Optimized, Low-Power Dissipative and Precise Pulsating Constant Current Source Based Temperature Measurement System

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ABSTRACT: *A constant voltage source based temperature measurement system; using PRT-1000 is one of the currently used methods to measure the temperature of subsystems in Indian Satellites. One such subsystem which uses PRT-1000 is solar panels. This paper describes a constant current source based temperature measurement system and the advantages it offers in terms of linearity, sensitivity and power dissipation. Simulations using MATLAB and Simulink® are carried out to illustrate the differences between the two methods. To overcome self-heating effects in the resistor a pulsating constant current source based temperature measurement system is described.*

Keywords: *Linearity, pulsating constant current source, PRT-Platinum Resistance Thermometry, SADA- Solar Array Drive Assembly, self-heating, sensitivity.*

I. INTRODUCTION

Remote Sensing as well as Geostationary satellites use deployable solar panels [1], [2], [3] to convert solar energy to electrical energy. The solar panels at a time either face the sun or the dark space. The orientation thus, leads to a large temperature variation of about 400 ºC (-200 ºC to +200 ºC). This temperature variation is sensed using PRT-1000 and associated circuitry. The paper presents two methods that can be used with PRT-1000 namely constant voltage source method and constant current source method.

II. CONSTANT VOLTAGE SOURCE METHOD

The constant voltage source method employs the PRT-1000 as one of the resistor of a voltage divider circuit and maps the associated voltage change to the corresponding temperature changes. The following circuit setup is currently used. R_{SADA} is the resistance offered by the slip rings of the rotary power transferring assembly called SADA.

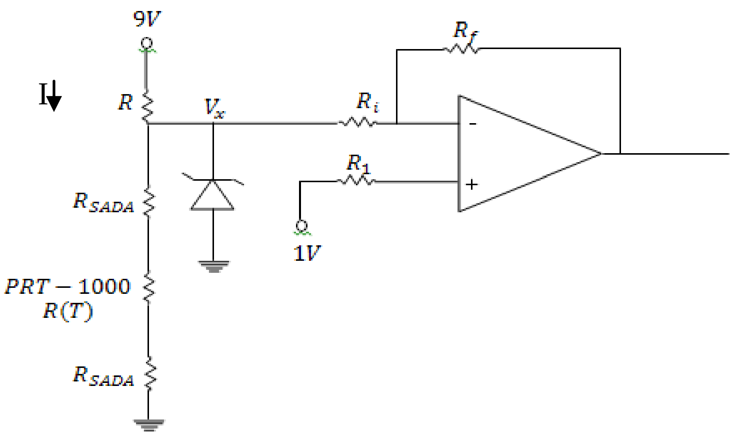

Fig 1: Temperature measurement system using constant voltage source and PRT-1000

2.1 Mathematical analysis

Let a current I flow as shown. If R= 10K, then by Ohm's Law and assuming infinite input impedance for the op-amp:-

$$I = \frac{9V}{10K + R(T)} \quad (1)$$

where R(T) is the resistance of the PRT-1000 that varies with temperature.
We have

$$V_x = V + V_{NOISE} \quad (2)$$

where
V_x is the voltage at one end of R_{in}
V is the voltage induced by the voltage divider circuit
V_{NOISE} is the voltage noise added due to SADA. It is approximately 10mV/Amp.
We have, the voltage at the Zener due to voltage divider circuit as:-

$$V = \left(\frac{R(T)}{10K + R(T)}\right) \times 9V \quad (3)$$

Writing Kirchoff's loop equation for the op-amp, we obtain

$$\frac{V_x - 1}{R_{in}} = \frac{1 - V_{out}}{R_f} \tag{4}$$

Simplifying the above equation and rearranging the terms, we obtain

$$V_x - 1 = \beta(1 - V_{out}) \tag{5}$$

Where

$$\beta = \frac{R_{in}}{R_f} \tag{6}$$

Solar Array Drive Assembly (SADA) of the satellite introduces voltage noise that is proportional to the current flowing through it and given as:-

$V_{NOISE} = 10\frac{mV}{A} \times I$

Taking into account the negative path SADA, we have

$V_{NOISE} = 2 \times 10mv \times \left(\frac{9v}{10k + R\ (T)}\right)$

$$V_x = \left(\frac{R(T)}{10K + R(T)}\right) \times 9V + 2 \times 10mV \times \left(\frac{9V}{10K + R(T)}\right) \tag{7}$$

The linearity of the system can be measured by analyzing the differential of the system w.r.t the variable parameter. If the differential is constant, the system linearly depends on the variable parameter. Differentiating (5) w.r.t temperature (T), we obtain

$$\frac{dV_x}{dT} = -\beta\frac{dV_{out}}{dT} \tag{8}$$

Substituting, V_x from equation (7), equation (8) modifies to

$$\frac{dV_x}{dT} = \frac{d}{dT}\left\{\left(\frac{R(T)}{10K + R(T)}\right) \times 9V\right\} + \frac{d}{dT}\left\{\left(\frac{0.02}{10K + R(T)}\right) \times 9\right\} \tag{9}$$

Simplifying equation (9)

$$\frac{dV_x}{dT} = \frac{d}{dT}\left\{\left(\frac{(9R(T) + 0.18)}{10K + R(T)}\right)\right\} \tag{10}$$

$$\frac{dV_x}{dT} = \frac{(90K - 0.18)}{\left(10K + R(T)\right)^2} \times \frac{dR(T)}{dT} \tag{11}$$

The differential term $\frac{dR(T)}{dT}$ represents the differential variation of resistance of PRT w.r.t temperature. The relation between the resistances of PRT w.r.t temperature is a complex n-th order equation in temperature. However, the higher order equations are negligible and can be ignored; thus reducing the dependence of R (T) to first order equation as shown below

$$R(T) = R_o(1 + \alpha dT) \tag{12}$$

Differentiating equation (12) we obtain $\frac{dR(T)}{dT}$ as

$$\frac{dR(T)}{dT} = R_o\alpha \tag{13}$$

Substituting values of R_o and α, in equation (13), and thereafter substituting the result in (11), we have

$$\frac{dV_x}{dT} = \frac{(90K - 0.18)}{\left(10K + R(T)\right)^2} \times 3.85 \tag{14}$$

$$\frac{dV_x}{dT} = \frac{(90K - 0.18)}{\left(10K + 1000(1 + 3.85\Delta T)\right)^2} \times 3.85 \tag{15}$$

Equation (15) illustrates that the change in voltage w.r.t is not constant and varies with change in temperature. However, for a linear system the differential should be constant to yield a linearly varying integral (or the system). The output depends on the input as given by equation (16)

$$V_{out} = \frac{\beta + 1 - V_x}{\beta} \tag{16}$$

The linear relationship between V_{out} and V_x makes V_{out} nonlinear w.r.t temperature. Thus, it can be concluded that a constant voltage source based temperature measurement system is non-linear method of measurement.

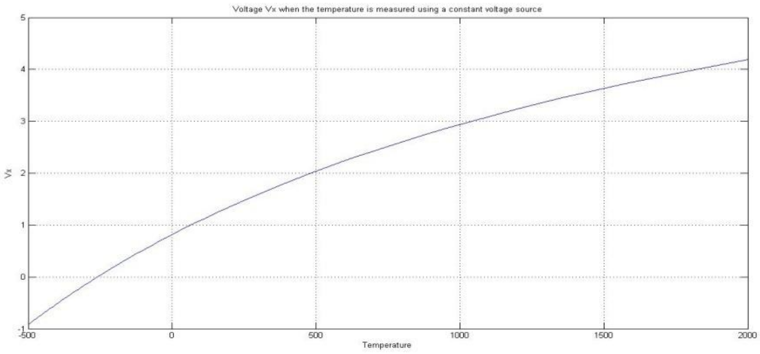

Fig 2: MATLAB simulation depicting nonlinear curve between Vx and Temperature (T) when constant voltage source based temperature measurement system is employed

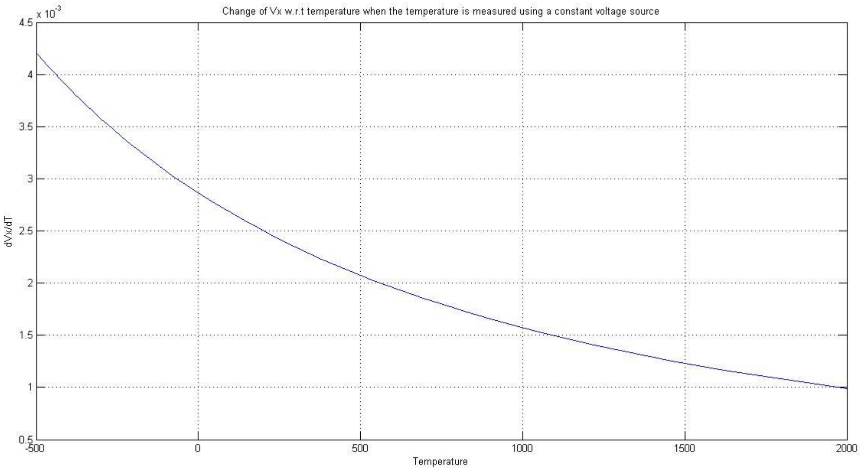

Fig 3: MATLAB simulation showing the nonlinear behavior of the differential of Vx w.r.t Temperature (T) when constant voltage based temperature measurement system is employed

2.2 Sensitivity Analysis

Sensitivity discussed in this section refers to the variation of the output voltage with changes in temperature. By equation (8) it is evident that the change in output voltage is proportional to the change in V1 w.r.t temperature. Sensitivity in the output voltage is a factor multiplied to the sensitivity of V_X. The analysis here shown that the voltage source based temperature measurement system lacks an optimized discrete value of R for which the system is most sensitive. Keeping the fixed resistor of the voltage divider as the optimizing parameter, we differentiate V_X w.r.t temperature.

Applying Ohm's Law and assuming infinite input impedance for the op-amp, we have:

$$V = \frac{R(T)}{R + R(T)} \times 9V \tag{17}$$

Taking into account the noise introduced by SADA:

$$V_x = V + V_{NOISE} \tag{18}$$

Differentiating equation (18), w.r.t temperature

$$\frac{dV_x}{dT} = \frac{d}{dT}\left\{\left(\frac{R(T)}{R + R(T)}\right) \times 9V\right\} + \frac{d}{dT}\left\{\left(\frac{0.02}{R + R(T)}\right) \times 9\right\} \tag{19}$$

Clubbing the derivatives of summation terms from equation (19), we arrive at equation (20) as:

$$\frac{dV_x}{dT} = \frac{d}{dT}\left\{\left(\frac{(9R(T) - 0.18)}{R + R(T)}\right)\right\} \tag{20}$$

Simplifying equation (20), gives the derivatives in terms of $\frac{dR(T)}{dT}$, R and $R(T)$ as written in equation (21)

$$\frac{dV_x}{dT} = \frac{(9R(T) - 0.18)}{\left(R + R(T)\right)^2} \times \frac{dR(T)}{dT} \tag{21}$$

Substituting $\frac{dR(T)}{dT}$ as 3.85 $\Omega/^0$C

$$\frac{dV_x}{dT} = \frac{(9R(T) - 0.18)}{\left(R + R(T)\right)^2} \times 3.85 \tag{22}$$

The change in Vx is maximum when the differential of Vx w.r.t T is zero, i.e. to say the second derivative of Vx w.r.t T should be zero. Therefore, differentiating equation (22)

$$\frac{d^2V_x}{dT^2} = \frac{d}{dT}\left(\frac{(9R(T) - 0.18)}{\left(R + R(T)\right)^2} \times 3.85\right) = 0 \tag{23}$$

Simplifying

$$\frac{d^2V_x}{dT^2} = \frac{-(9R - 0.18) \times \left(R + R(T)\right) \times 3.85 \times 2}{(R + R(T))^4} = 0 \tag{24}$$

Solving equation (24) yields R in terms of R(T) which itself varies with temperature. Thus, there is no optimized value of R for which the circuit is most sensitive, i.e. to say R should also change over temperature so that the output voltage experiences maximum change with corresponding change in temperature.

III. CONSTANT CURRENT SOURCE METHOD

A constant current source based temperature measurement system proposes the following advantages over constant voltage source based temperature measurement system:

(a) Linear Relationship between V_{out} and temperature.
(b) Greater sensitivity independent of R.
(c) Reduced power dissipation.

The following setup shows a constant current source based temperature measurement system.

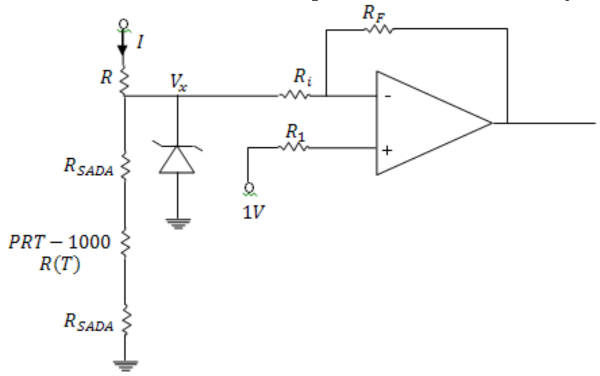

Fig 4: Temperature measurement system using constant current source and PRT-1000

3.1 Mathematical analysis

The mathematical analysis is aimed to prove the linearity of a constant current source based temperature measurement system. The approach is similar to the one followed for constant voltage source based temperature measurement system. Here too, the aim is to prove the linearity of the system, by showing that the derivative of Vx is constant w.r.t temperature.

Let a constant current I flow as shown. The voltage induced due to PRT, because of a constant current flowing is

$$V = IR(T) \tag{25}$$

The voltage observed at the zener is the sum of V and the noise introduced by the SADA resistances. This is given as:

$$V_x = V + V_{NOISE} \tag{26}$$

$$V_x = V + \frac{10I}{1000}V \tag{27}$$

Substituting V from equation (25) into (27)

$$V_x = IR(T) + \frac{I}{100} \tag{28}$$

Writing KVL for the inverting input of the op-amp

$$\frac{V_x - 1}{R_i} = \frac{1 - V_{out}}{R_f} \tag{29}$$

$$V_x - 1 = \beta(1 - V_{out}) \quad (30)$$

$$V_{out} = \frac{\beta + 1 - V_x}{\beta} \quad (31)$$

Where

$$\beta = \frac{R_{in}}{R_f}$$

The linearity of the system can be found by differentiating equation (31) w.r.t temperature (T). We have

$$\frac{dV_{out}}{dT} = \frac{d}{dT}\left(\frac{\beta + 1}{\beta}\right) - \frac{d}{dT}\left(\frac{V_x}{\beta}\right) \quad (32)$$

Substituting Vx from equation (28)

$$\frac{dV_{out}}{dT} = \frac{-1}{\beta}\frac{d}{dT}\left(IR(T) + \frac{I}{100}\right) \quad (33)$$

Since, I is constant its differential is zero w.r.t 'T'

$$\frac{dV_{out}}{dT} = -\frac{I}{\beta}\left(\frac{dR(T)}{dT}\right) \quad (34)$$

$\frac{dR(T)}{dT}$ is the change of PRT resistance with temperature, and first order relation between R(T) and T, we have

$$\frac{dV_{out}}{dT} = -\frac{R_o \alpha I}{\beta} \quad (35)$$

Equation (35) clearly illustrates that the change of Vout w.r.t is constant, i.e. Vout varies linearly with temperature. The following equations derive the linear relation between the output voltage and temperature.

$$V_{out} = \frac{\beta + 1 - V_x}{\beta} \quad (36)$$

$$V_{out} = \frac{\beta + 1 - IR(T) + {}^{I}/_{100}}{\beta} \quad (37)$$

$$V_{out} = c - \frac{I}{\beta}R(T) \quad (38)$$

$$c = \frac{\beta + 1 + {}^{I}/_{100}}{\beta} \quad (39)$$

Equation is an equation of line. Proper op-amp biasing will make the circuit perfectly linear.

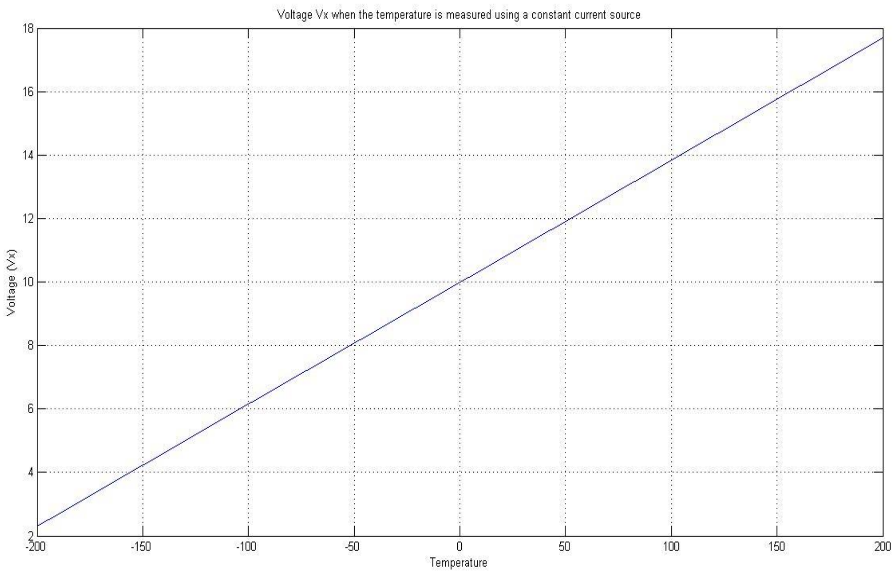

Fig 5: MATLAB simulation depicting nonlinear curve between Vx and Temperature (T) when constant voltage source based temperature measurement system is employed

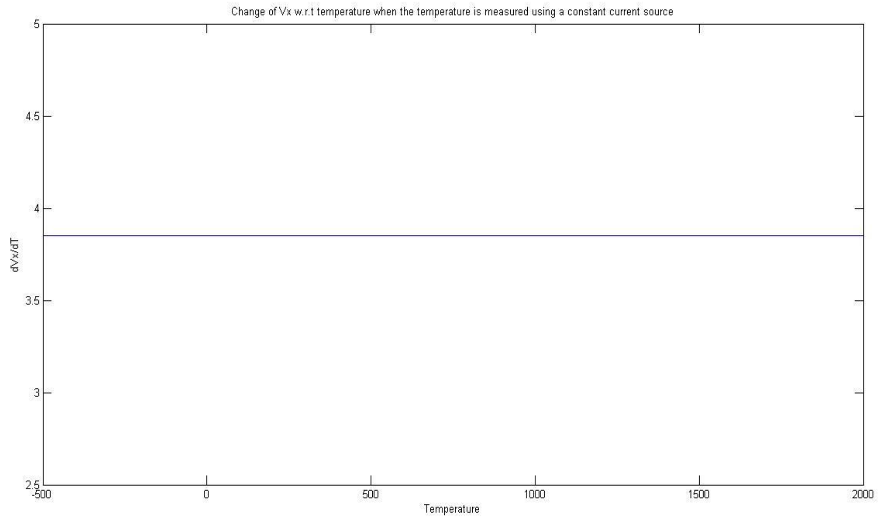

Fig 6: MATLAB simulation showing the nonlinear behavior of the differential of Vx w.r.t Temperature (T) when constant voltage based temperature measurement system is employed

3.2 Sensitivity Analysis
The constant current source based temperature measurement system can be simplified to the following.
We have

$$V = IR(T) \tag{40}$$

We observe that V is independent of R and thus sensitivity depends only on R(T). R can be chosen so as to address power dissipation issues.

IV. OP-AMP BASED CONSTANT CURRENT SOURCE

A constant current source can be realized using a power op-amp and a current sense resistor. The following circuit setup shows a constant current source realization.

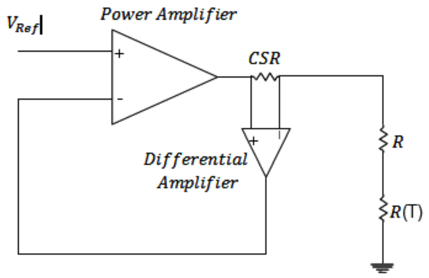

Fig 7: A constant current source using power op-amps

The voltage drop across the CSR is monitored using a differential amplifier. Any change in current I, causes a change in the voltage across the CSR. This change is sensed using a differential amplifier and is fed back to the power op-amp. The op-amp adjusts its output voltage so as to maintain constant current through the CSR. The CSR is typically of very small value, so as to minimize power dissipation.

V. CONSTANT CURRENT PULSES BASED TEMPERATURE MEASUREMENT METHOD

A constant current source based temperature measurement system proposes several advantages over constant voltage source based temperature measurement system. However, it suffers from the self-heating effects of PRT, which causes erroneous temperature measurement. This can be overcome by a pulsating constant current source based temperature measurement system.

Microcontroller based pulsating constant current source

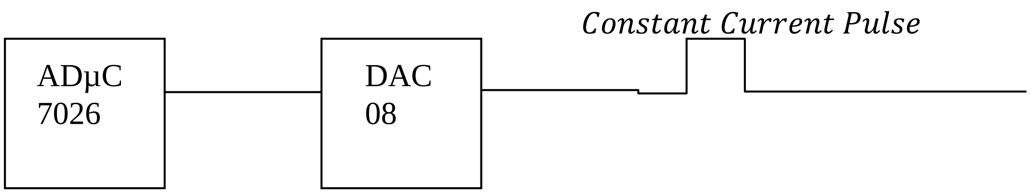

Fig 8: A pulsating constant current source using power op-amps

Pulsating constant current source is realized using a microcontroller (ADμC 7026) and DAC 08. DAC 08 is a voltage to current conversion chip. It produces small current proportionally to the voltage fed to it. Constant signal pulses are programmed and sent through the microcontroller periodically (Appendix B) and these pulses are converted to current pulses. These current pulses when passed through the PRT generate corresponding voltages and can be used to measure the resistance and in turn to temperature.

VI. CONCLUSION

The paper draws a comparative picture between a constant voltage source based temperature measurement system and a constant current source based temperature measurement system. The constant current source has been proved to be linear analytically as well as through simulations. A constant current source based temperature measurement system induces power dissipation in PRT and leads to self-heating . A constant pulsating current source based temperature measurement system is proposed over constant current source based temperature measurement system. The later method highlights the following:

- An optimized temperature measurement system that eliminates the effect of constant series resistance from the sensitivity of the circuit.
- A constant current pulse of short duration leads to low power dissipation and reduces the self-heating effect of PRT, thereby making the system more precise.

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