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A simple analog behavioural model for NTC thermistors including selfheating effect

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Abstract

In this paper, a model is presented to simulate loaded, as well as unloaded thermistors with negative temperature coefficients. This analog behavioural model (ABM) is particularly suitable for the steady-state large signal time-domain analysis and design of NTC thermistor circuits, making it possible to simulate complete static current-voltage characteristic of a thermistor element, including the effect of selfheating.

Keywords: NTC thermistors; Analog behavioural modeling; Circuit simulation; PSPICE

1. Introduction

Although semiconductor device temperature is a function of the amount of power dissipated, in most circuit simulation software, the temperature of all devices is set to a user defined value prior to simulation. In fact, device electrical parameters also change with temperature, resulting in modification of power dissipated by device, therefore causing an alteration in the operation temperature. Thermal feedback effects on various semiconductors and their analysis using SPICE circuit simulation packages were reported in literature [1–4]. Theoretical bases of thermistor problem were studied by various researchers [5–7]. A modeling approach (without implementing SPICE) was reported for thermistor simulation applications in [8]. A measuring system for generating the static voltage versus current characteristics of various resistance sensors was described in [9].

Negative temperature coefficient thermistors (NTCTs) are thermally sensitive semiconductor resistors which exhibit a large decrease in resistance as temperature increases. In some cases NTC element is treated as a fixed resistor whose resistance R_T varies with ambient temperature, T_A

$$R_T = R_N \exp\left(\frac{\beta}{T_A} - \frac{\beta}{T_N}\right) \quad (1)$$

where β is the material constant, and R_N the resistance at the nominal temperature T_N, in Kelvin. However, when a current flows through the NTC thermistor, it will heat up by power dissipation. In the following analysis, we neglect the effect of geometry of the thermistor itself. Self-heating effect can be described by,

$$P = \frac{dH}{dt} = \delta(T - T_A) + C_{th}\frac{dT}{dt} = VI \quad (2)$$

Here dH/dt is the change of stored thermal energy with time, δ the dissipation factor of NTCT, C_{th} = heat capacity of NTCT, T = instantaneous thermistor body temperature, T_A = ambient temperature, V, I, P are the instantaneous NTCT voltage, current and power, respectively. After same time a constant electrical power is applied to the thermistor, a steady state will be reached where the power is dissipated by thermal conduction or convection, therefore dT/dt = 0 and,

$$I = \left(\frac{\delta(T - T_A)}{R_{NTC}}\right)^{1/2} \quad (3a)$$

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or

$$V = (\delta(T - T_{\rm A})R_{\rm NTC})^{1/2} \tag{3b}$$

which yield the parametric description of the *V*/*I* curves that are calculated for different (constant) ambient temperatures. The linear part of log–log plotted *V*/*I* characteristic curve of NTCT is used when this element is employed as a temperature sensor. Beyond a certain limit, *V*/*I* characteristic behaves in non-linear fashion, first reaching a maximum and than displaying a negative resistance behaviour. There are many applications which are based upon the static *V*/*I* NTCT characteristic. (a) Applications where δ is varied (which is exploited in flow meters, vacuum manometers, liquid level control, and gas chromatography). (b) Applications where the electrical parameters of the circuit are varied. (c) Applications where the ambient temperature is varied which can be due to radiation absorbed by the thermistor, such as in microwave power measurement. Considering the cost of physical realization in these wide variety of applications, as well as the time spent in their design, it is apparent that, a model which helps to simulate NTCT steady-state response including selfheating (i.e., simulating complete static *I*–*V* characteristic, rather than partial formulations) will be advantageous. Motivated by this fact, a model is presented in this paper to simulate the NTC thermistor behaviour including the effect of selfheating in dc operating point analysis.

2. Modeling of NTC thermistors

In conventional circuit analysis software, an unloaded NTCT can be modelled with a look-up table, or an expression can be used to describe how the resistance varies with temperature by implementing an analog behavioural model (ABM). Here, procedure is to sense the current (*I*) and then generate the voltage *V (=IR)* with a voltage source. For example, to sense current, recent versions of PSPICE uses a voltage source which is set to 0 V, so there's no effect on the output voltage. The other source, which is connected in series to the first one, generates the voltage across the "resistor" based on the sensed current times the desired resistance. The important aspect of this source is that its output voltage can be described by an equation. The "resistor" described above is extended to include the characteristic equation of the NTCT and the sensor's temperature, to create the NTCT model. The sensor's temperature and the voltage nodes are included symbolically in the characteristic equation in volts (represents degrees celsius), and in the sub-circuit statement, respectively. For example, the subcircuit NTC given below defines the resistance of a 1 kΩ NTCT (with β = 3060), as follows:

```
.subckt NTC 1 2 5 6
eth 1 3 value = {i(vs) × 1k × exp(3060/(v(5, 6)+273) − 3060/(298))}
vs 32 dc 0
.ends
```

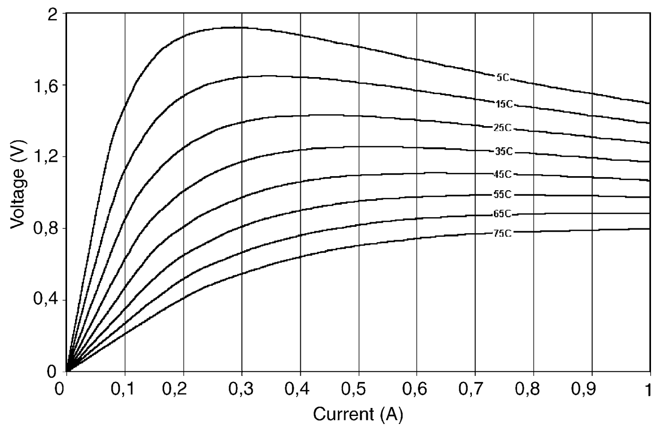

Fig. 1. Typical linear scaled *I*–*V* characteristics for a NTCT (S-237-10, [10]), at various ambient temperatures. These curves are constructed using the manufacturer data for δ = 17 mW/K.

As one can see, nodes 5 and 6 have been added in the sub-circuit statement. The ambient temperature, *V*(5, 6) is included in the characteristic equation, also. This is the sensor's temperature in volts (but it represents degrees celsius). Finally, characteristic equation has been included in the "eth" statement to create the NTCT model.

However, if the element operates in its non-linear *I*/*V* region, this model is insufficient to completely describe a NTCT.

3. Electrically loaded NTC thermistor

As long as data of a given NTCT are in hand, it is possible to compute the characteristic.

I–*V* curves at different ambient temperatures as shown in Fig. 1, and modify a PSPICE model described above, to represent steady state selfheated NTCT behaviour. The temperature change due to selfheating can be given as,

$$\Delta T = T_{\rm X} - T_{\rm A} = \frac{IV}{\delta} \tag{4}$$

Here temperature circuit is modified by the addition of a self-heating temperature equivalent of voltage source whose value is made equal to the change in voltage. This is shown in Fig. 2

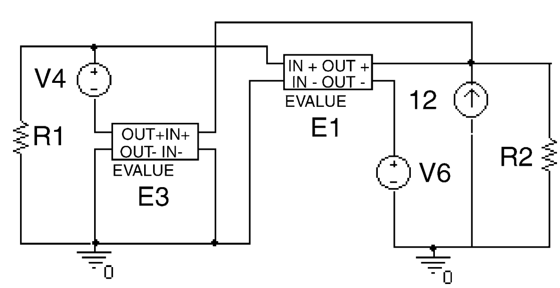

Fig. 2. Complete PSPICE ABM for NTCT with selfheating effect. VALUE(E1)= $I(V6)\,R_{\rm N}\exp[\beta/(V\%{\rm IN1+},\ \%{\rm IN1-}) + 273) - \beta/298]$, VALUE($E$3)= $I(V6)(V\%{\rm IN3+},\ \%{\rm IN3-})/\delta$.

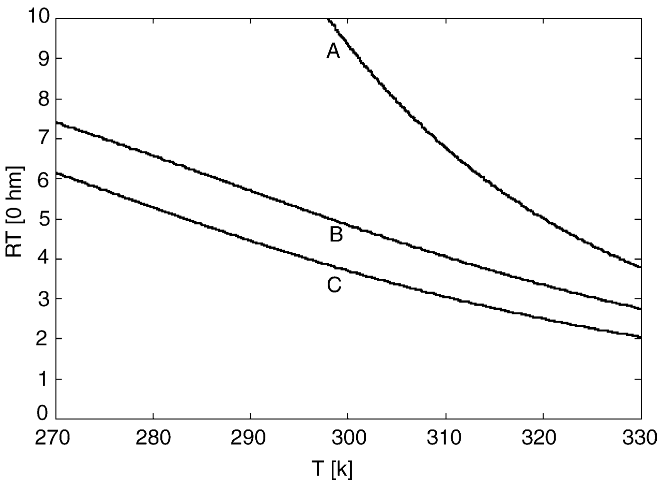

Fig. 3. Resistance vs. temperature curves of (A) unloaded NTC thermistor, R_N = 10 Ω, without linearization, (B) same NTCT linearized by a parallel fixed resistor of 10 Ω, under no-load conditions, (C) same NTCT with a current I_T = 200 mA and in parallel with a fixed resistor of 10 Ω.

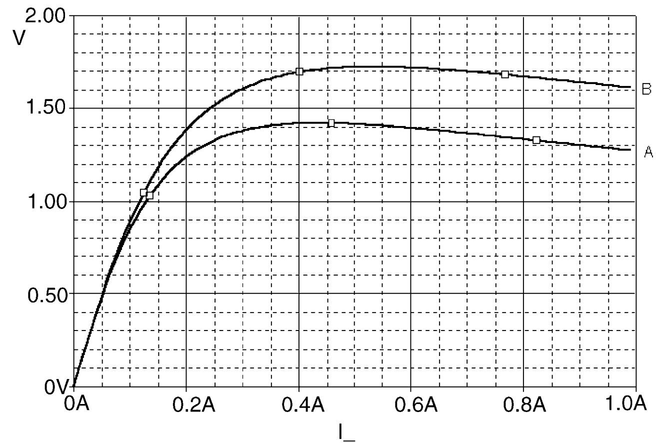

Fig. 4. PSPICE reconstructed current–voltage characteristic curve obtained from the NTCT ABM proposed in Fig. 2. The curve A is for δ = 17 mW/K in still air, while B is for δ = 25 mW/K non-conductive liquid. Ambient temperature is 25 °C.

which is a generalized form of the NTCT ABM model including the selfheating (thermal feedback) effect, using PSPICE simulation package [11]. In this figure, voltage source *V*6 is used to sense current, which is set to 0 V, *E*1 generates the voltage across the "NTCT" based on the sensed current times the NTCT resistance. *V*1 represents the "ambient temperature", while *E*3 is an ABM component which provides the selfheating information in thermal circuit. The resistors *R*1 and *R*2 have high values; however, proper *R*2 value must be selected, for example, if the NTCT is to be linearized.

Example: Assume that a NTCT whose dissipation constant is 17 mW/K and steady state *I–V* curve is shown in Fig. 1 [10], operates at 25 °C under no load conditions. If the current is increased to 200 mA, the amount of self heating at steady state will be (0.2 A) (1.255 V)/(0.017) = 14.8 °C, and NTCT temperature will be 39.8 °C. Therefore, in the abovegiven PSPICE netlist, the value of *v*(5, 6) is now 39.8 V. If it is required to design a linearized, unloaded NTCT circuit with this component within the temperature range 270–330 K, a parallel connected fixed resistor R_P = 10 Ω can be used. This yields a fair linearization of the *R–T* characteristics around the ambient (=nominal) temperature of NTCT, as shown in Fig. 3B, under no-load conditions. However, this "linearity" is offset by the amount of selfheating, if considerable amount of current flows through the thermistor, e.g., I_{NTCT} = 200 mA, as depicted in Fig. 3C.

As a check of how well the model can predict current–voltage characteristic curves for a given NTCT at different ambient temperatures, the current source *I*2 is swept in the interval of (0–1 A) while keeping the *V*4 voltage fixed in Fig. 2, corresponding to constant ambient temperature. PSPICE reconstructed current–voltage characteristic curve obtained from the NTCT ABM (Fig. 2) at 25 °C ambient temperature is shown by curve A of Fig. 4 As shown by Eqs. (3a) and (3b) the voltage/current curve is influenced not only by the NTCT resistance R_T, but also by the dissipation factor δ, which depends on size, shape and leads of the device as well as on the medium surrounding the thermistor. In stirred air or in a liquid the dissipation factor increases and the *V/I* curve shifts towards higher values of voltage and current. The voltage/current curve thus indicates by which medium the thermistor is surrounded. The curve B of Fig. 4 demonstrates this fact using the proposed NTCT model, assuming that the element is immersed in a dielectric liquid, causing NTCT dissipation factor to have a new value of 25 mW/K at the same ambient temperature (T_A = 25 °C).

Using the proposed model, response of the NTCT (whose parameters [10] have been given above) to different unbiased sinusoidal currents with different amplitudes (but the same frequencies) at T_A = 25 °C (still air), are depicted in Fig. 5. The voltage waveform observed over the element has been

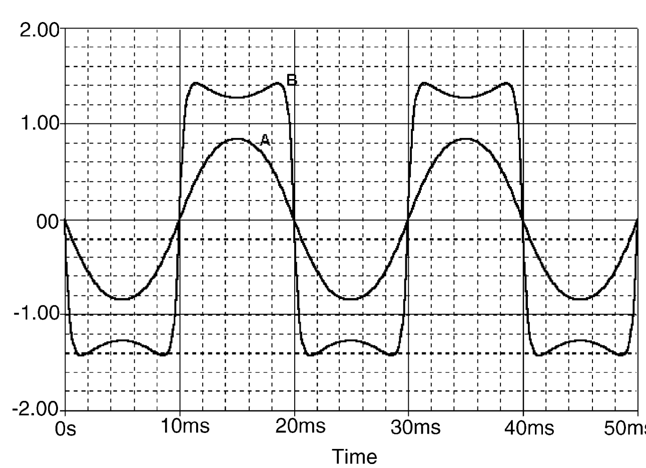

Fig. 5. Time domain transient analysis of the NTCT ABM for two sinusoidal currents of the same frequencies (50 Hz) with different amplitudes, in still air at 25 °C. (A) I_{max} = 0.1 A, (B) I_{max} = 1 A.

distorted for larger amplitude current input, as expected from the inspection of (both calculated and simulated) V/I curves of the NTCT under consideration.

A comparative analysis of the reconstructed I/V curves with the corresponding ones plotted in Fig. 1 proves that the proposed NTCT ABM is a good approximation to simulate the steady-state behaviour of NTC thermistors.

4. Conclusion

An analog behavioural model is presented in this paper to simulate the NTC thermistor behaviour including the self-heating effects in dc operating point analysis. The method proposed in this work uses currently available circuit simulation software, such as PSPICE. This method is found to be an effective tool for the steady-state large signal time domain analysis of NTCTs whose specifications are either given by their manufacturers or determined experimentally. A comparison of the simulation results employing the proposed NTCT ABM with the corresponding theoretically calculated ones using manufacturer specified data proves that the NTCT model presented in this work is a good approximation to simulate the steady-state behaviour of NTC thermistors, including the effect of selfheating.

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Biography

Ali Ümit Keskin was born in Bursa, Turkey. He received his BSEE degree from Bogazici University in 1978, MSEE from Yildiz University (1980) and PhD degree from the Institute of Science and Technology, Istanbul Technical University (1984), respectively. In 1985, he joined Siemens AG, Turkey. He was engaged in the field of Medical Imaging Technology throughout his professional career in Siemens AG. Since September 2002, he has been affiliated as an assistant professor in Department of Electrical Engineering, Yeditepe University, Istanbul. His main research interests are analog signal processing, sensors and transducers, spectroscopy, medical imaging theory and its applications.