposed, a fault is detected. Otherwise no fault is detected and k is incremented by 1. However, the random noise in the measurement can sometimes make this FDT statistic erroneously violate the threshold. Hence, another test is required which acts on a data window of the size N. A FCT is such test, which acts on the summation of the FDT statistics over the entire window of the size N.If the FCT statistic also exceeds the threshold set based on statistical properties of the system, a fault is declared by the GLRT at the instant k=$\hat{\boldsymbol{\theta}}$. The fault signature matrices $G_{\hat{\theta},\hat{\theta}}$ to $G_{\hat{\theta}+N_f-1,\hat{\theta}}$ are used to compute the fault magnitude $\hat{b}$, through the maximum likelihood ratio calculation.This $\hat{b}$ can be used to correct the thermocouple output affected by the abrupt fault

.

IV. RESULTS AND DISCUSSION

In this section, results of the Kalman filter-based dynamic compensation and FDI are presented.

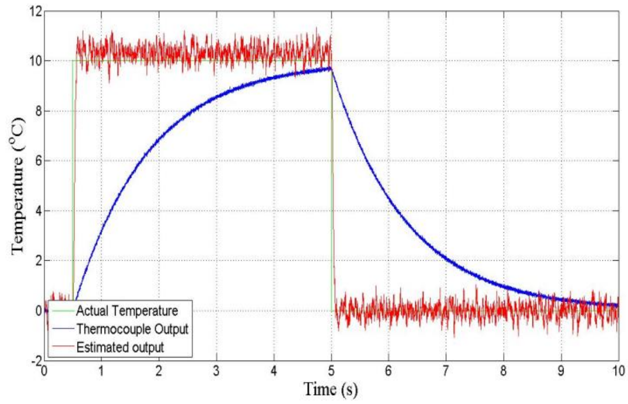


Fig. 2(a) Response of K-Type Thermocouple with Dynamic Compensation, with Q and R matrices not optimally tuned.

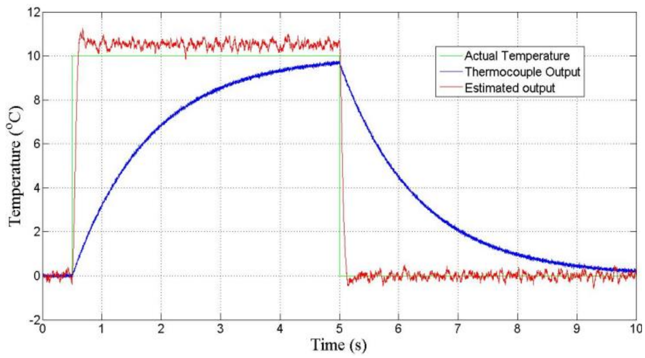


Fig. 2(b) Response of K-Type Thermocouple with Dynamic Compensation with proper tunung of Q and R matrices.

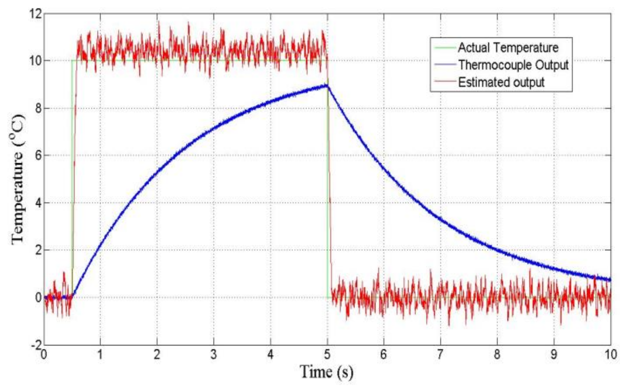


Fig. 3(a) Response of E-Type Thermocouple with Dynamic compensation with Q and R matrices not optimally tuned.

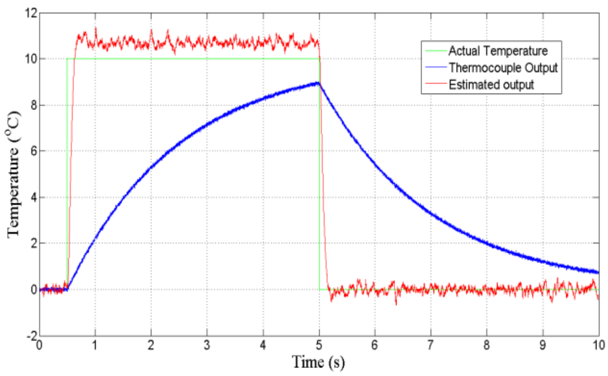


Fig. 3(b) Response of E-Type Thermocouple with Dynamic compensation with proper tuning of Q and R matrices.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

1. Dynamic compensation without faults:

In this section the dynamic compensation of the thermocouple output for the case of no faults in the signal are presented. Fig.2 and 3 show the actual temperature, thermocouple output (delayed) and the estimated output (as prompt as the change in the actual temperature) for K and E type thermocouples, whose models respectively are $\begin{bmatrix} T(k) \\ T_g(\mathrm{k}) \end{bmatrix}$=$\begin{bmatrix} -0.769 & 0.769 \\ 0 & 1 \end{bmatrix}$

And

$\begin{bmatrix} T(k) \\ T_g(\mathrm{k}) \end{bmatrix}$=$\begin{bmatrix} -0.5 & 0.5 \\ 0 & 1 \end{bmatrix}$

From Fig.2 and 3, it is evident that the Kalman Filter-based dynamic compensation could follow the actual temperature changes in nature of the input signal available to it. From 2(b) and 3(b) it is also seen that error in the extinction can be significantly reduced with a suitable choice of the Q and R matrices, which are

$$Q = \begin{bmatrix} 0.1 & 0 \\ 0 & 1000 \end{bmatrix} \, and \; R = [100]$$

And

$$Q = \begin{bmatrix} 0.01 & 0 \\ 0 & 1000 \end{bmatrix} \, and \; R = [100]$$

For K and E type thermocouples respectively. It may be noted that this case is just for the sake of demonstration as physical processes don't undergo such abrupt changes in the actual temperatures. It can also be noted that this case doesn't consider the faults into consideration.

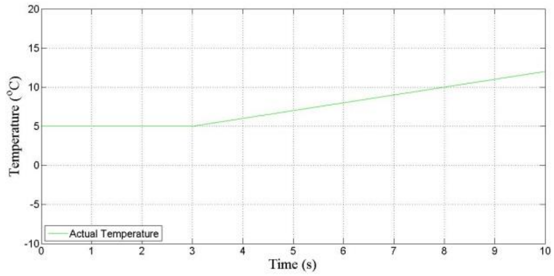
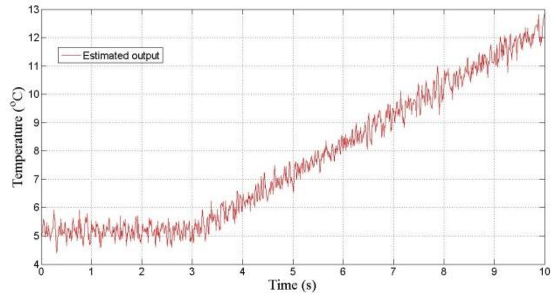


Fig. 4(a) Actual change in the temperature



. Fig. 4 (b) Output of the thermocouple delayed.

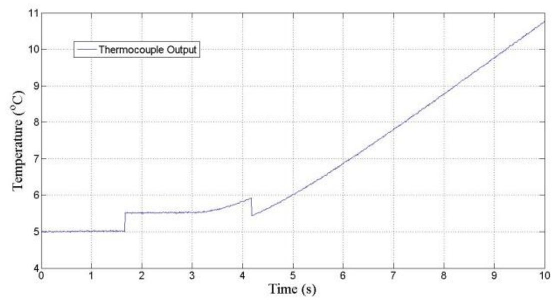


Fig. 4(c) Thermocouple output corrupted by additive faults..

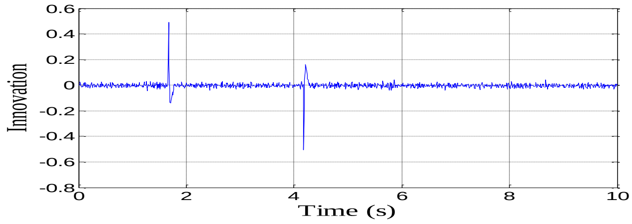


Fig. 5(a) GLR testoutcome

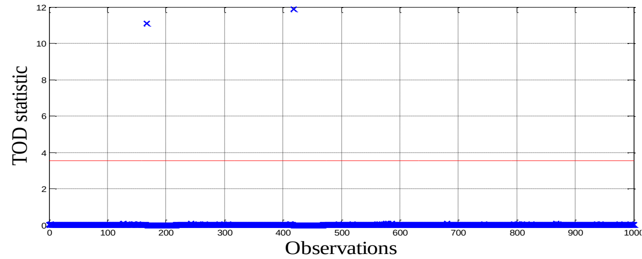


Fig. 5(b) GLR testoutcomes

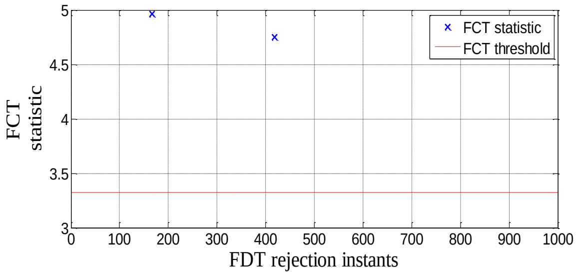


Fig.

Fig. 6(a) Thermocouple output

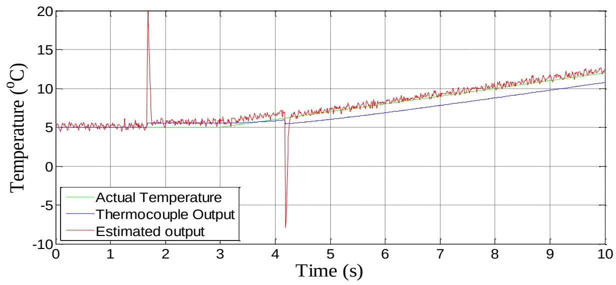


Fig. 6(b) Thermocouple output

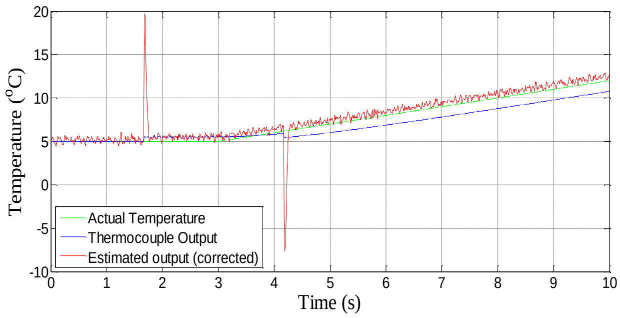


Fig. 6(c) Thermocouple output

2.Dynamic Compensation in the presence of faults:
In order to test the efficiency of the proposed method a realistic situation is considered in which the actual temperature of the plant slowly varies as shown in Fig. 4(a). The k-type thermocouple output corresponding to this temperature change is as shown in Fig. 4(b). Two number of additive faults are also considered in the thermocouple output as shown in Fig. 4(c), in which the signal from the thermocouple experiences a jump(upward) at t= 1.8s and another jump downward at t=4.2s.

When the data shown in Fig. 1(c) is fed to the Kalman filter based dynamic compensation scheme the innovation sequence is generated as shown in Fig. 5(a).It can seen from this Fig. 5(b). that the innovation sequence experiences jumps at t= 1.8s and t= 4.2s, i.e., exactly at the presence of additive faults. The FDT and FCT statistics (Fig.(2)) for this data are as shown in Fig. 5(b) and Fig. 6(a) respectively. It may be observed from Fig. 5(b) that the statistic exceed the threshold at the instant of faults, and the subsequent FCT also sees its statistic violating the threshold at these instants and this confirms the presence of additive abruptive faults in the data. The associated estimate of bias magnitudes are +19 and -8 at the instants t=1.8s and t= 4.2s, respectively.

The results of the dynamic compensation are shown in Fig. 6(b) and Fig. 6(c), out of which Fig. 6(b) represents the situation where estimated thermocouple output follows the actual temperature. While Fig. 6(c) represents the same when the bias magnitude estimated from the thermocouple is removed from the delayed thermocouple output. In both the situations it can be seen that the proposed scheme could quite accurately represent the actual temperature irrespective of the delayed thermocouple output and the presence of additive faults.

V. CONCLUSIONS

From the above results it can be concluded that by applying dynamic compensation using Kalman filter to a thermocouple effectively reconstructs the input temperatures .By tuning the filter parameters optimally the noise in the output signal can also be reduced. These optimally tuned parameters provide required response times and signal to noise ratio in the reconstructed signal. And by applying Generalized Likelihood Ratio Test for fault detection and isolation could effectively handle the abrupt changes in the thermocouple output and also identify the time of occurrence of fault, fault magnitude and could correct the signal to compensate for the effect of the fault.

REFERENCES

[1] V.Arunprasath, Jigar V Patel, and Kallol Roy "In-situ measurement and dynamic compensation of thermocouple time constant in nuclear reactors," IJATEE.2016.322003

[2] Yellapu VidyaSagar, A.K.Mishra, A.P.Tiwari,andS.B.Degweker," Online Fault Detection and Diagnosis of In-Core Neutron Detectors Using Generalized Likelihood Ratio Method", IEEE Transactions on nuclear science, V0l. 62, no. 6, December 2015

[3] A.S. Willsky, "A survey of design methods for failure detection in dynamic systems," Automatica, vol. 12, no. 6, pp. 601–611, Nov. 1976.

[4] A.S.Willsky and H. Jones, "A generalized likelihood ratio approach to the detection and estimation of jumps in linear systems," IEEETrans.Autom. Control, vol. AC-21, no. 1, pp. 108–112, Feb. 1976.

[5] Amit Kumar Mishra, SreyasRajagopalShimjith, TarangUpendra Bhatt and AkhilanandPatiTiwari,"Kalman Filter-Based Dynamic Compensator for Vanadium Self Powered Neutron Detector,"IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL 61,NO.3 ,JUNE 2014.

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication