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A CONSTANT TEMPERATURE OPERATION THERMORESISTIVE SIGMA-DELTA SOLAR RADIOMETER

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Abstract – In this paper we propose a feedback system, with thermo-resistive sensor, based on sigma-delta modulation. The system uses a one-bit sigma-delta modulator in which considerable part of conversion functions is performed by a thermoresistive sensor. The sensor is modelled using the power balance principle and the applied measurement method is constant temperature. This transducer architecture is able to realize digital measurement of physical quantities that interacts with the sensor: temperature, thermal radiation and fluid velocity. This paper presents simulations results of this system applied to thermal radiation measurement.

Keywords Thermoresistive sensor, measurement, sigma-delta modulation.

1. INTRODUCTION

Negative feedback system configurations with thermoresistive sensor using the power balance principle have been employed in measurement of thermal radiation, H [1-2], fluid velocity, U [3-5], and temperature, T_a, [6]. In the most used method, called constant temperature, the sensor is heated by Joule effect to a chosen temperature and the thermal radiation (or fluid velocity, or temperature) variation is compensated by a change in electrical heating due to the negative feedback employed, and the sensor is kept at an almost constant temperature.

Some configurations were studied to implement a measurement system with a sensor heated to a constant temperature. The most usual is the configuration that uses a Wheatstone bridge with the sensor in one of its branches [7]. In that paper, the relation between the output signal and input physical quantity is not a linear one. Another configuration uses a pulse width modulation in the feedback loop, which has the advantage of having a linear relation between output signal and input, in temperature and thermal radiation measurements. In addition, it permits direct input signal conversion to digital voltage [2].

Another attractive possibility is the use of sigma-delta configurations with the sensor being part of the feedback loop. One-bit sigma-delta modulation is already a feedback configuration in which output signal is an oversampled version of the analog input signal [8-9]. Sigma-delta modulator has been employed, in signal processing, to convert an analog quantity to a digital quantity using simple analog circuitry. Sigma-delta converters are recognized to be robust and high performance A/D converters.

This work presents a solar radiometer architecture composed of a one-bit sigma-delta modulator in which some of its blocks are the thermoresistive sensor itself. In this way, it is possible to obtain a digital oversampled version of the physical quantities. All results presented here were obtained by simulation.

Two thermal sigma-delta systems were simulated using standard signals: step and sine wave, to evaluate the system performance. One has the functional characteristics of a physical system but cannot be implemented on an integrated circuit. The other structure is equivalent to the first one but can be implemented on an integrated circuit.

2. PROPOSED SYSTEM

2.1. Problem Definition

The dynamic heat equation for a thermoresistive sensor is expressed by [4-5].

$$\alpha SH + I_s^2 R_s = hS\left(T_s - T_a\right) + mc\frac{dT_s}{dt} \qquad (1)$$

In (1), αSH is the incident thermal radiation absorbed by the sensor, $I_s^2 R_s$ is the electrical power delivered to the sensor, h is the heat transfer coefficient referred to the sensor surface area S, T_s is the sensor temperature, T_a is the surrounding temperature (ambient or fluid temperature), m is the sensor mass, c is the sensor specific heat and α is the sensor transmission heat coefficient. The sensor temperature, T_s, can be given by:

$$T_s(t) = \int_{-\infty}^{t} \frac{1}{mc}\left[\alpha SH(\tau) + R_s(\tau) I_s^2(\tau) + hS\left(T_a(\tau) - T_s(\tau)\right)\right] d\tau \quad (2)$$

The block diagram of a first order sigma-delta modulator is shown in Fig. 1. The summation and integration blocks are evidenced to show the similarity with (2).

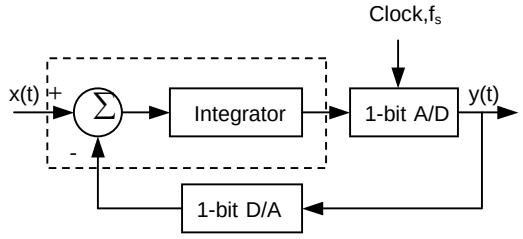

Fig. 1. 1-bit, first order sigma-delta modulator block diagram.

The idea of including the sensor into an one-bit, first order sigma-delta loop becomes from the similarity mentioned and from the fact that the sensor temperature response curve leads to an almost exponential function in response to a square current step for steps of small amplitudes. If the sample frequency, f_s, is much greater than the sensor linear transfer function pole, this exponential can be approximated by an integration function in which the gain is the exponential function initial slope. The resulting structure can be used to estimate the incident radiation, H, fluid velocity, U, or environment temperature, T_a, according to the case.

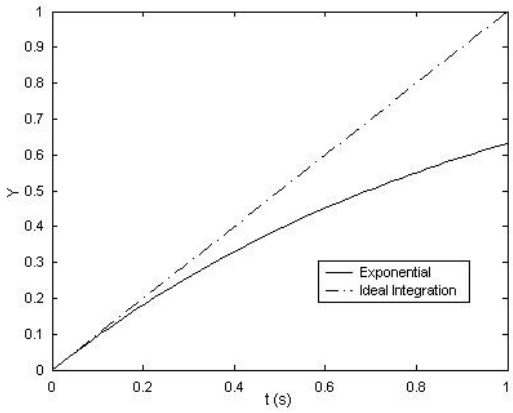

Fig. 2. Step response: ideal integration and exponential.

Fig. 2 shows, for a time constant equal to 1 s, that the step response for an ideal integration, and for the exponential are almost coincident until 10% of this time constant. Based on this fact the transducer model was developed.

This assumption was verified for environment temperature estimation [10]. In that paper, h was considered constant and H was considered equal to zero. Here, we present a sigma-delta modulator structure for estimating thermal radiation. In this case, T_a and h are considered constant. T_s can be done by:

$$T_s(t) = \int_{-\infty}^{t} \frac{1}{mc}\left(hS\left(T_a(\tau) - T_s(\tau)\right) + R_s(\tau) I_s^2(\tau) + \alpha SH(\tau)\right) d\tau \quad (3)$$

The thermal characteristic for Positive Coeficient Temperature, (PTC) and Negative Coeficient Temperature, (NTC) thermoresistors are given by [4]:

PTC: $$R_s = R_o\left[1 + \beta\left(T_s - T_a\right)\right] \quad (4)$$

NTC: $$R_s = R_o e^{B\left(\frac{1}{T_s} - \frac{1}{T_o}\right)} = A e^{\frac{B}{T_s}} \quad (5)$$

R_o is the sensor resistance at reference temperature T_o.

2.2. Sensor model for small signals

Sensor model for small signals is developed for a PTC sensor heated around equilibrium point (T_{so}, R_{so}, T_{ao}). Small variations of T_s around this point can be modelled by a tangent straight line taken at this point. The same is valid for NTC sensor [10].

Rewritting (1), considering the substitutions: mc for C_{th}, hS for G_{th}, I_s^2 for X_s and R_s for $R_o(1+\beta T_s)$and, including thermal radiation measurement restrictions on T_a and h, we obtain:

$$C_{th}\frac{dT_s(t)}{dt} = G_{th}\left(T_a - T_s(t)\right) + R_o\left(1 + \beta T_s(t)\right) X_s(t) + \alpha SH(t) \quad (6)$$

After linear process and applying Laplace's transform the sensor transfer function is obtained as:

$$T_s(s) = \frac{1}{s - p}\left[k_x X_s(s) + k_h H(s)\right] \quad (7)$$

In which k_x, k_h and p are given by:

$$k_x = \frac{R_{so}}{C_{th}}; \qquad k_h = \frac{\alpha S}{C_{th}}$$

and $$p = \left(\frac{\beta R_o X_{so} - G_{th}}{C_{th}} \right)$$

Sensor square current X_{so} is given by:

$$X_{so} = \frac{1}{R_{so}} \left(G_{th} \left(T_{so} - T_{ao} \right) - \alpha S H_o \right) \qquad (8)$$

If sensor temperature is kept almost constant, H can be evaluated from sensor square current knowledge.

$$H = \frac{1}{\alpha S} \left(G_{th} \left(T_{so} - T_{ao} \right) - R_{so} X_s \right) \qquad (9)$$

Fig. 3 shows the PTC sensor model used as a component in the continuous current system of the proposed solar radiometer and this model represents (3). Thermal radiation H and sensor square current I_s^2 are the input signals and sensor temperature T_s is the output signal.

2.3. Continuous Current Transducer Model

Fig. 4 shows the block diagram for the system in which X_s is the sensor square current, I_s^2, $T_s(t)$ is the controlled variable and $H(t)$ is the measurand (thermal radiation). T_{so} and X_{so} are the sensor temperature and the sensor square current, respectively, in thermal equilibrium. Current gain is obtained from (8) with H_{max} and H_{min} being respectively the full and the bottom scale of solar radiation.

$$\Delta X_s = \frac{\alpha S}{R_{so}} \left(\frac{H_{\max} - H_{\min}}{2} \right) \qquad (10)$$

Two changes must be performed in transducer continuous current model of Fig. 4 to obtain a transducer model that could be implemented on a chip. This is necessary for two reasons: a) first because the sensor model input is a square current; b) second because the quantizer input is a thermal signal and must be changed to an electrical signal.

2.4. Pulsed Current Transducer Model

To obtain this model, we first substitute sensor square current, I_s^2, for a pulse width modulated current, which square rms value is given by [2]:

$$I_{srms}^2 = I_m^2 \frac{\Delta_T}{T_{PWM}} \qquad (11)$$

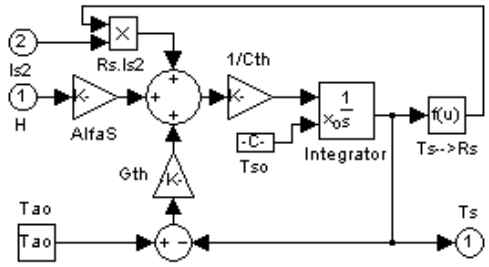

Fig. 3. Block diagram of PTC sensor model

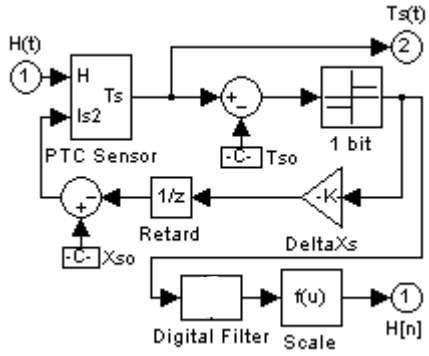

Fig. 4. Continuous current transducer model

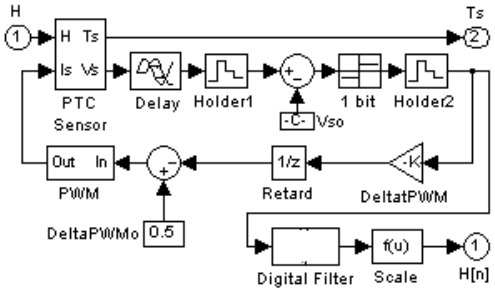

Fig. 5 . Pulsed current transducer model

I_m, Δ_T and T_{PWM} are respectively, pulse amplitude, pulse width and pulse width modulator (PWM) period. In the pulsed current model, I_s^2 is substituted by the pulse width modulator input, Fig. 5, proportional to Δ_T and I_{srms}^2. This is a special PWM which generates only two pulse widths, one pulse width for quantizer output equal to +1 and another pulse width for quantizer output equal to –1. Pulse width, in equilibrium point, has theoretical value equal to 50 % of PWM period. The information of current gain is now in the pulse width, which has a linear relationship with the solar radiation.

$$\frac{\Delta_T}{T_{PWM}} = \frac{\alpha S}{R_{so} I_m^2} \frac{H_{\max} - H_{\min}}{2} \qquad (12)$$

Second we substitute sensor model output, $T_s(t)$, for sensor voltage, $V_s(t)$.

Fig. 5 shows pulsed current transducer model, a modified version of continuous current transducer

model including a PWM, and a holder to sample the voltage during current pulse. The sampled voltage between sensor terminals, in equilibrium condition, is given by:

$$V_{so} = R_{so} I_m \quad (13)$$

If V_{so} is kept constant by the feedback loop, R_s is also constant and therefore, the sensor temperature too. The transport delay is included, only in simulation, to guarantee the sampling during PWM current pulse.

2.4 Results

The PTC sensor characteristics used to test both systems were: β = 0,00385 °C^{-1}, R_o = 102,48 Ω, G_{th} = 2,982x10^{-3} W/°C, C_{th} = 43,06x10^{-3} J/°C, S = 20x10^{-6} m^2, α = 0,95.

For both system characteristics: T_{so} = 50 °C, T_s(t=0) = 24 °C, H_{min} = 50 W/m^2, H_{max} = 1550 W/m^2, T_{ao} = 24 °C, R_{so} = 122,21 Ω, p = 64,58x10^{-3} rad/s, f_B = 10.(p/2π) = 1,028x10^{-1} Hz, *Over Sampling Rate (OSR)* = 256, $fs \geq 2.f_B$.OSR = 80 Hz.

The continuous current model characteristics were: X_{so} = 510,05x10^{-6} A^2, *currentgain* = 116,6x10^{-6} A^2.

The pulsed current model characteristics were: I_m = 31,94 mA, T_{PWM} = 1/f_s=0,0125 s, *widthPWM*$_o$ = 0.5xT_{PWM}, *widthgain* = 0,1143xT_{PWM}.

A solar radiation step degree from 800 W/m^2 to 1400 W/m^2 was applied to the input of continuous current system and to the input of the pulsed current system at t=300 s. The output sensor temperature, T_s, and the estimated solar radiation, *H[n]*, were observed in both systems. Fig. 6 and Fig. 7 show that sensor temperature quickly gets around 50 °C and remains surrounding this temperature value.

The detail, in Fig. 8 and Fig. 9, shows that this variation remains between 49,99 °C and 50,015 °C in continuous current system. In the pulsed current system this variation remains between 49,985 °C and 50,02 °C. This variation depends on input solar radiation amplitude and system resolution.

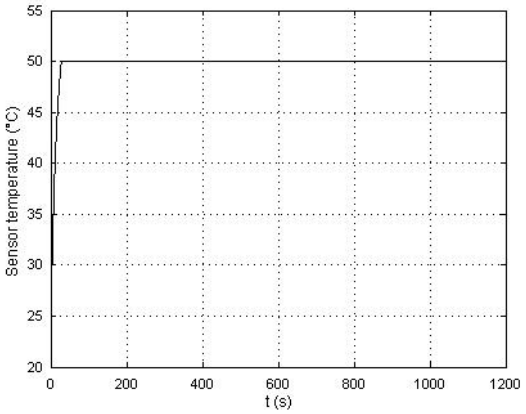

Fig. 6. Continuous current (CC) model: Sensor temperature response to a step of solar radiation at 300 s.

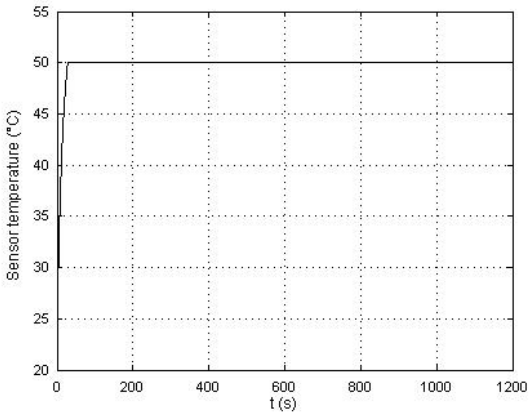

Fig. 7. Pulsed current (PC) model: Sensor temperature response to a step of solar radiation at 300 s.

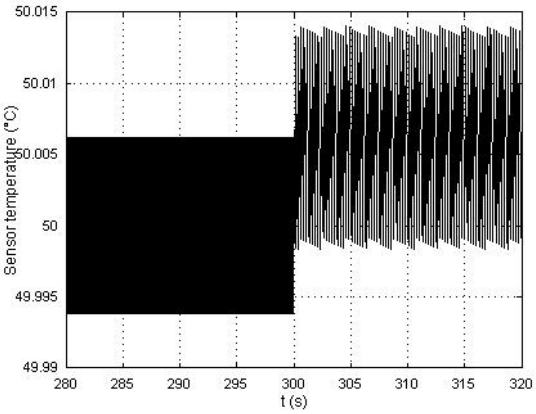

Fig.8. CC model: Sensor temperature response detail to a step of solar radiation at 300 s.

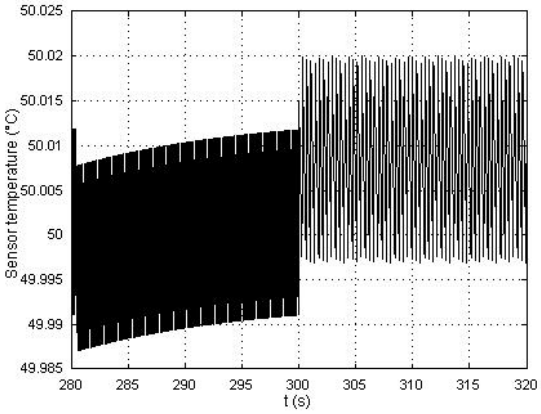

Fig. 9. PC model: Sensor temperature response detail to a step of solar radiation at 300 s.

Fig. 10 and Fig. 11 shows estimated solar radiation for the continuous current system and for the pulsed current system, respectively. The average value of solar radiation begins at 800 W/m^2 and moves to nearly 1400 W/m^2 after the step time.

Detail of estimated thermal radiation for both systems, after output stabilization, can be seen in Fig. 12. This two values are very close.

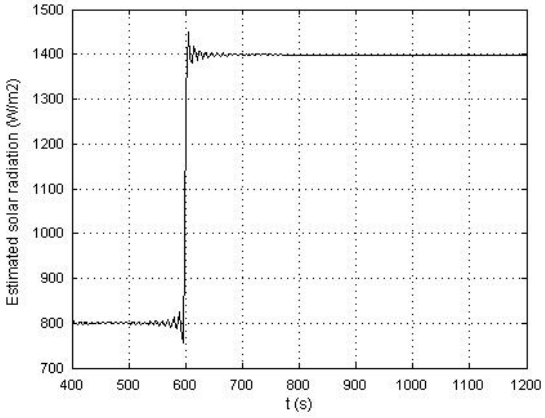

Fig. 10. CC model: Estimated solar radiation, response to a step of solar radiation at 300 s.

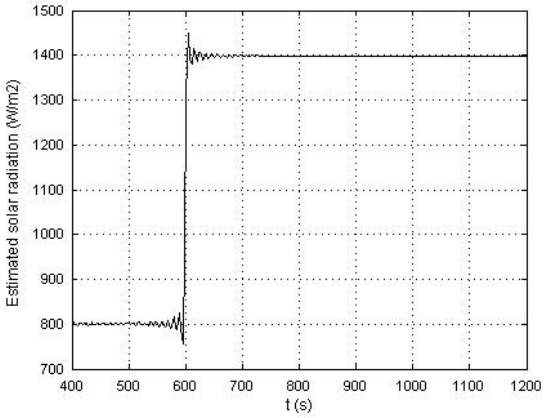

Fig. 11. PC model: solar radiation, response to a step of solar radiation at 300 s

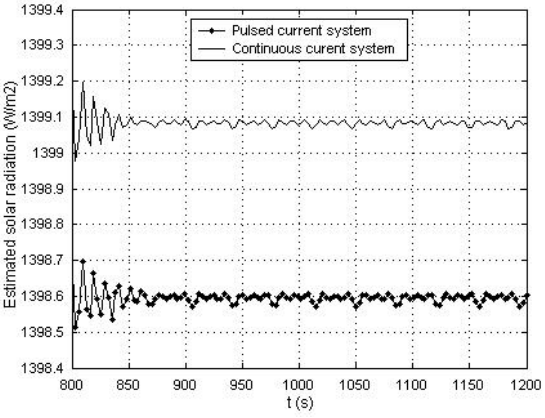

Fig. 12. Both system estimated solar radiation response detail after output stabilization.

Solar radiation value for continuous current system remains surrounding 1399,1 W/m^2, with better resolution than pulsed current system, which solar radiation value remains surrounding 1398,6 W/m^2.

A sine wave of solar radiation equal to $H(t) = [800+750\sin(2\pi t/600)]$ W/m^2 was applied to the pulsed current system input at t=0 s and the outputs (sensor temperature, T_s, and estimated solar radiation, $H[n]$), were observed.

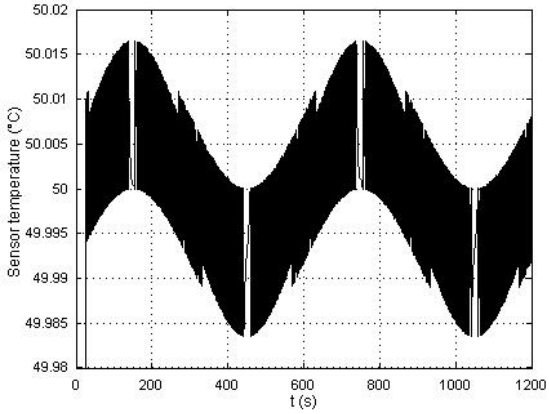

Fig. 13. PC model: Sensor temperature response detail to a sine wave of solar radiation.

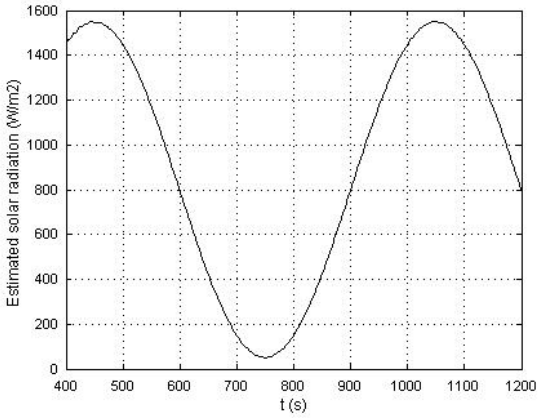

Fig. 14. PC model: Estimated solar radiation, response to a sine wave of solar radiation.

Fig. 13 shows that sensor temperature is kept around 50 ^{o}C, and followed the sine wave input characteristics.

Fig. 14 shows detail of estimated solar radiation corresponding to the input applied to the pulsed current model.

3. CONCLUSION

The pulsed current solar radiation architecture presented here as an equivalent system to the continuous current architecture, realized the expected A/D conversion with good resolution when compared to continuous current architecture.

This pulsed current transducer architecture does not need a 1-bit D/A converter in the feedback loop because this function is realized by PWM.

This pulsed current architecture, based on sigma-delta modulation, is well indicated for integrating sensor and circuits on a chip as a microsensor.

This thermal sigma-delta solar radiation, compared to other methods using power balance principle, has the advantage of transforming directly the physical quantity to its corresponding digital value.

The time response of this architecture should still be better analyzed. It is hoped that the systems with

pulsed current have, in the worst case, the same time response of the continuous systems, but with the advantage of directly digital output signal, avoiding errors due to the signal analog processing.

Fluid velocity transducer based in this same principle, will be our future objective.

4. AKNOWLEDGEMENTS

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