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## Modeling and Simulation of a Wheatstone bridge Pressure Sensor in High Temperature with VHDL-AMS

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**Abstract-** This paper presents a model of a Wheatstone bridge sensor in VHDL-AMS. This model is useful to take into account the temperature effect on the sensor accuracy. The model is developed on the basis of a resistor model. Simulations are performed for three different combinations of parameters values. They confirm the resistors mismatch effect on the sensor accuracy in high temperature (HT).

**Keywords:** Wheatstone bridge, sensor, resistance, mismatch, high temperature, VHDL-AMS

### I. Introduction

Using sensors is mandatory in many industrial fields. These systems are essential for the accomplishment of many industrial processes [1]. Their great asset is their capacity to convert physical quantities to electrical signals that can be treated in specific circuits. Sensors have to be robust, accurate and insensitive to external parasites or to the environment conditions. Unfortunately, some sensors are constrained to work in extreme conditions (high pressure, high temperature, etc.) In order to limit the errors caused by the environment, it is necessary to model the dependency of the sensor performance to the environment. This modelling effort starts with a first step of characterization that could lead to mathematical relations linking the performance parameters to the environment ones (temperature, pressure, etc) [1], [2]. In this work, we examine the influence of the temperature on the Wheatstone bridge sensor. We model the effect of the resistors mismatch in HT on its accuracy using VHDL-AMS language. Section II reminds the Wheatstone bridge sensor structure. Section III details the development of the model and the simulation results.

### II. Wheatstone bridge

Fig. 1 describes a well-known structure of a “Wheatstone bridge” sensor formed with four resistances and used to measure the pressure. This is possible as the resistance value depends on the pressure. In this circuit, three resistances are supposed to be ideally similar and have known values ( $R_1=R_2=R_3=R$ ). The value of the fourth resistance  $R_s$  is unknown. It can be calculated by using Kirchoff Laws as shown in the equation (1).

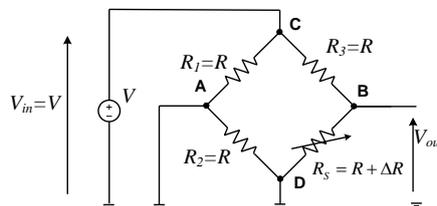


Figure 1: Wheatstone bridge sensor structure

$$V_{out} = V_B - V_A \approx V \frac{\Delta R}{4R} \quad (1)$$

The relation between  $V_{out}$  and  $V_{in}$  is linear and depends obviously on  $R_s$  but also on the nominal resistance  $R$ .  $V_{out}$  is not measured directly; it will be rather filtered and amplified by further appropriate instrumentation circuits.

### III. Development of a VHDL-AMS model of a Wheatstone bridge in HT

As explained in [3], [4], [5], modelling of industrial electronics in HT requires development of accurate models. In [4], we confirmed that the SPICE model of an industrial op-amp is inaccurate in [120°C, 220°C]. In [3], we compared many modelling approaches and languages to model performances of different circuits of an analog front-end (AFE). Two examples of circuits were already modeled with the selected modeling language VHDL-AMS: an ADC and an op-amp]. We continue to use the same modelling language in this work

$$R(T) = R(T_0) + R(T_0) \left[ TC_1(T - T_0) + TC_2(T - T_0)^2 \right] \quad (2)$$

The resistor is the elementary component of the Wheatstone bridge. It will be more practical to develop first a resistor model in VHDL-AMS. The Wheatstone bridge model will be created by instantiating this resistor model in the sensor model. The dependency of the resistor to the temperature is described by equation (2), where  $T$  is the considered temperature and  $T_0$  is the reference temperature.  $R(T)$  and  $R(T_0)$  are respectively the resistances values in  $T$  and  $T_0$ .  $TC_1$  and  $TC_2$  are called coefficient temperature. The theoretical effect of the resistance mismatch in HT is described by equation (3). We denote  $x_i$ ,  $\{i=1, 2, 3, s\}$  the resistances variations after temperature increasing. The  $x_i$  factors depend on the temperature coefficients  $TC1R_i$  and  $TC2R_i$ ,  $\{i=1, 2, 3, s\}$ .

$$V_{out}(T) = \frac{V}{2} \left[ \frac{\Delta R + x_s - x_3}{2R + x_s + x_3} - \frac{x_2 - x_1}{2R + x_1 + x_2} \right] = \frac{V}{2} \cdot \alpha(T, \Delta R, R) \quad (3)$$

According to (3), the relation between  $V_{out}$  and  $V_{in}$  is always linear. However, the slope  $\alpha$  of the linear curve depends on the resistance variation  $x_i$ , the temperature  $T$  and on the nominal resistance  $R$ . If all  $x_i$  are equal, we can prove that  $V_{out}$  is unchanged even if the temperature  $T$  increases. This means that in order to guarantee a precise measurement in HT, resistances have to be almost similar (they have almost the same variation  $x_i$ ).

$$V_{out}(T) = \frac{V}{2} \cdot \frac{\Delta R}{2R + 2x} \approx \frac{V \Delta R}{4R} \approx V_{out}(T_0) \quad (4)$$

The simulation results are illustrated by Fig 2 and table 1. We have considered 3 cases of simulations. Each case represents specific values combination of  $T$ ,  $TC1R_i$ , and  $TC2R_i$  ( $R=1K\Omega$ ,  $\Delta R=1\Omega$ ). The table 1 compares the theoretical values and the simulation values of  $V_{out}$  when  $V_{in}=1V$ . It is clear that there is a good agreement between VHDL-AMS simulation result and theoretical value of  $V_{out}$ . This good agreement validates the VHDL-AMS Wheatstone bridge model in HT.

	$T=27^\circ C,$ $TC1R_i = TC2R_i = 0$	$T=220^\circ C,$ $TC1R_i = TC2R_i = 10^{-6}$	$T=220^\circ C, TC1R_i \neq TC1R_j,$ $TC2R_i \neq TC2R_j$
$V_{out,th}$ (theoretical value)	250 $\mu V$	250 $\mu V$	-467,2mV
$V_{out,sim}$ (simulation)	249,86 $\mu V$	249,863 $\mu V$	-470,05mV

Table1: Comparison of simulation results

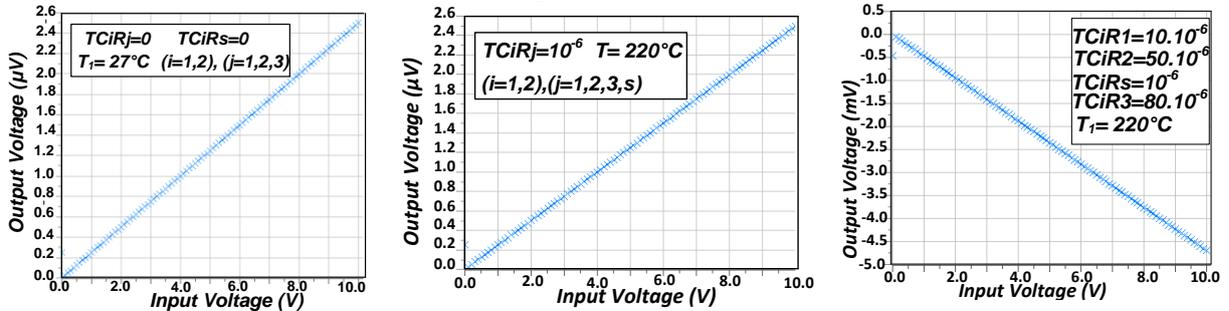


Figure 2: Evolution of  $V_{out}$  as function of  $V_{in}$  for different parameters combination of  $T$ ,  $TC1R_i$  and  $TC2R_i$

With a DC analysis of the test-bench which is represented in Figure 1, we plotted  $V_{out}$  as function of  $V_{in}$ . As predicted, the evolution of  $V_{out}$  as function of  $V_{in}$  is always linear. Moreover, if all resistance variations  $x_i$  are equal (second case), the slope of the linear curve does not change in  $220^\circ C$ . But, if the temperature coefficients are not identical (third case), the slope value and sign change in  $220^\circ C$ . That is why; for a same input voltage  $V_{in} = 1V$ ,  $V_{out}$  has a different value in each case ( $V_{out} = 249,863\mu V$  in the second case and  $-470,05mV$  in the third case). This means that due to the changing of the temperature coefficients values,  $V_{out}$  does not only changes its sign, but its absolute value increase also considerably as it is almost multiplied by about 2000 times.

## II. Conclusions

This paper is a continuity of previous works that aim to model AFE circuits in HT [3], [4], [5]. We developed a VHDL-AMS model of a Wheatstone bridge sensor. Formed by four resistances, this sensor is very sensitive to temperature variation. First, we created a VHDL-AMS model of a resistor for which the temperature effect is described by two temperature coefficients. Then, by using the instantiating property, the HT VHDL-AMS model of the Wheatstone bridge model is created. This model was first validated by comparing simulation results to the theoretical results. Then, an example of the effect of resistance mismatch due to the temperature increasing was simulated in  $220^\circ C$ . This confirms the impact of the temperature on this sensor accuracy.

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