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Measurement 39 (2006) 267–273

Measurement

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A constant temperature operation thermoresistive sigma–delta solar radiometer

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Received 9 August 2004; accepted 16 November 2005
Available online 27 December 2005

Abstract

In this paper we propose a feedback system, with thermoresistive sensor, based on sigma–delta modulation. This system uses an 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 measure method is constant temperature. This transducer architecture is able to perform digital measurement of physical quantities that interacts with the sensor: temperature, thermal radiation and fluid velocity. This paper presents simulation results of this system applied to thermal radiation measurement.

Keywords: Thermoresistive sensor; Measurement; Sigma–delta modulation; Constant temperature method; Transducer

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 configuration, 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 [2].

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doi:10.1016/j.measurement.2005.11.015

Another attractive possibility is the use of sigma–delta configurations [8], here 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 [9,10]. 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 an 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 as a circuit.

2. Proposed system

2.1. Problem definition

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

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

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

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

The block diagram of a first order sigma–delta modulator is shown in Fig. 1. The summation and integration blocks are in evidence, showing the similarity with (2).

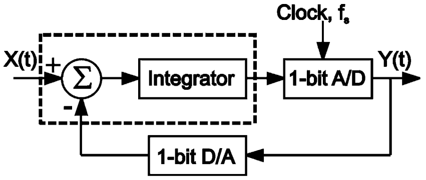

Fig. 1. One bit first order sigma–delta modulator block diagram.

The idea of including the sensor into an one-bit, first order sigma–delta loop comes 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 small steps 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 result structure can be used to estimate the incident radiation, H, fluid velocity, U, or environment temperature, T_a, according to the case.

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 up to 10% of this time constant. Based on this fact the transducer model was developed.

This assumption was verified for environment temperature estimation [11]. 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 expressed as

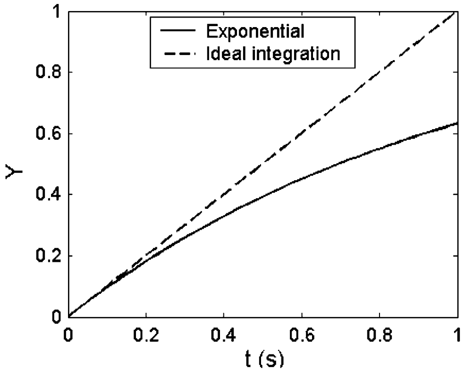

Fig. 2. Step response: ideal integration and exponential.

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

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

$$\text{PTC}: R_s = R_o[1 + \beta(T_s - T_o)] \quad (4)$$

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

R_o is the sensor resistance at reference temperature T_o.

Rewriting (1), considering the substitutions: mc for C_{th}, hS for G_{th} and I_s^2 for X_s, including thermal radiation measurement restrictions on T_a and h, we obtain

$$C_{th}\frac{\mathrm{d}T_s(t)}{\mathrm{d}t} = G_{th}[T_a - T_s(t)] + R_s(t)X_s(t) + \alpha SH(t) \quad (6)$$

In thermal equilibrium condition the sensor square current X_s can be expressed by

$$X_s = \frac{1}{R_s}[G_{th}(T_s - T_a) - \alpha SH] \quad (7)$$

If the sensor temperature is kept constant, H can be evaluated from X_s knowledge.

$$H = \frac{1}{\alpha S}[G_{th}(T_s - T_a) - R_s X_s] \quad (8)$$

Fig. 3 shows the PTC sensor model used as a component in the continuous current system of the proposed solar radiometer. This model is based on (3) with the imposed restrictions. The thermal radiation H and the sensor square current I_s^2 are the input signals whereas the sensor temperature T_s is the output signal.

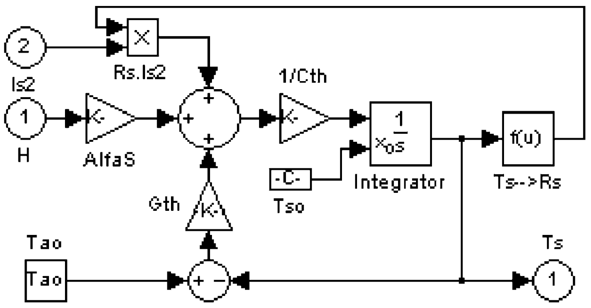

Fig. 3. PTC sensor model.

2.2. Continuous current transducer model

Fig. 4 shows the block diagram for the transducer in which $T_s(t)$ is the sensor temperature and $H(t)$ (thermal radiation) is the variable under measure. T_{s0} and X_{s0} are the sensor temperature and the sensor square current, respectively, in thermal equilibrium. Current gain is obtained from (9) with H_{max} and H_{min} being, respectively, the full and the bottom scale of solar radiation

$$\Delta X_s = \frac{\alpha S}{R_{s0}}\left(\frac{H_{max} - H_{min}}{2}\right) \quad (9)$$

Two changes must be performed in transducer continuous current model of Fig. 4 to obtain a transducer model that could be implemented as a circuit. This is necessary for two reasons: (a) first one of 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.

2.3. Pulsed current transducer model

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

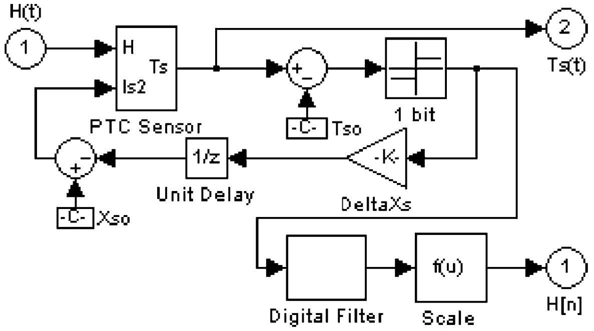

Fig. 4. Continuous current transducer model.

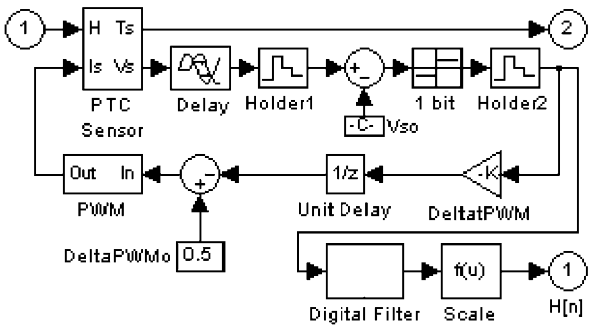

Fig. 5. Pulsed current transducer model.

transducer model including a pulse width modulator (PWM), and a holder to sample the voltage during current pulse. To obtain this model, we first substitute sensor square current, I_s^2, for a pulse width modulated current, which the square rms value is obtained by [2]:

$$I_{\mathrm{srms}}^2 = I_{\mathrm{m}}^2 \frac{\Delta_{\mathrm{T}}}{T_{\mathrm{PWM}}} \tag{10}$$

I_m, T_PWM and Δ_T are respectively, pulse amplitude, period and pulse width proportional to the PWM input. Secondly, we substitute the sensor model output, $T_\mathrm{s}(t)$, for the sensor voltage, $V_\mathrm{s}(t)$.

The PWM 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.

$$\frac{\Delta_{\mathrm{T}}}{T_{\mathrm{PWM}}} = \frac{\alpha S}{R_{\mathrm{s0}} I_{\mathrm{m}}^2} \left(\frac{H_{\max} - H_{\min}}{2} \right) \tag{11}$$

The pulsed amplitude of the sampled voltage between the sensor terminals is expressed by

$$V_\mathrm{s} = R_\mathrm{s} I_\mathrm{m} \tag{12}$$

If V_s is maintained in a constant value (equilibrium condition) by the feedback loop, then R_s and, consequently, the sensor temperature T_s are also constant.

The transport delay is included, only in simulation, to guarantee the sampling during PWM current pulse.

3. Simulation results

The PTC sensor characteristics used to test both systems were: $\beta = 0.00385\ °\mathrm{C}^{-1}$, $R_\mathrm{o} = 102.48\ \Omega$, $G_\mathrm{th} = 2.982 \times 10^{-3}$ W/°C, $C_\mathrm{th} = 43.06 \times 10^{-3}$ J/°C, $S = 20 \times 10^{-6}\ \mathrm{m}^2$, $\alpha = 0.95$.

For both system characteristics: $T_\mathrm{so} = 50$ °C, T_s $(t = 0) = 24$ °C, $H_\mathrm{min} = 50\ \mathrm{W/m^2}$, $H_\mathrm{max} = 1550\ \mathrm{W/m^2}$, $T_\mathrm{ao} = 24$ °C, $R_\mathrm{so} = 122.21\ \Omega$, $p = 64.58 \times 10^{-3}$ rad/s, $f_\mathrm{B} = 10 \cdot (p/2\pi) = 1.028 \times 10^{-1}$ Hz, Over Sampling Rate (OSR) = 256, $fs \geqslant 2 \cdot f_\mathrm{B} \cdot \mathrm{OSR} = 80$ Hz.

The continuous current model characteristics were: $X_\mathrm{so} = 510.05 \times 10^{-6}\ \mathrm{A}^2$, currentgain $= 116.6 \times 10^{-6}\ \mathrm{A}^2$.

The pulsed current model characteristics were: $I_\mathrm{m} = 31.94$ mA, $T_\mathrm{PWM} = 1/f_\mathrm{s} = 0.0125$ s, width-$\mathrm{PWM_o} = 0.5$, widthgain = 0.1143.

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. Figs. 6 and 7 show that sensor temperature quickly gets around 50 °C and remains surrounding this temperature value.

The detail, in Figs. 8 and 9, shows that this variation remains between 49.99 °C and 50.015 °C for the continuous current system. For the pulsed current system this variation remains between

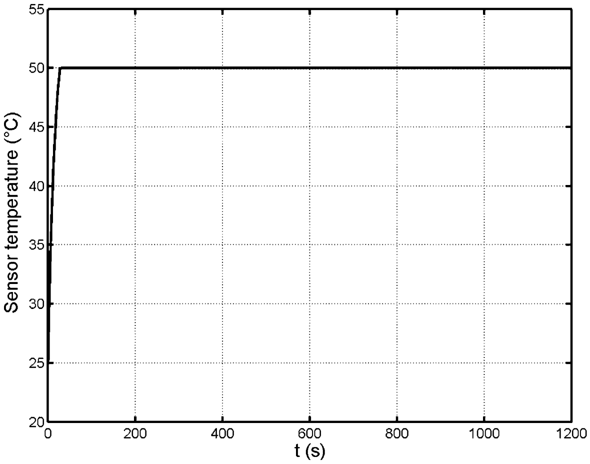

Fig. 6. Continuous current (CC) model: sensor temperature response to a step of solar radiation at 300 s.

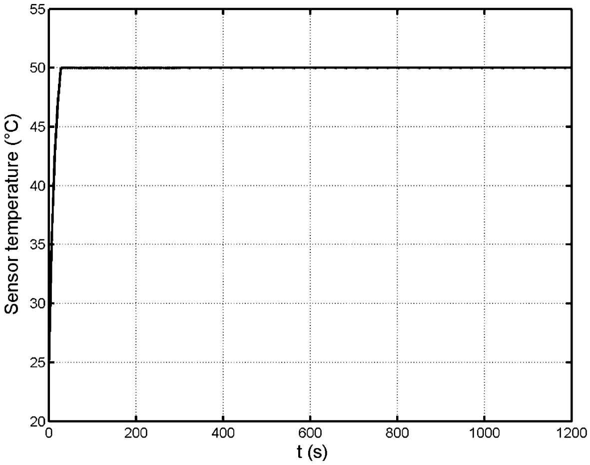

Fig. 7. Pulsed current (PC) model: sensor temperature response to a step of solar radiation at 300 s.

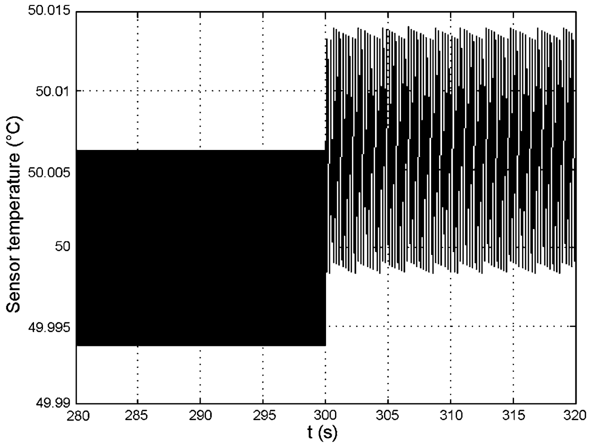

Fig. 8. CC model: sensor temperature response detail to a step of solar radiation at 300 s.

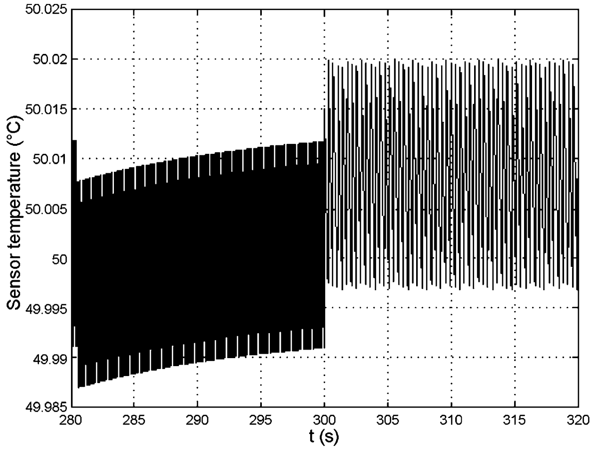

Fig. 9. PC model: sensor temperature response detail to a step of solar radiation at 300 s.

49.985 °C and 50.02 °C. This variation is very small and depends on the input solar radiation amplitude and the system resolution.

Figs. 10 and 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. These two values are very close.

Estimated solar radiation value for the 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.

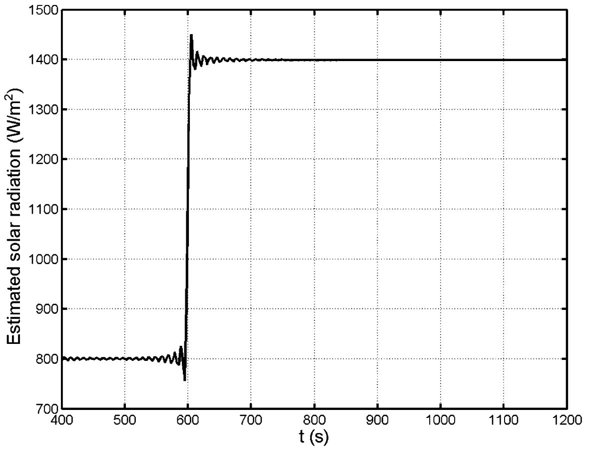

Fig. 10. CC model: estimated solar radiation, response to a step of solar radiation at 300 s.

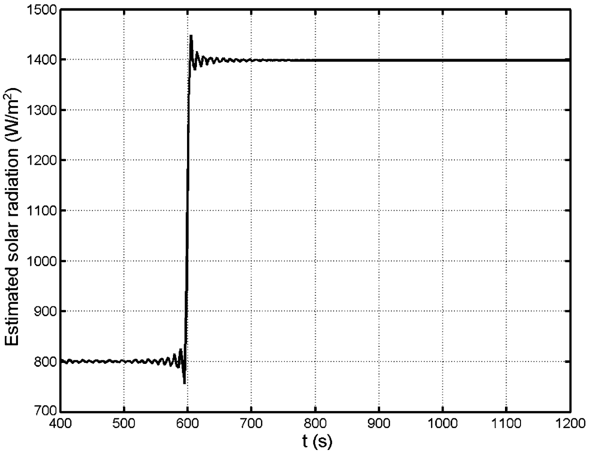

Fig. 11. PC model: solar radiation, response to a step of solar radiation at 300 s.

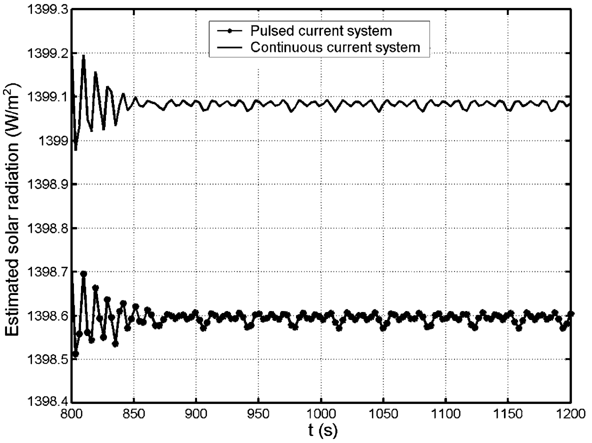

Fig. 12. Both systems estimated solar radiation response detail after output stabilization.

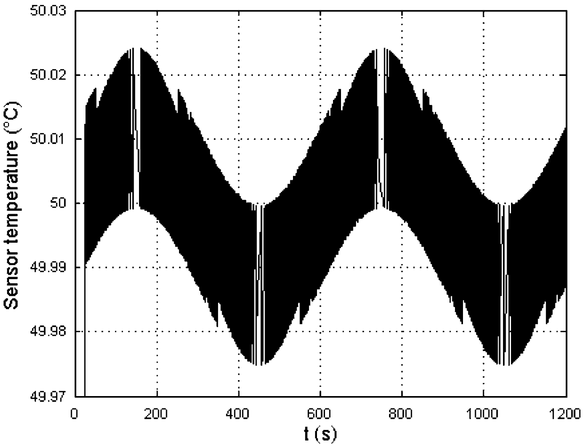

Fig. 13. PC model: sensor temperature response detail to a sine wave of solar radiation.

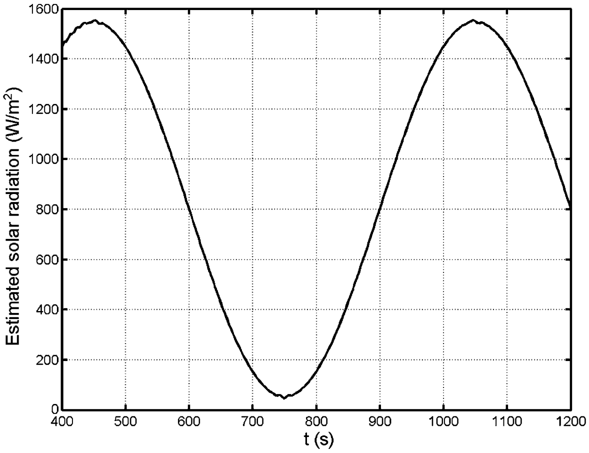

Fig. 14. PC model: estimated solar radiation, response to a sine wave of solar radiation.

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 shows that the sensor temperature is kept around 50 °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.

4. Conclusion

From the simulated results presented here it is possible to say that the pulsed current solar radiometer architecture presented here as an equivalent system to the continuous current architecture, performed 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 because of the simplicity of the circuitry enveloped.

This thermal sigma–delta solar radiometer is based on the electrical sigma–delta modulation with part of conversion functions being performed by a thermoresistive sensor and incorporating its characteristics. Compared to other methods using power balance principle, it has the advantage of transforming directly the physical quantity to its corresponding digital value.

The time response of this architecture should be better analysed. It is expected 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 analog signal processing.

Acknowledgements

The authors wish to thank CAPES/Procad and CNPq for financial support and the award of fellowships during investigation period.

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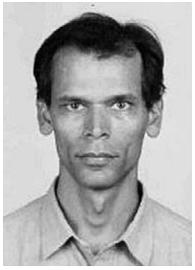

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