FACTA UNIVERSITATIS (NIŠ)
SERIES: ELECTRONICS AND ENERGETICS VOL. 12, NO.1 (1999), 1-14

UDC 681.586

SMART TEMPERATURE SENSOR

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Abstract. The paper describes a new smart temperature sensor based on a modified servo A/D converter with a nonlinear ladder reference. The device is designed to be connected with different sensor types for contact temperature measurements. It includes thermal management and protection. The programmability of the smart temperature sensor enables simple calibration of the device by changing parallel digital words. This device which uses the silicon temperature sensor KTY83–110 (Siemens), NTC thermistor and Pt100 temperature dependent resistor is realized and simulated within SPICE software package in different temperature ranges, respectively. The results of simulated measurements were found to be in excellent agreement with the theoretical predictions.

1. Introduction

Recent measuring systems for control and monitoring of technical and technological processes based on digital processing and transfer of signals consist of peripheral devices such as converters of nonelectrical quantities into electrical domains (analog, semidigital or digital). These peripheries have a great importance in telemetry, measuring instruments and data acquisition and processing systems.

A/D conversion should be very close to the source of the measurement signal, in order to eliminate the influence of errors especially in industrial aggressive conditions. The sensible element is integrated with VLSI electronic circuits which the sensor turn from the passive dipole component into

Manuscript received May 14, 1998.
A version of this paper was presented at the first International Conference on Elect. Engeen. and Electron., Gabrovo, Bulgaria 1998.
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intelligent periphery (smart sensor) [1],[3]. So, within the system, the sensor is the periphery giving information about the intensity of a measurable quantity in an appropriate form. The peripheries of this types should supply the computer with the collected data, important for the performances of the measuring quantities obtained as an unarranged set. Also the peripheries should be adaptable with respect to many different sources of nonelectrical quantities. The errors due to the applied measuring strategy generally would be trimmed within acceptable limits. In addition, the peripheries would enable the feedback control of the input quantity and repetition of the measuring sequences. Such a way of forming a measure point simplifies designing and decreases the total cost of the whole system. Besides, digital processing of analogue quantities guarantees a reliable and fast transfer of data to the measuring system.

This paper describes a smart new design capable of digital processing of analogue sensor signals. The appropriate approximation is used for transfer characteristics of sensors. Results are given for three temperature sensors. The nonlinearity error of the smart sensor is not function of the clock accuracy. Moreover, the device does not contain time circuits which are the main cause of nonstability of the conversion parameters.

2. The concept for the signal processing

Fig. 1 shows a function diagram of the electronic circuit. The device is a modified conventional servo A/D converter based on the appliance of the nonlinear conversion. The proposed modification is in relation with the programmable nonlinear reference generator. In such a way, undesired effects, as multiple conversions of the input quantity or its degradation which is typical of digital converters with indirect temperature conversion in time–interval or frequency [7],[8],[9],[10] are eliminated.

The process of conversion begins with a starting pulse which resets the counter while the output of the analogue comparator is set on a high voltage level. This provides conditions which enables the increment of the counter by the clock pulses after the starting pulse. The counter is in operation until the output voltage of the programmable generator becomes equal to the output voltage of the sensor circuit. In that instant the analogue voltage comparator changes its level and the counting is over. The process of conversion is ended. The last state of the counter is recorded in the latch register on the falling edge of the pulse from the output of the analogue comparator. The latch register content is compared with the digital equivalent of the desired temperature D. The applied full adder with logical EXOR circuits serves to show the negative temperatures in the two's complement.

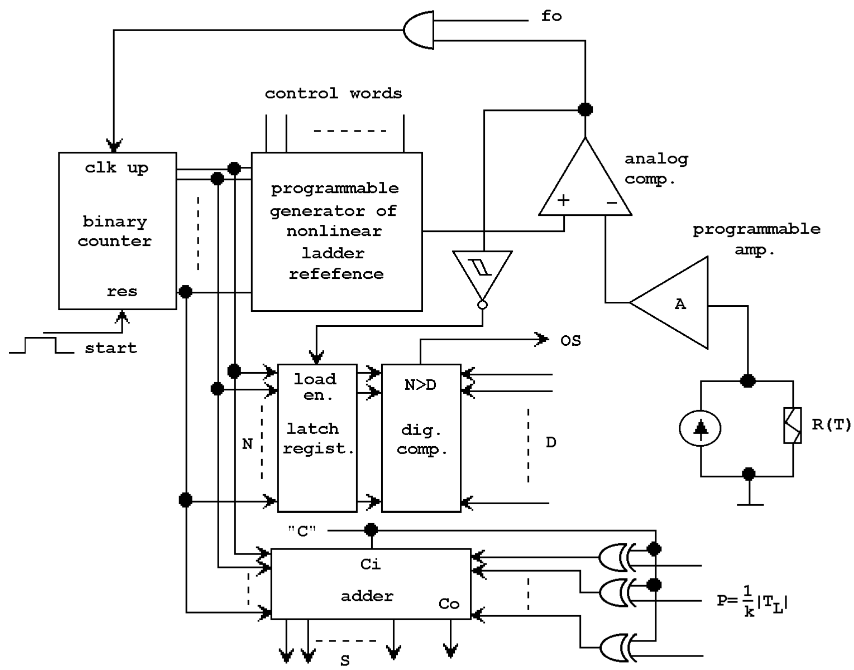

Fig. 1. Programmable smart temperature sensor principle.

In order to linearize nonlinear transfer characteristics of the sensors the inverse curve is generated. This solution suggests the comparison of equal transfer curves of the temperature sensor circuit and the programmable generator, Fig. 2. The goal is to obtain a linear final response. The sensor circuit characteristic is approximated by the second order polynomial in order to minimize the square deviation. The programmable generator is a function generator of second order polynomial. Its programmable coefficients can be adjusted so that both transfer characteristics should be equal. Thus a direct relation parallel digital word versus temperature is set. The choice of conversion sensitivity depends on the adopted resolution of the device and the temperature range width.

The output OS (overtemperature shutdown) behaves as a thermostat. This output becomes active when temperature exceeds the desired limit and leaves the active state when the temperature drops below the limit. Evidently, the accuracy of such a circuit configuration does not depend on the clock frequency stability.

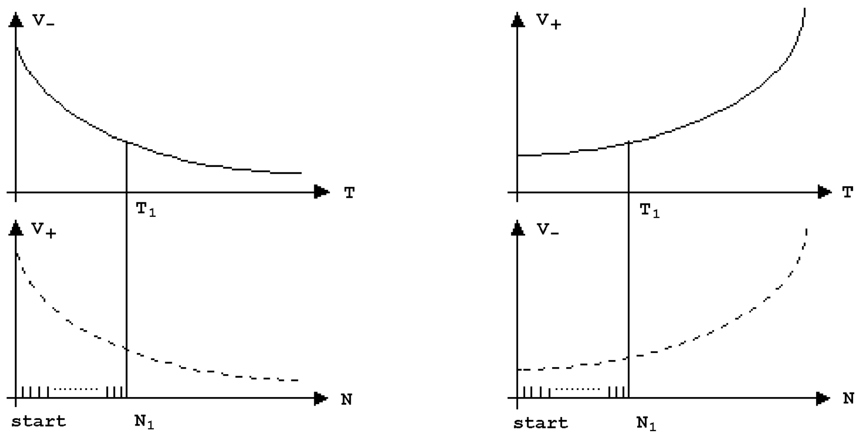

Fig. 2. Comparison of two equal curves for the NTC and PTC sensors.

3. The circuit arrangement

The realization and simulation of the device is developed within SPICE software package with standard integrated circuits applied. Twelve bit resolution of the system is adopted. The complete scheme of the device is shown in Fig. 3. The temperature sensor circuit consists of a temperature dependent resistor, DC current source and the programmable amplifier. A good compromise involving minimum self–heating and the maximum signal for the most termoresistant sensors is found for a DC measurement current of $1mA$. The duty cycle system clock period is $1mS$ and the stimulus reset pulse duration is $0.1mS$.

The programmable generator is designed so that five four–quadrant 12–bit multiplying D/A converters and an inverting operational amplifier are connected as a unit. It is easy to show that the output voltage of the amplifier (point A) is given by

$$V_A(N) = -\frac{R_3 V_r}{R_0 2^{12}} D_0 - \frac{R_3 V_r}{R_1 2^{24}} D_1 N - \frac{R_3 V_r}{R_2 2^{36}} D_2 N^2, \qquad (1)$$

where D_0, D_1 and D_2 are the control digital words, V_r is a referent voltage of D/A converters and N is the output parallel word. The equation (1) can be reduced to a simplified form

$$V_A(N) = A_0(D_0) + A_1(D_1)N + A_2(D_2)N^2. \qquad (2)$$

Since the sensor circuit temperature characteristic is approximated by the second order polynomial in the range T_L–T_H the voltage to terminal B has the form of

$$V_B(T) = B_0 + B_1 T + B_2 T^2. \quad (3)$$

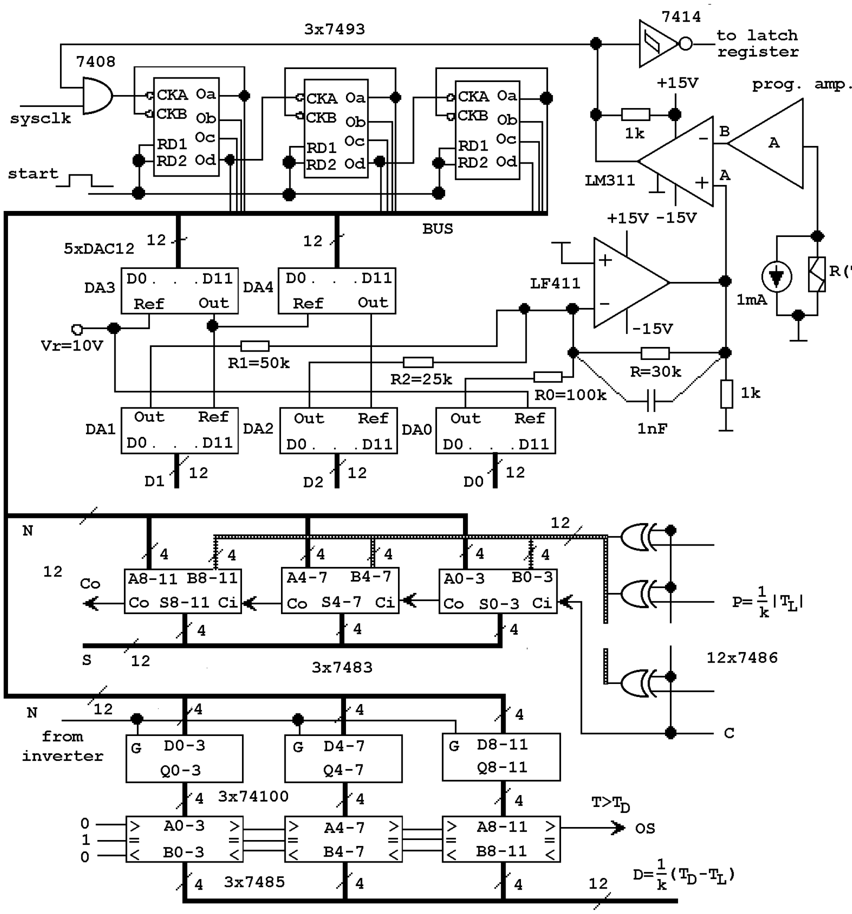

Fig. 3. Complete scheme of the device.

As the limitary temperature T_L can be negative and the output digital word N can not, it is necessary to translate the transfer characteristic of the sensor circuit for same value T_L to the origin so that

$$V_B(T + T_L) = B_0 + B_1(T + T_L) + B_2(T + T_L)^2. \quad (4)$$

If the programmable coefficients of the equation (2) fit as it follows

$$\begin{aligned} A_0(D_0) =& B_0 \\ A_1(D_1) =& kB_1 \\ A_2(D_2) =& k^2 B_2 \end{aligned} \tag{5}$$

where $1/k$ represents the conversion sensitivity, by equalizing the expressions (2) and (4) and taking the conditions (5) and starting value of N into account, the output digital word will be proportional to the temperature

$$N = \frac{1}{k}(T - T_L), \quad \text{for} \quad T \geq T_L. \tag{6}$$

Consequently, we choose three control words D_0, D_1 and D_2 to provide the conditions (5). Thus we get the linear response on the output. With regard to the positive output word, to show the negative temperatures in the two's complement, we include the 12–bit binary full adder/subtractor with the mode control input "C". An operand is the output word N and the other is the binary numerical value $P = (1/k) \mid T_L \mid$. The addition/subtraction of the numbers N and the permanent binary number P give the sum S as a result

$$S = N \pm P = N \pm \frac{1}{k} \mid T_L \mid . \tag{7}$$

When the mode control input is low, $C = 0$, operands are added but they are subtracted when the mode control input C is high. By substituting (6) in (7) the equation (7) is found to be

$$S = \frac{1}{k}T. \tag{8}$$

The logic state of the mode control input C depends on the sign of the limitary temperature T_L. If $T_L < 0$, $C = 1$, the sum S is shown in the two's complement for negative temperatures. If $T_L \geq 0$ the sum S is a positive binary number with P as a start value.

The state of the carry-out shows whether the binary number S is in the form of two's complement ($C_0 = 0$) or not ($C_0 = 1$). The sum S does not include the value of the carry–out bit. In the case when $T_L = 0$ the adder/subtractor circuit can be omitted.

The output word N is recorded in the 12–bit latch register at the end of conversion. It is compared with the digital equivalent of the desired temperature D. The value of the equivalent is chosen by

$$D = \frac{1}{k}(T_D - T_L), \tag{9}$$

where T_D is the desired temperature. The connection of the latch register with S bus is unfavorable in respect to the its resolution. In this case the resolution of the latch register or magnitude comparator depends on the values of T_L and T_H, see equations (10) and (11).

For example, the output OS can be used to turn a cooling fan on to initiate an emergency system shutdown or a heater control. The main requirement for this is to provide the repetition of the measured sequences. Since temperature is a slow variable quantity, this requirement is easily achieved.

4. The design of the device and the choice of parameters

The device is designed so as to provide that all D/A converters as well as the latch register and magnitude comparator have the same resolution n. If k is a temperature resolution then the temperature range $R = T_H - T_L$ is chosen by

$$R \leq k(2^n - 1), \tag{10}$$

so that the conversion sensitivity (1/k) is an integer number.

The resolution of the applied adder, s, without the carry out bit, is determined by

$$\left|\frac{1}{k}T_L\right| \leq \left|\frac{1}{k}T_H\right| \leq 2^s - 1. \tag{11}$$

The choice of the measuring strategy implies a selection of an available approximation for accurate description of the sensor transfer characteristic. In practice the total conversion error is primarily the result of the applied approximation error. In the proposed solution the second order approximation by the least squares method [6] is adopted. An approximation by the polynomials of a higher order than the second give as result a more complex hardware and a greater measurement error, especially in the lower temperature range, see equation (1).

The resolution of each D/A converter need not be the same. Moreover the resolution of the D/A converters with fixed digital words should be higher. This provides for the wider dynamics of the input signal. As a rule, two other D/A converters have the same resolution.

5. The converter appliance for various types of sensors

The simulation of the described circuit is performed for different types of sensors as follows:

- the silicon temperature sensor KTY83–110 (Siemens) in the temperature range from $-55°C$ to $175°C$ and with the temperature resolution of $k = 0.1°C$,
- the thermistor whose parameters are $B = 2460.84°C$ and $R(35°C) = 9205.93\Omega$ in the clinical temperature range from $30°C$ to $45°C$ and with the temperature resolution of $k = 0.01°C$,
- $Pt100$ temperature–dependent resistor in the range from $0°C$ to $800°C$ and with the temperature resolution of $k = 0.2°C$.

The corresponding resistance and temperature values of the silicon temperature sensor are listed in Table 1. The sensor supply current is 1 mA and the DC voltage gain of the programmable amplifier is $A = 3$. In the specified temperature range from $-55°C$ to $175°C$ the transfer characteristic of the silicon sensor circuit is approximated by the polynomial regression in the form of

$$V_B(T) = 3(819.86322 + 6.7694T + 0.01732T^2)10^{-3} \quad [V]. \tag{12}$$

Upon substituting the variable T with the expression $(T - 55)$ in (14), the new equation should be

$$V_B(T) = 3(499.9392 + 4.8642T + 0.01732T^2)10^{-3} \quad [V]. \tag{13}$$

The error of approximation in the entire temperature range is limited to $\pm 0.45\Omega$. The conversion sensitivity is $1/k = 10$ $pulses/°C$ and the mode control input C is set to the logical one. The values of the remaining parameters of the circuit are shown in Fig. 3.

On the bases of the equations (1), (13) and (5), the values of the control digital words are calculated and rounded off to the closest integer numbers $D_0 = 2048$, $D_1 = 4080$, $D_2 = 2976$. The initial word value of the inputs of the EXOR circuits is $P = 550$.

The same converter circuit is applied with thermistor as a sensor. The transfer characteristic of the thermistor is explicitly given by

$$R(T) = 9205.93 \exp\left[2460.84(\frac{1}{T} - \frac{1}{35})\right] \quad [\Omega]. \tag{14}$$

The last equation is approximated by the least squares method at the measurement current across the sensor of 1 mA. Here, the DC voltage gain of the programmable amplifier is $A = 0.2$. The approximation in the temperature range from $30°C$ to $45°C$ is in the form of

$$V_B(T) = 0.2(23734.19802 - 563.87166T + 4.25411T^2)10^{-3} \quad [V]. \tag{15}$$

Table 1. Ambient temperature and corresponding resistance values of sensor ($I_c = 1\ mA$)

T_{amb} $^\circ C$	Resistance Ω	T_{amb} $^\circ C$	Resistance Ω
−55	500	70	1379
−50	525	80	1472
−40	577	90	1569
−30	632	100	1670
−20	691	110	1774
−10	754	120	1882
0	820	125	1937
10	889	130	1993
20	692	140	2107
25	1000	150	2225
30	1039	160	2346
40	1118	170	2471
50	1212	175	2535
60	1288		

The substitution of the variable T with the expression $(T + 30)$ in (15) gives the following new equation

$$V_B = 0.2(10646.75 - 308.6251T + 4.25411T^2)10^{-3} \quad [V]. \qquad (16)$$

The error of approximation in the proposed temperature range is found to be in the limits $\pm 10\ \Omega$. The conversion sensitivity is $1/k = 100\ pulses/^\circ C$ and the mode control input C is set to the logical zero. The values of the control digital words are rounded off to the integer numbers $D_0 = 2907$, $D_1 = 1726$, $D_2 = 487$, while the value of the initial word is $P = 3000$.

With regard to the negative temperature coefficient of the thermistor and the negative sign of one term of the polynomial (16), the circuit of Figure 3. is primitively modified. In fact, by setting up the sign bit of the bipolar converter DA1, the sign of the second term of the polynomial (16) will be alternated. Also, the converters DA0, DA1 and DA2 are bipolar with the sign bit.

Because of the negative temperature coefficient of the sensor the commutation of the input analogue comparator terminals is indispensable. Fig. 4. shows a simple implementation of demultiplexers for selection of a sensor type, NTC or PTC, to be measured. In this case the demultiplexers are controlled by the line S.

The third simulation is performed by the standard platinum $Pt100$ resistor as a sensor. The resistance of platinum is accurately related to the temperature, but it is also sensitive to small amounts of impurities. The temperature characteristics of industrial Pt resistors slightly deviate from those of pure platinum. The nominal characteristics and their tolerances are specified in various standards. The European community upholds the standard DIN–IEC 751 [5]. For a platinum resistor in the temperature range from $0°C$ to $850°C$ it specifies the following relation

$$R(T) = R(0)(1 + aT - bT^2)[\Omega], \tag{17}$$

where $a = 3.90802 \cdot 10^{-3}(°C)^{-1}$ and $b = 0.58020 \cdot 10^{-6}(°C)^{-2}$

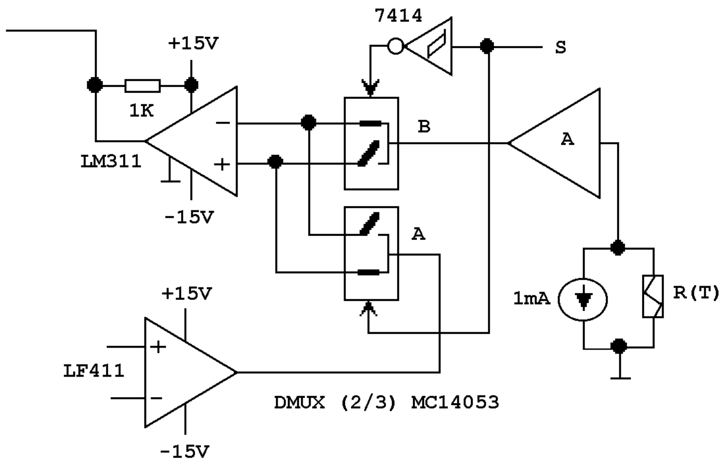

Fig. 4. The scheme of a circuit input part for communication of analogue comparator input terminals.

The constant $R(0)$ is the nominal resistance at $0°C$. A wide range of components with different values of $R(0)$ is commercially available. In our design we focused on the type $Pt100$ for which $R(0) = 100\Omega$. However, the presented circuit can easily be adapted to resistors with higher nominal values. According to the DIN–IEC 751 standard, the tolerances for class A resistors are given by

$$\Delta T = \pm(0.15°C + 0.002 \mid T \mid).$$

The DC gain of the programmable amplifier $A = 3$ is adopted for the $Pt100$ sensor. So the voltage on the point B is

$$V_B(T) = 3(100 + 3.90802 \cdot 10^{-1}T - 0.5802 \cdot 10^{-4}T^2)10^{-3}\ [V]. \tag{18}$$

The conversion sensitivity is $(1/k) = 5$ (pulses/$^\circ C$). The upper temperature which can be indicated is $819^\circ C$. It is a bit lower than the one specified in the IEC 751 standard by equation (17). The mode control input C is set to the logical zero and the initial word is $P = 0$. With regard to the lower limitary temperature $T_L = 0^\circ C$, the modified adder/subtractor can be excepted in this case. The control words are calculated similarly as in the previous two cases and their values are $D_0 = 410$, $D_1 = 656$ and $D_2 = 40$. Since the third term of polynomial (18) is negative, the sign bit of the bipolar converter DA2 is set to one. It should be noticed that temperature coefficient of the sensor is positive.

6. The results of simulations

According to the facts mentioned in the Section 5, the simulation of the device is performed within SPICE software package. Simulations of silicon temperature sensor are performed by taking appropriate values of the fixed resistance as described in Table 1. The converter was tested over a resistance range corresponding to the temperatures between $-55^\circ C$ and $175^\circ C$. The output words N and S are given by $N = 10(T + 55)$ and $S = N - P = 10T$.

In the temperature range $-55^\circ C \leq T < 0^\circ C$ the output word S is given in the form of two's complement. The results of the analysis show that the conversion error amounts to $1LSB$ or $0.1^\circ C$ in the entire range. This error is calculated as a difference between the measured and the theoretically obtained output digital word.

The device with thermistor as sensor is simulated by the change of the resistance corresponding to the temperature change of $1^\circ C$. In this case the output words N and S are given by $N = 100(T-30)$ and $S = N+P = 100T$.

With respect to the 12–bit resolution of the device the upper temperature which can be converted is lower than the specified temperature in the adopted range. It is about $41^\circ C$. The maximum conversion error is $2LSB$ or $0.02^\circ C$ in the range from $30^\circ C$ to $41^\circ C$.

During the simulation with platinum resistor $Pt100$ the sensor is also substituted by a variable resistor. In this case the output words N and S are the same $N = S = 5T$. The maximum nonlinearity error is $-2LSB$ or $-0.4^\circ C$ within the range from $0^\circ C$ to $819^\circ C$.

In the Fig. 5 the state of the full–adder outputs for the time and after the conversion is shown. With the silicon temperature sensor at $T = -10^\circ C$ the full–adder output digital word, after the conversion, is given in the two's complement (carry–out is set to the logical zero). The conversion duration is about 450 mS.

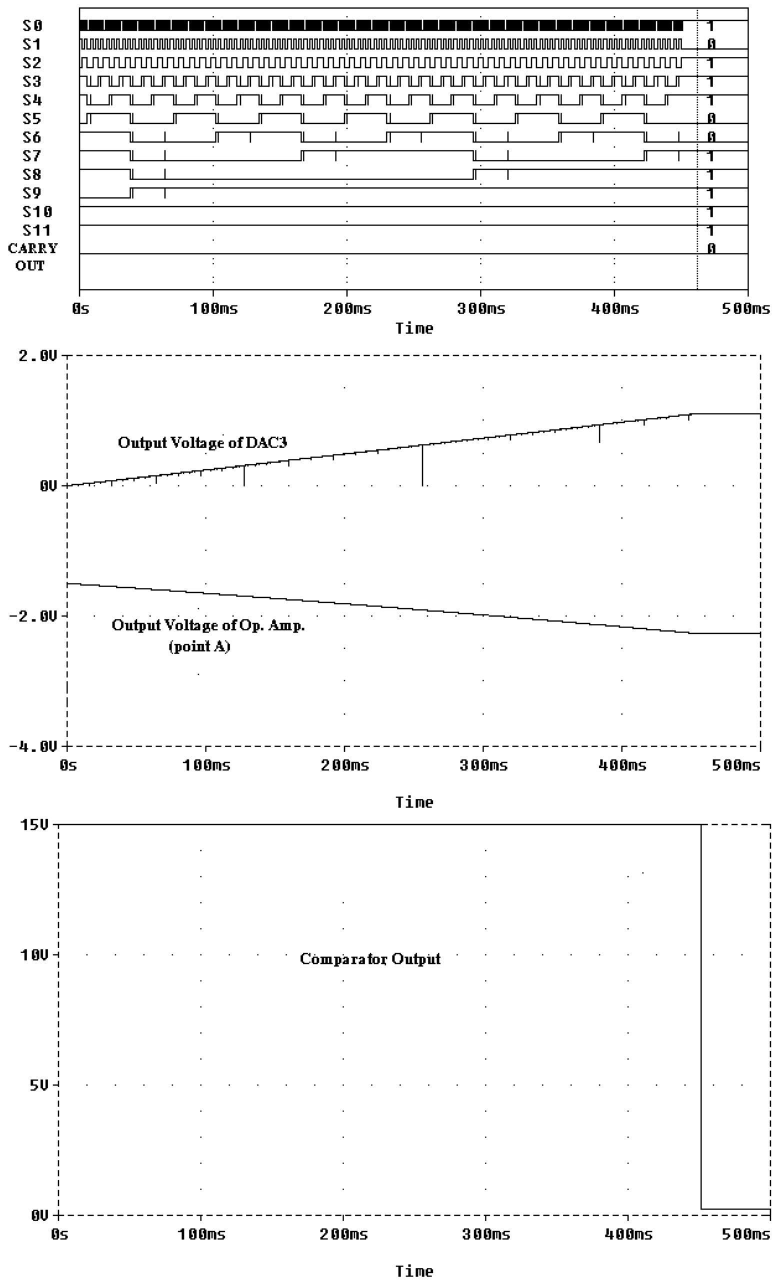

Fig. 5. A Spice simulation of the output full–adder signals, the output voltage of the DAC3, op. amp. and comparator for silicon temperature sensor at $T = -10°C$.

In the range of ambience temperature from $-25°C$ to $+80°C$, no converter instability has been noticed. Deviations increasing the total conversion error have been noticed above this temperature. In practice, the total error may be attributed to the tolerance of the used components and to any uncertainties involved in the calibration of sensor parameters and to the op–amps and comparator offset voltages and to approximation error and finally to error caused by rounding off the digital words.

The glitch phenomenon has no influence on the nonlinearity error because the glitch has an opposite accession with respect to the ladder reference accession (point A), see Fig. 5.

7. Conclusion

The analysis and design of the circuit presented in this paper show that it is possible to fabricate an inexpensive smart sensor which is capable of processing various sensor signals for temperature measurement, giving the possibility of the feedback impact on the input quantity. Principal advantages of the described device are a digital programmable calibration, stability of its characteristics and the possibility of keeping the error within the maximally acceptable limits in a relatively wide range of the input quantity change.

A significant characteristic of the smart temperature sensor is the independence of the conversion sensitivity from the circuit parameters.

The digital output enables a simple communication with micro–controllers, PC and other equipment. The output signals are two parallel digital words.

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