AN INVESTIGATION ON ENHANCING THERMOCOUPLE PERFORMANCE IN NPPS

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Abstract:

In-core temperature measurements are pivotal in maintaining nuclear reactors in a safe state of operation. Thermocouples serve as the liaison in ensuring this state to be achieved. The realization of the thermocouple's full potential is hindered by two facts: (1) thermocouples cannot be situated in areas with high radiation fields, since radioactive particles have the potential of generating voltages in the thermocouple wires, hence producing an error in the temperature transmitter output and (2) thermocouples posses a disadvantageous transient response. In this paper, the methods to alleviate these drawbacks are discussed. Firstly, the effect of radioactive particles can be minimized by using an innovative electric circuit design. Secondly, the means by which to enhance the thermocouple's transient response is investigated through the use of a "compensation" technique.

Keywords: In-core Temperature Measurement, Radiation, Reaction-curve Based PID Tuning, Thermocouple

I. INTRODUCTION

Thermocouple is widely adopted in industry as a temperature measurement device. The fundamental principle of operation of thermocouples is known as the Seebeck effect, whereby when two dissimilar metals are joined together, an electromotive force (emf) will be developed between the endpoints A and B, as shown in Fig. 1. This emf is a function of the temperature at the junction.

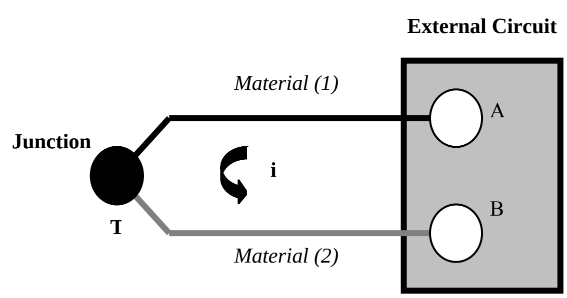

Fig. 1 Thermocouple Circuit[1]

Temperature is one of the most fundamental process parameters in typical industrial control environments. This holds true for Nuclear Power Plants (NPPs) as well, whereby the monitoring and control of temperature is pertinent to the operation of the plant.

The two primary methods by which the thermal power is measured in NPPs are (1) measuring the heat output from the reactor and (2) measuring the heat input to the steam generators. With respect to the first method, it is imperative to understand that the useful heat output from a CANDU reactor is situated in the fuel channels. Thus, to measure the thermal power, the heat transferred to the fuel coolant is obtained by determining the flow rate and the temperature difference from the fuel channel's inlet and outlet. The second method computes the heat input to the steam generators by measuring the steam flow and the feedwater flow and their respective temperatures.[2] As can be seen, temperature measurements are of paramount importance when computing the thermal power output of the reactor. A simplified thermocouple temperature transmission circuit in NPPs is shown in Fig. 2.

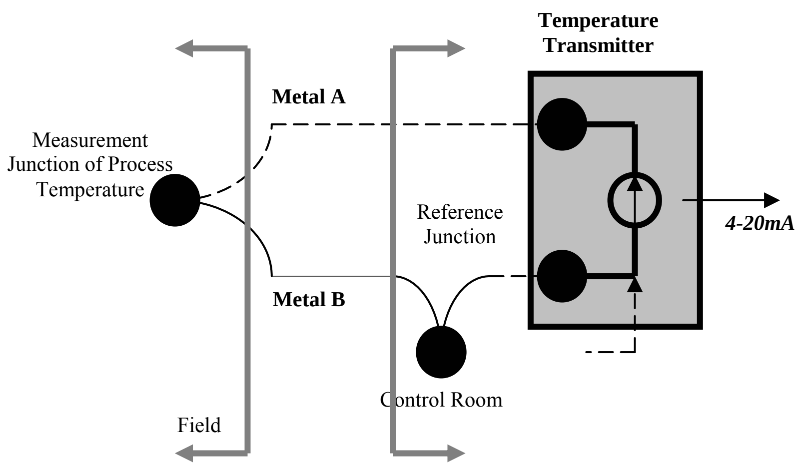

Fig. 2 Simplified Thermocouple Temperature Transmitter Circuit[3]

II. PROBLEMS ASSOCIATED WITH THE USE OF THERMOCOUPLES IN NPPs

The two fundamental problems associated with the use of thermocouples in the reactor core and in the heat transport system are the effect of radiation on the voltage reading from the thermocouple circuit and the thermocouple's transient response.

To gain a better understanding of how radiation can affect the emf of a thermocouple circuit, one must understand the properties of radiation and how it affects the thermocouple circuit. Primarily, radioactive particles (or fission products, in the case of a nuclear reactor) possess energy. This energy can be converted into a current and a voltage when it interacts with a resistive element, such as the internal resistance of a wire. Thus, the radiation will insert excess voltage into the thermocouple circuit and produce erroneous temperature results.

The time delay of the thermocouple circuit poses another problem. For instance, the temperature of the reactor coolant at the fuel channel's inlet and outlet are obtained only after a time delay. What constitutes the time delay are (1) the time it takes the coolant to reach the vicinity of the thermocouple (which is around the feeder pipes) and (2) the time delay of the thermocouple itself.[2]

III. PROPOSED SOLUTIONS

A. OFFSETTING THE EFFECT OF RADIATION

In order to offset the effect of radioactive particles on temperature measurement, the question to be answered is how to quantify the current and voltage that the radioactive effect induces. To obtain the current, the following elements are essential: (1) the radiation particle's energy (in eV), (2) the work function of the thermocouple metals, and (3) the time that it takes for the radiation particle to have an effect on the thermocouple.

In NPPs, the type J thermocouple is most popularly used. The related energy of the particles in typical fission products is shown in Table 1. The work function of the type J thermocouple metals is shown in Table 2. The response times of the type J thermocouple are shown in Table 3. Due to physical needs of nuclear plant operation, the type J thermocouple with the largest cross sectional area is often used. Thus, this paper explores the use of type J thermocouple with a 0.032 inch diameter. Thus the response time of 40 seconds is used.

Table 1 Energies of typical fission products in a CANDU reactor[4]

Energies of Fission Products (eV)			
Product	***Alpha Energy***	***Beta Energy***	***Gamma Energy***
U-238	***4.20E+06***	-	***1.30E+04***
U-235	***4.40E+06***	-	***1.86E+05***
Pu-239	***5.16E+06***	-	***1.36E+04***
Sr-90	-	***1.96E+05***	-
Cs-137	-	***1.57E+05***	-
Te-99	-	***8.46E+04***	***8.94E+04***
I-128	-	***8.36E+05***	***4.43E+05***
I-131	-	***1.92E+05***	***3.64E+05***
Kr-85	-	***2.51E+05***	***5.14E+05***
Kr-87	-	***1.50E+06***	***4.03E+05***

Table 2 Response times of type J thermocouple[5]

Type J Constants	
Wire Diameter (inch)	***Response Time (s)***
0.005	**1**
0.01	**5**
0.02	**20**
0.032	**40**

Table 3 Work function of Type J Thermocouple [6]

Work Function of Type J Thermocouple	
Constituent Element	***Work Function (eV)***
Iron	*4.5*
Copper	*4.5*
Nickel	*4.6*
Total Work Function	**9.045**

With the data provided in Tables 1, 2, and 3, the current can then be calculated as follows:

$$I = \frac{E}{\Phi \tau} \qquad \textbf{(1)}$$

Where $I = \text{current}\left(A\right)$

$E = \text{particle energy}\left(eV\right)$

$\Phi = \text{work function}\left(\frac{eV}{ip}\right)$

$\tau = \text{time constant}\left(s\right)$

The current of each of the fission products shown in Table 1 can be calculated via Eqn. (1) and the results are shown in Table 4.

Table 4 Current of fission products

Current of Fission Products (A)			
Product	***Alpha Energy***	***Beta Energy***	***Gamma Energy***
U-238	***1.16E+04***	-	***3.59E+01***
U-235	***1.22E+04***	-	***5.13E+02***
Pu-239	***1.42E+04***	-	***3.76E+01***
Sr-90	-	***5.41E+02***	-
Cs-137	-	***4.33E+02***	-
Te-99	-	***2.34E+02***	***2.47E+02***
I-128	-	***2.31E+03***	***1.96E+06***
I-131	-	***5.30E+02***	***1.01E+03***
Kr-85	-	***6.95E+02***	***1.42E+03***
Kr-87	-	***4.15E+03***	***1.11E+03***

In order to find the voltage that the fission product induces, the resistance of the type J thermocouple needs to be determined. This can be calculated by Eqn. (2), where the related resistivities for the type J thermocouple can be found in Table 5 and a diameter of 0.032 inch and a length of 1.2m have been chosen.

$$R = \frac{\rho l}{A} \qquad \textbf{(2)}$$

Where $R = \text{resistance}\left(\Omega\right)$

$\rho = \text{resistivity}\left(\Omega \bullet m\right)$

$l = \text{length of specimen}\left(m\right)$

$A = \text{cross section of specimen}\left(m^2\right)$

Therefore:

$$R\left(\text{thermocouple}\right) = 1.34\Omega \qquad \textbf{(3)}$$

The voltage of the respective fission products are then calculated using Ohm's Law and the results are shown in Table 6:

Table 5 Total resistivity of type J thermocouple[6]

Type J Resistivity	
Constituent	***Resistivity (Ωm)***
Iron	**9.71E-08**
Constantan	**4.90E-07**
TOTAL	**5.87E-07**

Table 6 Voltages of fission products

Voltage of Fission Products (V, via Ohm's Law)			
Product	***Alpha Energy***	***Beta Energy***	***Gamma Energy***
U-238	***1.55E+04***	-	
U-235	***1.63E+04***	-	
Pu-239	***1.91E+04***	-	
Sr-90	-	***7.25E+02***	-
Cs-137	-	***5.81E+02***	-
Te-99	-	***3.13E+02***	***3.31E+02***
I-128	-	***3.10E+03***	***2.62E+06***
I-131	-	***7.10E+02***	***1.35E+03***
Kr-85	-	***9.31E+02***	***1.90E+03***
Kr-87	-	***5.56E+03***	***1.49E+03***

In order to offset the effect of the radiation, a system as shown in Fig. 3 is formed by undertaking the following procedures:

(1) Build a type J thermocouple circuit which read in voltages from both the environment and radiation.
(2) Build an electric circuit in the vicinity of the thermocouple circuit. This circuit consists of resistor which has the same resistance as that of the type J thermocouple (which is 1.34Ω). This circuit will also interact with radiation such that a voltage will be created when the radiation current interacts with the resistor.
(3) To find an accurate thermocouple voltage to the order of $+/-10^{-5}$V, the voltage readings from system one will be subtracted from that of system two.
(4) The result of step (3) will then be added to a correction factor that will implement the desired accuracy of $+/-10^{-5}$V.

It must be noted that radiation sources are random numbers. In an effort to simulate a more realistic system, different probability distributions are used. i.e., different combinations of fission products and consequently different combinations of voltages will interact with the circuit built in step 1 and 2.

The voltage components of each system in Fig. 3 are summarized in Table 7. The voltage of the overall configuration in Fig. 3 can then be calculated as follows:

$$V_{total} = \left(V_1 + V_{R_1}\right) - \left(V_{R_2}\right) + \left(-\left(V_{R_1} - V_{R_2}\right) \pm 0.00001\right) \quad \textbf{(4)}$$

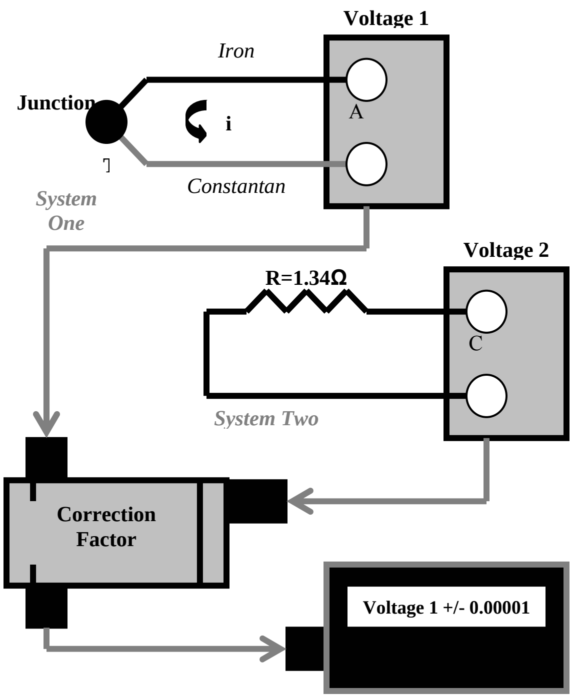

Fig. 3 Schematic Representation of Proposed System.

Table 7 Voltage components of each stage in the derived system

Component	***Voltage Source***	***Radiation Source***
System (1)	Voltage 1 (**V_1**: *voltage from the environment*)	Radiation 1 (**V_{R1}**: radiation voltage that interacts with thermocouple)
System (2)		Radiation 2 (**V_{R2}**: radiation voltage that interacts with circuit)
Correction Factor	0.00001 – (Radiation 1 – Radiation 2)	

Equation (4) then reduces to:

$$V_{total} = V_1 \pm 0.00001 \quad \textbf{(5)}$$

To demonstrate the effectiveness of the proposed system, simulation is performed using Matlab. The relation between the temperature and the voltage reading for a type J thermocouple is:

$$T(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 + a_5 x^5 \quad \textbf{(6)}$$

Where x represents the voltage reading and the coefficients are shown in Table 8.

Table 8 Constants for Type J Thermocouple[1]

Type J Thermocouple Constants	
Coefficient	***Value***
a_0	**-0.048868252**
a_1	**19873.14503**
a_2	**-218614.5353**
a_3	**11569199.78**
a_4	**-264917531.4**
a_5	**2018441314**

The transfer function of a type J thermocouple can then be derived based on Eqn. (7) as follows:

$$T(s) = \frac{a_0 s^5 + a_1 s^4 + 2a_2 s^3 + 6a_3 s^2 + 24a_4 s + 120a_5}{s^6} \tag{7}$$

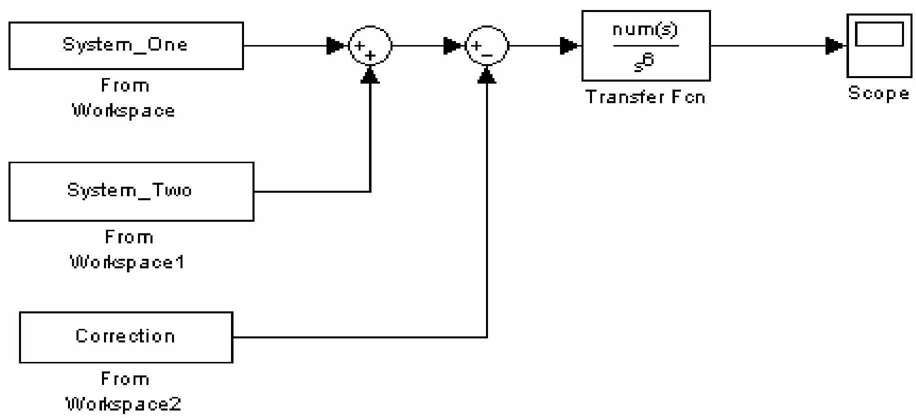

Fig. 4 Block Diagram of Proposed System.

The block diagram of the proposed system can then be represented in Fig. 4, where "Workspace, Workspace1, Workspace2" denote the MATLAB workspace where the voltages from system one, system two, and the voltages processed in the correction factor, are stored. The voltages from ITS (90) as shown in Table 9 were used as system inputs. The simulation results are shown in Table 10. The comparisons between the tabulated and simulated voltage and temperature are further showed in Fig. 5 and Fig. 6. It can be seen that by adopting the proposed system, there are only minor differences between the expected and real values even though the system is in an environment with radiation.

Table 9 Tabulated temperatures and voltage for type J thermocouple[1]

Type J Voltage and Temperature (ITS (90))	
Temperature (° C)	***Voltage (V)***
25	**1.28E-03**
50	**2.59E-03**
75	**3.92E-03**
100	**5.27E-03**
150	**8.01E-03**
200	**1.08E-02**
300	**1.63E-02**
400	**2.18E-02**
500	**2.74E-02**
600	**3.31E-02**

Table 10 Results of the simulation run

Results of Simulation Run	
Voltage (V)	**Corresponding Temperature (° C)**
0.0013	25.44143012
0.0026	50.33494855
0.0039	74.75807766
0.0053	100.6597142
0.008	149.8494301
0.0108	200.3481599
0.0163	299.5246286
0.0219	401.070079
0.0274	500.1902659
0.0331	599.9892971

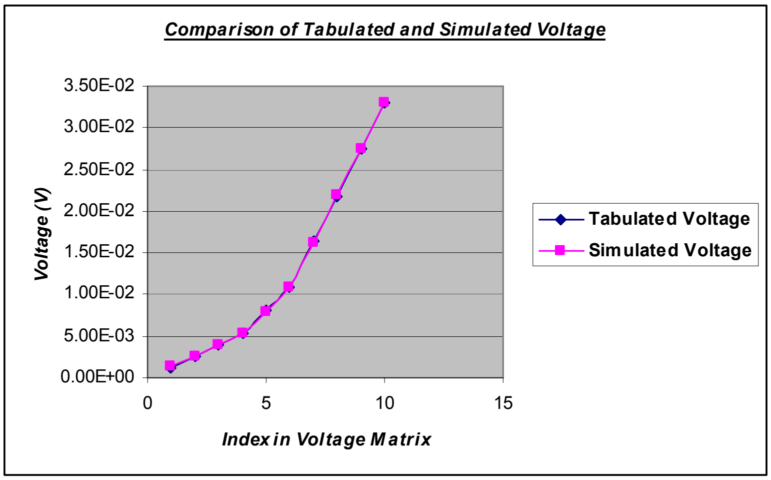

Fig. 5 Comparison of Tabulated and Simulated Voltage

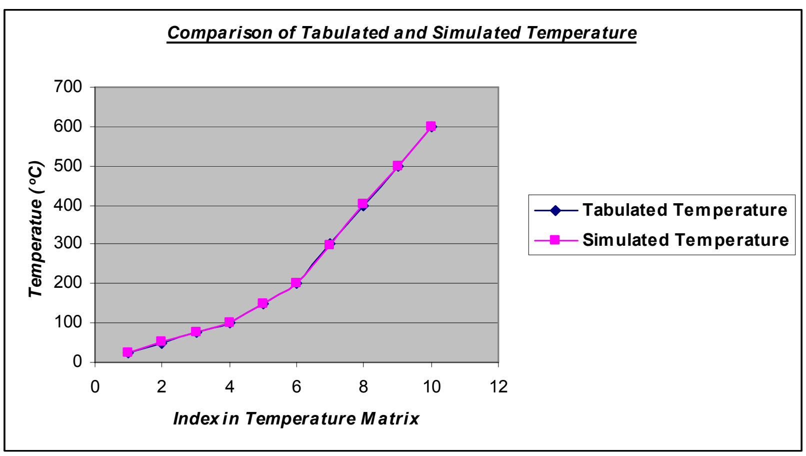

Fig. 6 Comparison of Tabulated and Simulated Temperature

B. IMPROVING THERMOCOUPLE PERFORMANCE

The response of the thermocouple when measuring the voltage and consequently the temperature of an environment is of interest. As discussed in the previous section however, the effect of radiation on the thermocouple system can be detrimental. Consequently, the response of the thermocouple will be altered. To offset such a problem, one must examine methods by which the voltage induced from the radiation can be disposed of and to enhance the response of the thermocouple. The primary method which comes to mind is a system whereby its principle of operation is as follows:

(1) The system processes voltage readings (the sources for the reading are from the environment in which the thermocouple is situated in and from the radiation source).

As a result of individually processing the voltage readings, this system must be able to handle the voltage induced by the respective fission products. To do this, it important to recall that voltages induced from the environment in which the thermocouple is situated in are of the order of 10^{-3}V whereas the voltages of the fission products are of the order of 10^{2}-10^{4}V. Hence, this forms the basis of distinguishing what readings is characteristic of a fission product or of the surrounding environment. Consequently, a low pass filter will be used to implement this technique. More specifically, the cut-off voltage for this filter will be chosen as 10^{-1}V.

(2) To reduce the effect that the radiation source has on the thermocouple's response, a compensation system will be inserted into the thermocouple circuit (adopted from Holman). The primary purpose of this system is to increase the frequency response of the thermocouple.

The following figure shows a schematic representation of the derived system.

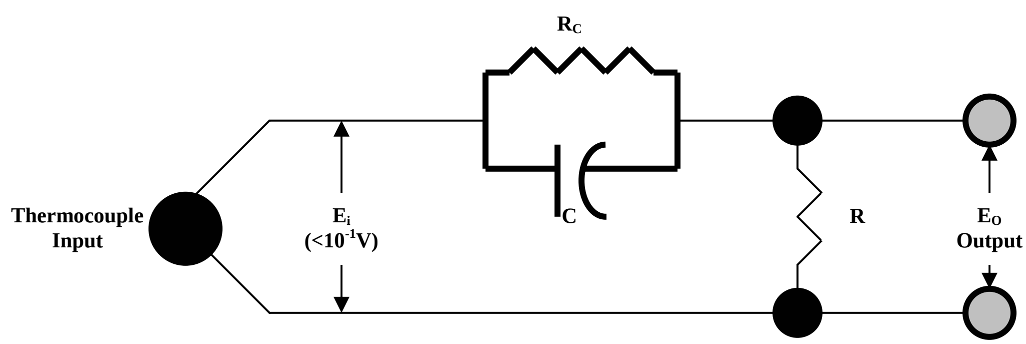

Fig. 7 Diagram of Proposed System[7]

The ratio between the output voltage to the input voltage for the above circuit is given by:

$$\frac{E_0}{E_i} = \alpha\left(\frac{1 + j\omega\tau_C}{1 + \alpha j\omega\tau_C}\right) \qquad \textbf{(8)}^{7}$$

The terms seen in expression (8) are as follows:
$\omega =$ Frequency of input signal
$\tau_C = R_C C$ (time constant of compensating system)

$$\alpha = \frac{R}{R_C + R}$$

The magnitude of the ratio seen in expression (8) is given by:

$$\frac{E_0}{E_i} = \alpha\left(\sqrt{\frac{1+(\omega\tau_C)^2}{1+(\alpha\omega\tau_C)^2}}\right) \qquad \textbf{(9)}^7$$

The ultimate aim of this approach is to compare the curvature of the output-to-input voltage ratio for different values of alpha.

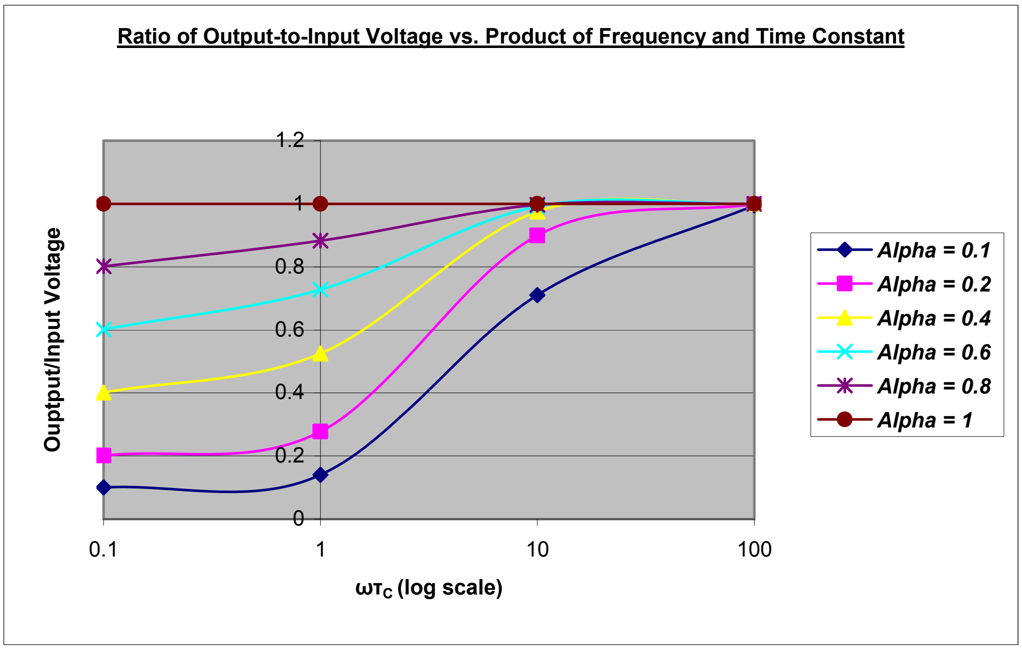

Fig. 8 The effect of varying the value of alpha on the response of the thermocouple system (with compensator)

What observations can be made from the above plot? Primarily, as the value of alpha increases, the output-to-input voltage ratio will have higher values for each respective value of $\omega\tau_C$. Thus, the frequency response of the system shown in figure seven has been increased for successive values of alpha. Secondly, if we assume that the curvature of the plot of the output voltage (as a function of alpha and $\omega\tau_C$) is analogous to the plot shown in figure eight, we observe several key features with respect to control system theory:

- As the value of alpha increases (more specifically, when alpha ≥ 0.4), the maximum value of the output voltage for each respective curve will occur at the same value of $\omega\tau_C$
- As a result of the curvature shown in figure eight, no significant percent overshoot exists

- The absence of an error band in the steady state region of the respective curves results in the fact that the settling time will be deemed insignificant

What advantages can be realized of implementing the system seen in figure seven and the plot in figure eight? If we are to treat the radiation that is in the vicinity of the thermocouple as noise, how can one dispose of the effects that such noise imposes on the thermocouple system? A common approach is to increase the signal-to-noise ratio by increasing the amplitude of the input signal.[8] Consequently, a greater signal is obtained by increasing the amplitude of the input signal. Thus, this has been achieved.

IV. CONCLUSION

The central focus of this paper is to enhance the performance of the type J thermocouple in nuclear plant operation. The underlying concepts of this temperature measuring device and how radiation affects its performance are quantitatively stated by mathematical expressions. Based on this, an innovative system is proposed to eliminate the effects of radiation interaction with the thermocouple wire. The transient response is improved by inserting a “compensation” system into the thermocouple circuit.

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