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A New Structure for Direct Measurement of Temperature Based on Negative Temperature Coefficient Thermistor and Adaptive Neuro-fuzzy Inference System

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ABSTRACT

Thermistors are very commonly used for narrow temperature-range high-resolution applications, such as in medicine, calorimetry, and near ambient temperature measurements. In particular, Negative Temperature Coefficient (NTC) thermistor is very inexpensive and highly sensitive, whose sensing temperature range and sensitivity are highly limited due to the intrinsic nonlinearity and self-heating properties of NTC thermistor at high operation currents. In this research, a new structure is proposed based on adaptive neuro-fuzzy system for the modeling of sensor nonlinearity. Apart from taking self-heating phenomenon of NTC thermistor sensor, the proposed structure also measures temperature directly, without any linearizing circuitry. Neuro-fuzzy network is trained and tested through data produced in the Laboratory environment. Examination of the proposed method on test data achieved a mean squared error of 0.0195, which is considered as a significant accomplishment.

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1. INTRODUCTION

Natural systems are usually nonlinear, which makes it difficult to model or work with them. In engineering problems, if possible such nonlinearities are usually tried to be linearized in a small neighborhood of the operating point with the cost of losing accuracy to some extent, but making them more convenient and less costly to approach. As an example from control systems, by performing a linearization process a simple PID controller would often be satisfactory [1-3]. Linearization of complex systems and then modeling them using linear differential equations bears uncertainties and may therefore fail to provide the appropriate performance. In such cases, either nonlinear techniques or intelligent methods such as neural networks, fuzzy inferences, or a combination of both is usually utilized. Fuzzy systems can model the qualitative aspects of human knowledge and reasoning processes through fuzzy logic rules, and without utilizing precise quantitative measures. Fuzzy modeling and identification was first explored by Takagi and Sugeno and later found many applications in control, identification and prediction [4]. In early 1990, Adaptive Neuro-Fuzzy Inference System (ANFIS) was introduced by combining neural networks and fuzzy logic with hopes to benefit from collective potentials of both systems. By utilizing if-then fuzzy rules within its structure as well as possessing capability of learning from new training data, the system has received particular interests in modeling nonlinear systems [5, 6]. In ANFIS, the existing model parameters are tuned through a hybrid learning algorithm based on a set of input-output data. Temperature is one of the important measurable parameters in engineering systems. Due to the significance of temperature measurement and to obtain the required precision in, various methods are employed. Depending on the physical condition of system, the required accuracy, and etc, the choice of these methods can affect the selection of the temperature measurement element. Most temperature

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measurement systems are made of common parts, while their basic difference is in the type of sensor, the related sensor driving circuitry, sensor linearization method, and etc. Nonlinearity of the sensors is one of the fundamental issues in the analysis of these systems. A thorough investigation of the thermal relationships for all of the commonly used temperature sensors such as negative temperature coefficient (NTC) thermistor, RTD, and thermocouple can reveal signs of nonlinear operation in diverse forms and magnitudes of exponential and second order terms [7, 8]. Among the mentioned sensors, NTC Thermistors (Thermal Resistors) are semiconducting devices which are ceramic temperature-sensitive components. Among several types already used in a wide variety of applications, we are primarily interested in the NTC thermistors for its specific characteristics including high sensitivity, good mechanical durability, small size, large ohmic resistance, decent priceand good replicability characteristics [8]. Sensitivity of NTC thermistor is around 3-5 percent which exceeds the sensitivities of most other sensors. Moreover, this sensor has a small size that makes it capable of quickly responding to temperature changes. Its good mechanical durability allows for better withstanding mechanical, thermal and vibration shocks compared to other types of temperature sensors. The high ohmic resistance of NTC thermistor sensors results in better performance when connecting to long cables, compared with other sensors. Additionally, since NTC thermistor sensors are manufactured with very close production tolerances, thus provide better changeability than rest of the sensors.A known drawback of thermistor when used as a temperature sensor, is the highly nonlinear relationship of its resistance to temperature [9]. To tackle this issue, various linearization circuits have been introduced [7, 10]. Moreover, there also exist some numerical linearization techniques for this purpose [11]. Besides these methods, the use of intelligent estimation approaches such as artificial intelligent networks [12] is also remarkable. The advantage of intelligent estimation approaches resides in their flexibility for the modeling of nonlinear phenomena. Another issue in the design of linearization circuitry for NTC thermistor is the elimination of NTC thermistor self-heating, due to its high complexity [13]. To resolve this issue, the operation current is extremely reduced down to about 10 uA (zero power assumption) to alleviate the self-heating effect to negligible levels. This however directly reduces from the sensitivity of NTC thermistor, which was ironically the main reason behind choosing NTC thermistor.

The novelty of this research is the modeling of nonlinear behavior of NTC thermistor which involves self-heating property, through the application of ANFIS for direct temperature measurement, and eliminating the need for additional components such as linearization circuitry. Moreover, a method is investigated here for the controlling of self-heating phenomenon and to use it for boosting system sensitivity. ANFIS can be used as general estimators in approximation-based problems [14]. Up to day, many researchers have also attempted to develop a hardware implementation of fuzzy systems using different types of electronic circuits such as FPGAs, microcontrollers, and DSP chips [15-17]. ANFIS are also employed in some references to help measurement system and to fix linearization issues [17-21].

Rest of the paper is organized as follows. In section two, characteristics of NTC thermistor sensor and related problems are first presented, and then ANFIS is briefly reviewed. Section three covers an introduction to the proposed method as well as generation of laboratory data. Finally, paper concludes by giving results and conclusions in sections four and five.

2. BASIC MATERIALS

The purpose of this research is modelling nonlinear NTC thermistor sensor by considering self-heating phenomenon through the use of ANFIS, for temperature measurement. Hence, NTC thermistor sensor and issues related to its use will be discussed first, and section will finally end by an introduction to ANFIS.

2. 1. NTC NTC is a sensor whose ohmic resistance decreases exponentially with increase in temperature. This property in one hand leads to high sensitivity to temperature changes, and to nonlinear operation of sensor on the other. Moreover, the flow of electricity through any component induces self-heating effect. This phenomenon is of much significance for the NTC thermistor sensor compared to other sensors, since any decrease in resistance will further increase the current flow and thereafter temperature. Normally, specific diagrams are provided by the manufacturers to facilitate the modeling and application of NTC thermistor sensors. A typical NTC diagram is shown in Figure 1 [13].

Such information is usually supplied by the manufacturing companies with high accuracy, and therefore in the first glance may seem to be suitable for practical applications. However, self-heating phenomena is not normally included in these diagrams. Moreover, NTC thermistor is a nonlinear sensor. Add to these, decay of the sensors over time which results in the altering of characteristics and hence the lowered accuracy of the related tables and diagrams.

To represent the resistor-temperature changes of NTC thermistor, two well-known equations of “B-Formula” and “Steinhart-Hart relation” are usually utilized [22]. Unfortunately, Steinhart-Hart equation is a very poor choice of calibration equation, as the original paper was based on a numerical mistake [23]. Hence, the use of this equation has strongly been discouraged. On the other hand, B-Formula as provided in Equation (1) represents a better choice:

$$R_T = R_{T_0} \exp\left\{B(\frac{1}{T}-\frac{1}{T_0}\right\} \quad (1)$$

where, R_{T_0} is the equation in ohms in temperature of T_0 degrees (in Kelvins), which can be obtained from the sensor's datasheet. As noticed from the B-Formula, NTC resistor exponentially decreases by the increase in temperature, demonstrating its strong nonlinear operation. Also B is dependent upon the type of material used to fabricate NTC thermistor sensor and the operating temperature. B-Formula requires two points for its calibration, with an error of 5% over its full range. A more precise equation between temperature and the resistance of NTC thermistor is known as Steinhart-Hart equation, which was introduced in 1968. It is given in Equation (2):

$$T_{(R)} = (A + B\ln(R) + C\ln^2(R) + D\ln^3(R))^{-1} \quad (2)$$

$\ln(R)$ being the natural logarithm of NTC's resistance. A, B, C and D are constant variables obtained through experiment and given in the related datasheets by the manufacturer of NTC thermistor sensor. This equation again demonstrates the strong nonlinearity of NTC thermistor with respect to temperature changes. Compensation of this strong nonlinearity necessitates application of various software and hardware circuitry, which apart from adding to the overall system costs and complexity, also lowers measurement precision and sensitivity owing to the use of numerous estimations.

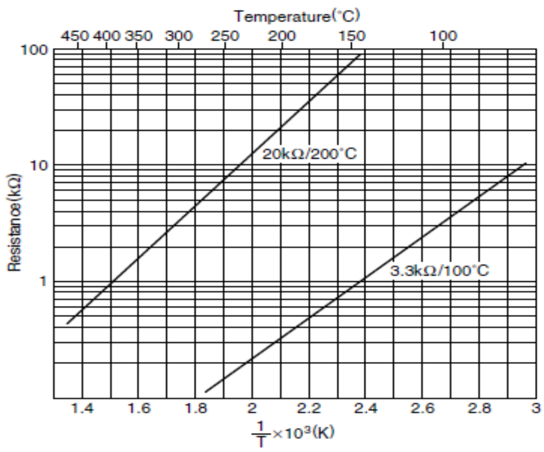

Figure 1. The characteristic diagram of NTC resistor with respect to temperature [13]

The passing of electric current through any element which in turn causes power dissipation, increases its temperature. This phenomenon is known as self-heating. Since temperature increase in NTC thermistor sensors results in the decrease of its resistance, self-heating property acts as a positive feedback, where an increase in NTC's body temperature (independent of ambient temperature) will further decrease the resistance. This positive feedback, induces sensing errors, decreases precision and even can end up with a burned-out element. For the proper operation of NTC thermistor, and for determining of the resistance changes, it is necessary to measure voltage changes against a fixed current, and therefore self-heating is always present.

To avoid the side effects of NTC's self-heating property, manufacturers provide the related terms and specifications for the zero power, where the current flow is so small that does not cause self-heating. Although this assumption may be acceptable for other types of sensors such as RTDs by using a proper approximation because of their very low sensitivity and their decrease of resistance with the rise of temperature, however it is not suitable for NTC thermistors for having several-fold sensitivity. In fact excessive sensitivities could be accessible, if a way is found to increase the operation temperature beyond zero power range in a controlled fashion, through the modeling of self-heating phenomenon. In overall, the flow of current i across the NTC thermistor due to ΔR changes resulting from ΔT drift in temperature, causes voltage changes of $\Delta V = \Delta R.i$ and power dissipation of $P = R.i^2$. Thus, sensitivity (S) can be written as:

$$S = \frac{\Delta V}{\Delta T} = \frac{\Delta R.i}{\Delta T} \quad (3)$$

It is obvious from Equation (3) that sensitivity is directly proportional with the current. Therefore, practically the sensitivity of system is highly reduced by excessive drop in current magnitude. Also, if the current magnitude is increased n-fold, sensitivity will increase n-fold. Hence:

$$S_n = \frac{\Delta R.\text{n}.i}{\Delta T} = n.S \quad (4)$$

It should be noted that in this case power dissipation will grow n2-fold, and self-heating will almost rise at the same rate, thereby nullifying the zero power assumption.

2. 2. Neuro-fuzzy System In general, neuro-fuzzy model is built by combining fuzzy logic and artificial neural network models, and consists of five layers [24-26]. The structure of a typical neuro-fuzzy network with two input and one output is depicted in Figure 2.

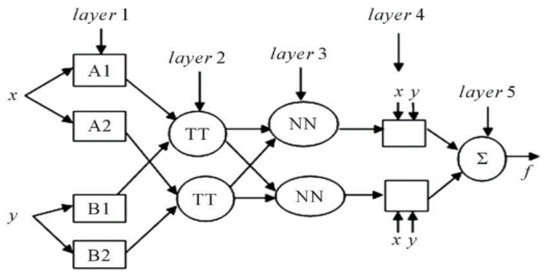

Figure 2. Structure of a neuro-fuzzy network

In Figure 2, the first layer is input layer which determines the degree of membership with respect to various fuzzy intervals through membership functions. For every input (x and y), two fuzzy sets are considered, and the form of membership function and the amount of overlap are determined by the user through following equation:

$$\mu_A(x) = (1 - \frac{x - c_i}{a_i})^{-2b_i} \quad (5)$$

where x is the input. Also a , b and c are adaptive parameters and nonlinear coefficients of the equation that determine membership function.

In this research, a neuro-fuzzy-network based direct temperature measurement method that does not require any further circuitry is proposed. The proposed structure comprises the current mirror source, NTC thermistor sensor, and the neuro-fuzzy network system. The current source is utilized to control and stabilize the current flow through NTC thermistor as well as its self-heating phenomenon, and will be further studied in the following. Neuro-fuzzy network is the most fundamental component of this proposed structure, and is responsible for meddling the whole system. The neuro-fuzzy network requires adequate training to adjust the network parameters to achieve a desirable performance, which is strongly dependent upon an adequate training data.

3. CURRENT MIRROR CIRCUIT

If the self-heating phenomenon is controlled, the current flow through NTC thermistor can be increased and system sensitivity can be raised by several fold. Therefore we have utilized current mirror source to ensure a fixed flow of current. The idea behind our proposed methodology is that, in theory by stabilizing NTC thermistor current through a current mirror source, once temperature is increased, NTC thermistor resistance will decrease while the current flow will remain constant, and therefore the power dissipation will be also reduced because of the lowered resistance of NTC thermistor. In practice though, an ordinary simple current mirror may not provide the best way for controlling current through a thermistor, since the output impedance of simple current sources is usually too low and will introduce extra nonlinearities into the measurements. Furthermore, simple current mirrors are very sensitive to the ambient temperature, and therefore are sometimes used as temperature sensors. However, we could watch for and compensate this issue, since our experiment was carried out in a controlled laboratory environment. In the laboratory realization of the system, we have employed a $1K\Omega$ NTC thermistor in the 0.1-10 mA current range.

Once the circuit was built and finalized, laboratory tests were carried out to measure NTC thermistor currents and voltages for a range of bias currents and operating temperatures, to produce necessary data for the training and test of ANFIS model. In overall, 184 data points of NTC thermistor current and voltage were collected from across a temperature range of almost 70 degrees Celsius, for different values of bias currents (due to the self-heating phenomenon) and operating temperatures. To have a better understanding of the nonlinear performance of NTC thermistor, the plot of changes in NTC thermistor resistance with respect to the changes in its current flow is sketched in Figure 3, using the experimental data.

Investigation of Figure 3 reveals that the change in the current flow of NTC thermistor leads to rather strong and nonlinear variations in its resistance.This, also shows the effect of self-heating phenomenon in NTC thermistor. From the overall 184 collected data points, 85% were randomly selected and used in the training of neuro-fuzzy network and the remaining 15% points were employed in its test.

4. RESULTS OF IMPLEMENTATION

Tunable parameters of a neuro-fuzzy network include those associated with the network structure, such as the numbers and types of the input and output membership functions. In our simulations, we have utilized a neuro-fuzzy network with an input layer having two nodes, a hidden layer, and an output layer. The input nodes receive the current and voltage of NTC thermistor, and the single node in the output layer generates the related temperature. Several simulations were carried out to determine the numbers and types of membership functions, and some of the best results are provided in Table 1. In this table, the numbers and types of the membership functions are varied, and the resulting MSE is subsequently calculated for 10 repetitions of each. As noticed from Table 1, the network with two gbellm membership functions for the first input (current) and six gaussmf membership functions for the second input (voltage) has generated the best result.

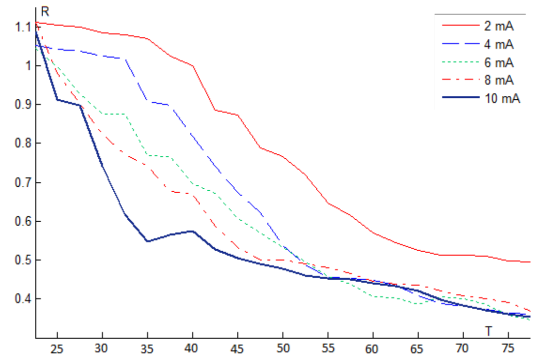

Figure 3. Demonstration of the nonlinear characteristics of NTC using real data

TABLE 1. Results obtained from the simulation of ANFIS

No.	Membership Type	Membership Number	Membership Type	Membership Number	Error
1	gbellmf	2	gaussmf	6	0.0195
2	gbellmf	3	gaussmf	6	0.0259
3	gbellmf	2	gaussmf	5	0.0236
4	gbellmf	2	gaussmf	6	0.0266
5	gbellmf	2	gaussmf	4	0.0292
6	gbellmf	3	gaussmf	4	0.0317
7	gbellmf	2	gbellmf	4	0.0263
8	Psigmf	2	gaussmf	6	0.0356
9	gaussmf	3	gaussmf	8	0.0303
10	gaussmf	4	trimf	2	0.0261

Considering the structure of neuro-fuzzy network, as well as the number of membership functions for the inputs, the proposed system will have 12 rules. The final structure of the neuro-fuzzy network is depicted in Figure 4.

Investigation of Figure 4 reveals the number of membership functions for the inputs, for the output, and the way they are combined.

Once the training of neuro-fuzzy network with proposed architecture was finished the 3D diagram of output changes of the neuro-fuzzy network with respect to the first and second inputs is plotted in Figure 5.

The trained structure was evaluated using test data, the results of which are shown in Figure 6 alongside the real data.

Analysis of Figure 6 indicates that the proposed structure bears negligible error. Further investigations reveal that the minimum, maximum and mean square error values were 0.0002, 0.0632 and 0.0195 respectively, demonstrating a very successful performance for the proposed system.

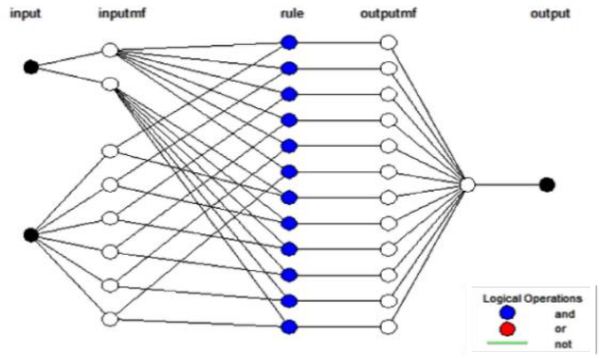

Figure 4. Final structure of the ANFIS

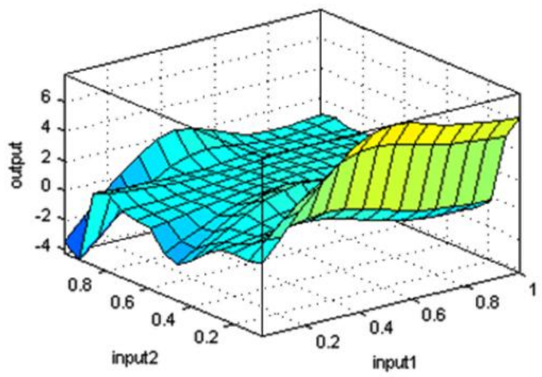

Figure 5. Diagram of the output changes with respect to the inputs 1 and 2

In a separate experiment, the results obtained from our proposed method were compared to those of "B-Formula" and "Steinhart-Hart relation" (Equations 1 and 2). Here again, the test data points were selected randomly. Figure 7 depicts error rates of these three methods when applied on the test data.

As shown in this figure, the proposed method exhibits with an acceptable error rate, better results compared to the both conventional methods.

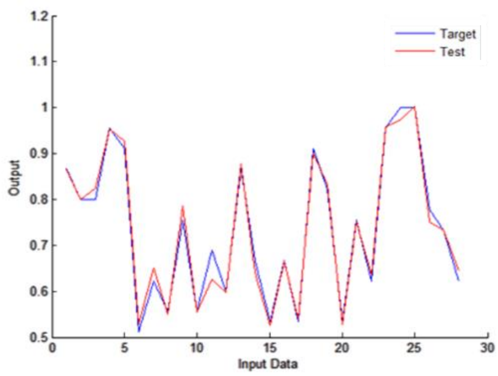

Figure 6. Error between test data and the output of ANFIS

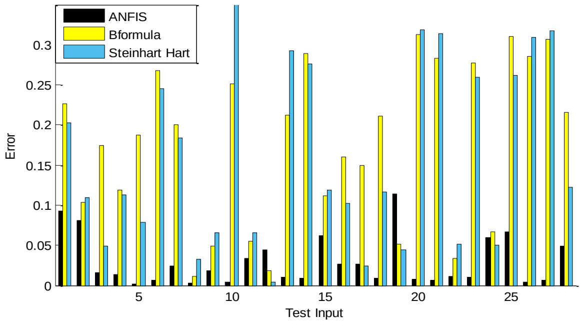

Figure 7. Error rates resulting from three methods when applied on the test data

5. CONCLUSIONS

Issues such as self-heating phenomenon and the simplifying assumptions degrade the functional accuracy of systems which employ NTC thermistor for temperature measurement. Excessive sensitivities could be accessible for NTC thermistor sensor by increasing the operation current in a controlled fashion beyond zero power range, thanks to the successful modeling of self-heating phenomenon. In order to tackle the self-heating problem, a current mirror circuit based structure was studied, which demonstrated capability of alleviating feedback issue caused by self-heating phenomenon. Another finding of this research is that, ANFIS can model both the nonlinear behavior and the self-heating phenomenon in NTC thermistor sensor with high accuracy. As a result of this, NTC thermistor current flow can without any worry about self-heating property be raised to a desired level, to substantially boost system sensitivity. The most important advantage of Fuzzy systems is their capability of modeling uncertainties. Our experimental data covers a wide range of almost 70 degrees Celsius. From among 184 measured data 85% of samples were randomly chosen for training and the remaining 15% samples were retained for test. Our model is verified using real laboratory produced data, and shows that by utilizing the circuit structure proposed in this paper, NTC thermistor sensor can now find many applications that were considered impossible in the past.

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چکیده

ترمیستور با مقاومت منفی (NTC) از جمله سنسورهای دمایی است که با داشتن قیمت بسیار پایین و حساسیت به مراتب بالا، به دلیل غیرخطی بودن و پدیده خودگرمایی کمتر از آن استفاده می‌شود. در این پژوهش، ساختاری جدید مبتنی بر شبکه عصبی-فازی تطبیقی برای مدلسازی غیرخطی بودن سنسور پیشنهاد شده است. ساختار پیشنهادی علاوه بر در نظر گرفتن پدیده خودگرمایی سنسور NTC، دما را بدون استفاده از مدارات خطی‌ساز و یا مدارات واسط دیگر، بطور مستقیم اندازه‌گیری می‌کند. در این پژوهش، با استفاده از داده‌هایی که در آزمایشگاه تولید شده‌اند، شبکه عصبی-فازی تطبیقی آموزش و آزمایش شده است. بررسی نتایج روش پیشنهادی بر روی داده‌های آزمایش، میانگین مربعات خطای ۰/۰۱۹۵ را نشان می‌دهد که دستاورد قابل ملاحظه ای است.

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