A NOVEL METHOD TO DECREASE THE ERRORS OF THE ANALOG THERMOMETERS

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Abstract - For the temperature measurement in small ranges (-20…+120^{o}C), the silicon bipolar junction transistor represents a cheap solution for the temperature sensor. Since the variation law of the base-emitter voltage with the temperature of the silicon bipolar junction transistor biased on constant current is nonlinear, it uses different ways for the characteristic liniarisation. This paper presents a detailed analysis of the accuracy of temperature measurements. A general expression is given for the calculation of the absolute error function. This expression has been found very useful in order to study a new liniarisation method of the thermometer characteristic for a minimum absolute error.

Rezumat - Pentru măsurarea temperaturii în domenii mici (-20……+120^{o}C), tranzistoarele bipolare cu siliciu constituie o soluţie ieftină pentru realizarea senzorului de temperatură. Deoarece legea de variaţie cu temperatura a joncţiunii bază - emitor, polarizată la curent constant, este neliniară, se folosesc diferite metode de liniarizare a acestei caracteristici. Acest articol prezintă o modalitate de calcul a erorilor termometrelor analogice care folosesc jonctiunea p - n ca senzor de temperatură, pe baza căreia propune o nouă metodă de liniarizare a caracteristicii termometrului, astfel încât eroarea absolută să fie minimă.

I. INTRODUCTION

The base - emitter voltage of a bipolar transistor can be determinate in any conditions of collector current and temperature if its value is known measured at a collector current and temperature T_O.

$$U_{BE}(T) = U_{GO} \cdot \left(1 - \frac{T}{T_O}\right) + U_{BEO} \cdot \frac{T}{T_O} + (n - 4) \cdot U_T \cdot ln\frac{T}{T_O} + U_T \cdot ln\frac{I_C}{I_{CO}} \qquad (1)$$

where U_{GO} is the band - gap voltage of silicon extrapolated at zero degrees Kelvin (U_{GO}=1.205V), n is dependent on doping level in the base (n=0.8…2.1), U_T is the thermal voltage evaluated at T and U_{BEO} is the base - emitter voltage measured at I_{CO} and T_O.

In the range -20……+120^{o}C, the silicon bipolar junction transistor can be used as a temperature sensor. The conceptual block diagram of the analog thermometer is shown in Figure 1, where U_P is a reference voltage needed in the calibration process of the thermometer. At constant collector current ($I_C = I_{CO}$), the base - emitter voltage depends only by the temperature. (1) becomes

$$U_{BE}(T) = U_{GO} \cdot \left(1 - \frac{T}{T_O}\right) + U_{BEO} \cdot \frac{T}{T_O} + (n - 4) \cdot U_T \cdot ln\frac{T}{T_O} \qquad (2)$$

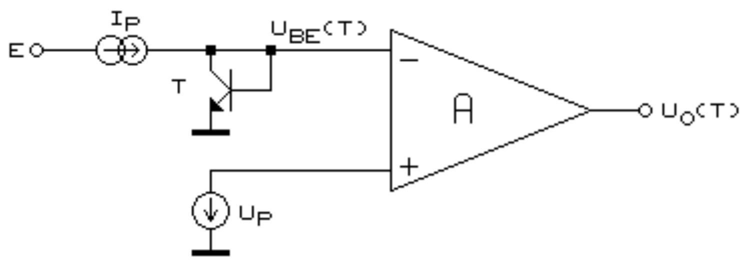

Figure 1. Conceptual block diagram of the analog thermometer.

If the temperature range is T_{min}… T_{max} , in Figure 2 are shown the variation law of the output voltage of the amplifier and the linear (ideal) law of variation with temperature of this voltage.

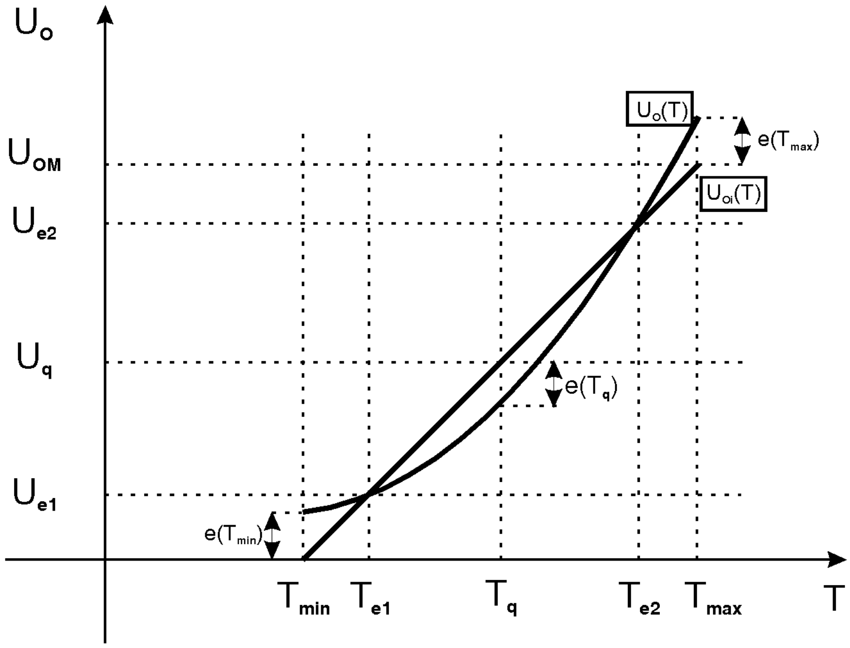

Figure 2. Output voltage variation with temperature

where (T_{e1}, U_{e1}) and (T_{e2}, U_{e2}) represent the two calibration points of the thermometer and T_q represents the temperature for a maximum negative error. We find the maximum positive error in $T = T_{min}$, or in $T = T_{max}$, function of temperature values T_{e1} and T_{e2}.

II. ERROR ANALYSIS

The absolute error of the thermometer defined as

$$e(T) = \left[U_O(T) - U_{Oi}(T)\right] \tag{3}$$

has the expression

$$e(T) = \frac{A \cdot (4 - n) \cdot U_{Te1}}{T_{e1} \cdot \left(T_{e2} - T_{e1}\right)} \cdot \left[T \cdot \left(T_{e2} - T_{e1}\right) \cdot \ln T - T_{e2} \cdot \left(T - T_{e1}\right) \cdot \ln T_{e2} + T_{e1} \cdot \left(T - T_{e2}\right) \cdot \ln T_{e1}\right] \tag{4}$$

where U_{Te1} represent the thermal voltage evaluated at T_{e1}. (4) can be rearranged to give

$$e(T) = \frac{A \cdot (4 - n) \cdot U_{Te1}}{T_{e1} \cdot \left(T_{e2} - T_{e1}\right)} \cdot \left(T \cdot T_{e1} \cdot \ln \frac{T_{e1}}{T} + T \cdot T_{e2} \cdot \ln \frac{T}{T_{e2}} + T_{e1} \cdot T_{e2} \cdot \ln \frac{T_{e2}}{T_{e1}}\right) \tag{5}$$

The maximum negative error is in $T = T_q$. We take the derivative of e(T) with respect to temperature to find the value of T_q. Differentiating (5) results in

$$T_q = exp\left[\frac{T_{e2}}{T_{e2} - T_{e1}} \cdot ln T_{e2} - \frac{T_{e1}}{T_{e2} - T_{e1}} \cdot ln T_{e1} - 1\right] \tag{6}$$

(6) can be simplified if we make the assumption that the quantities T_{e1}/T, T/T_{e2}, T_{e2}/T_{e1} from (5) are near unity. Using the approximation

$$lnx = ln(1 + x - 1) \approx x - 1 \tag{7}$$

thus

$$T_q \approx \frac{T_{e1} + T_{e2}}{2} \tag{8}$$

So that the absolute error is minimum in the entire temperature range, the calibration temperatures are given from

$$\begin{cases} e(T_{max}) = e(T_{min}) = -e(T_q) \\ T_q = exp\left(\frac{T_{e2}}{T_{e2} - T_{e1}} \cdot ln T_{e2} - \frac{T_{e1}}{T_{e2} - T_{e1}} \cdot ln T_{e1} - 1\right) \end{cases} \tag{9}$$

The voltage gain is computed function of the temperature coefficient (α). The value of the temperature coefficient is chosen by the designer.

$$A = \frac{\alpha \cdot (T_{max} - T_{min})}{\frac{T_{max} - T_{min}}{T_{min}} \cdot (U_{GO} - U_{BEmax}) + (4 - n) \cdot U_{Tmax} \cdot ln \frac{T_{max}}{T_{min}}} \tag{10}$$

where U_{Tmax} is the thermal voltage evaluated at T_{max}.

The maximum absolute error can be evaluated function of the temperature range making the assumption that the calibration temperatures are $T_{e1} = T_{min}$ and $T_{e2} = T_{max}$. If this is the case, (4) becomes

$$e(T) = \frac{A \cdot (4 - n) \cdot U_{Te1}}{T_{e1} \cdot (T_{e2} - T_{e1})} \cdot \left[(T_{max} + T_{min}) \cdot ln \frac{T_{max} + T_{min}}{2 \cdot T_{max}} - T_{min} \cdot ln \frac{T_{min}}{T_{max}}\right] \tag{11}$$

Using (7), (11) can be rearranged to give

$$e(T) = \frac{A \cdot (4 - n) \cdot U_{Tmax}}{4 \cdot T_{max}^2} \cdot \Delta T^2 \tag{12}$$

where ΔT represents the temperature range (T_{max}-T_{min}).

III. PROPOSED METHOD

The square-law of (12) is found to be an even closer approximation to the absolute error expression. The proposed method consists in the ideal characteristic approximation through 'm' segments. So that, if we divide the real characteristic in 'm' ranges, the maximum absolute error will decrease by m^2. The transfer characteristic of the thermometer, using this approximation, is shown in Figure 3. T_{Pi} (i=1…m-1) are the break - temperatures of the characteristic, T_{ej} (j=1…2m) represents the calibration temperatures for each region and T_{qk} (k=1…m) are the temperatures for a minimum negative error. The maximum positive error is obtain in T_{min}, T_{Pi} and T_{max}.

We have calculate the calibration temperatures (T_{ej}), but we also must calculate the break - temperatures to completely characterize the amplifier. The conditions between T_{Pi}, T_{ej} and T_{qk} for a minimum absolute error over the entire temperature range are given by

$$\begin{cases} e(T_{max}) = e(T_{min}) = e(T_{P_i}) = -e(T_{q_k}) \\ T_{q_k} = \dfrac{T_{e_{2k}} + T_{e_{2k-1}}}{2} \end{cases} \tag{13}$$

Making the assumption that the calibration temperatures are $T_{e2k-1} = T_{Pi-1}$ and $T_{e2k} = T_{Pi}$, (13) becomes

$$\begin{cases} e(T_{q_1}) = e(T_{q_i}) \\ T_{q_i} = \dfrac{T_{P_i} + T_{P_{i-1}}}{2} \end{cases} \tag{14}$$

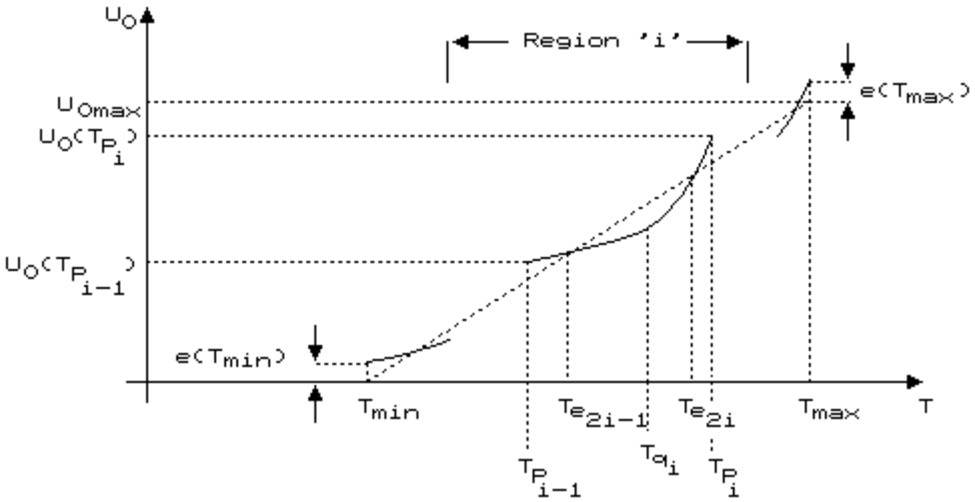

Figure 3. Ideal characteristic approximation.

Using (12), (14) can be simplified to

$$\begin{cases} \dfrac{A_1}{T_{P_1}} \cdot \left(T_{P_1} - T_{min}\right) = \dfrac{A_i}{T_{P_i}} \cdot \left(T_{P_i} - T_{P_{i-1}}\right) \\ T_{P_m} = T_{max} \end{cases} \tag{15}$$

where A_I are given by (10) for each region. Solving (15) we obtain the break - temperatures. The calibration temperatures are given (for each range) by (9).

IV. DESIGN ALGORITHM

A. Since the effective error of the temperature coefficient of the base-emitter voltage decrease for small values of this voltage, we are setting the base-emitter voltage at smaller possible value. If the temperature range is T_{min} = 253.15 K (-20^{0}C)…T_{max} = 393.15 K (+120^{0}C), we take $U_{BEmin} = U_{BE}(T_{max})$ = 500mV. The maximum base emitter voltage is given by (2) $U_{BEmax} = U_{BE}(T_{min})$ = 500mV.

B. The break - temperatures can be calculated solving (15). For T_{min} =253.15 K, T_{max}=393.15 K and m=4 we find T_{P1}=285.15K, T_{P2}=319.15K and T_{P3}=355.15K.

C. The calibration temperatures (T_e) are given by (9).

D. The break - voltages of the characteristic are computed function of the maximum output voltage. If we take U_{Omin} = 0V and U_{Omax} = 2.5V, the temperature coefficient of the output voltage is

$$\alpha = \frac{U_{O\,max} - U_{O\,min}}{T_{max} - T_{min}} = \frac{2500}{140}\left[mV / K\right] = 17.85\left[mV / K\right] \qquad (16)$$

The break - voltages are $U_O(T_{P1})$ = 571.72 mV, $U_O(T_{P2})$ = 1178.87 mV and $U_O(T_{P3})$ = 1821.72 mV. In this case we find the minimum absolute error (± 0.53 mV) for each region, equivalent to a minimum temperature error (± 0.03 K).

E. The voltage gain is computed by (9). We find A_1 = 9.09, A_2 = 8.94, A_3 = 8.81 and A_4 = 8.68.

F. The calibration process of the thermometer. Unlike the break - voltages are given by a single voltage reference, we like better to divide the entire temperature range in four equal ranges. In this case, the break - voltages are U_{REF} /4, U_{REF} /2 and 3U_{REF} /4 and the maximum absolute error is ± 0.71 mV, equivalent to ± 0.04 K. We make a fresh computation of the voltage gains and we obtain A_1 = 9.08, A_2 = 8.93, A_3 = 8.80 and A_4 = 8.68. The transfer characteristic of the amplifier is shown in Figure 4.

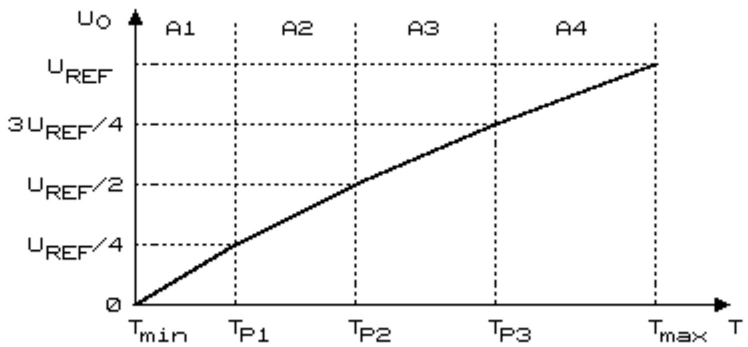

Figure 4. Transfer characteristic of the amplifier.

V. CONCLUSION

The described method of calibration proved to be simple and accurate. A standard calibration can be realized for each range. Since the practical calibration procedures are difficults at any calibration temperatures we calibrate the thermometer at T_{min} and T_{max}, if the output voltages of these temperatures are given by

$U_O(T_{min}) = e(T_{min})$ and $U_O(T_{max}) = U_{omax} + e(T_{max})$.

Thus over the entire temperature range, the absolute error is minimized, ± 0.04 K in the range -20…+120°C.

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