AN14127

RTD measurement system with NAFE13388/73388 family of devices

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Document information

Information	Content
Keywords	NAFE, resistance temperature detector (RTD), industrial, sensors, measure
Abstract	The NAFE13388/NAFE73388 family of products provides the designer with a versatile and optimized measurement system for 2-, 3-, or 4-wire RTDs. In addition, because one current injection path is used instead of two matched current sources used in other solutions, up to eight RTDs are supported by a single device.

1 Introduction

Resistance temperature detectors (RTD) are sensors that are commonly used to accurately measure temperature in an industrial environment. They are made of a wire wrapped around the substrate of a core made of a heat-resistant material. The wire is made of genuine metal, such as platinum, nickel, or copper. These materials are used because of their stable resistance-to-temperature relationship over the required temperature measurement range.

1.1 How to measure an RTD

The most common RTDs are the Pt100 and Pt1000, which have a resistance value of 100 Ω and 1000 Ω respectively at 0 °C. The RTD changes its resistance according to the temperature to which it is exposed. The change follows the Callendar-Van Dusen equation.

Callendar-Van Dusen for Pt100 RTD

Equation 1: $$R(T) = \begin{cases} R(0) \cdot (1 + AT + BT^2) & \text{if } T \geq 0\ ℃ \\ R(0) \cdot [1 + AT + BT^2 + C \cdot (T - 100) \cdot T^3] & \text{if } -200\ ℃ \leq T < 0\ ℃ \end{cases}$$

Where:

R(T) is the RTD resistance at the temperature T;

R(0) is the RTD resistance at 0 °C;

A = 3.9083×10^{-3};

B = -5.775×10^{-7};

C = -4.183×10^{-12};

This application note refers to the coefficients defined by the IEC-60751 standard, which also defines the tolerance classes starting from a base resistance of 100 Ω at a temperature of 0 °C[1].

By measuring the value of the resistance, the value of the temperature is calculated by resolving the above equations for T.

However, to get an accurate measurement, the value of the resistance at certain known temperature points must be taken to calibrate the system. Then, the stable resistance-to-temperature characteristic of the material allows high-accuracy measurement in the overall temperature range.

One way to measure the RTD is to inject a current (IEXC) in the RTD and measure the resulting voltage through a low-noise amplifier. An analog-to-digital converter (ADC) then converts the amplified voltage in the digital domain where its value is translated into temperature by a digital processor host. The host resolves Equation 1 using a best-fit polynomial expression.

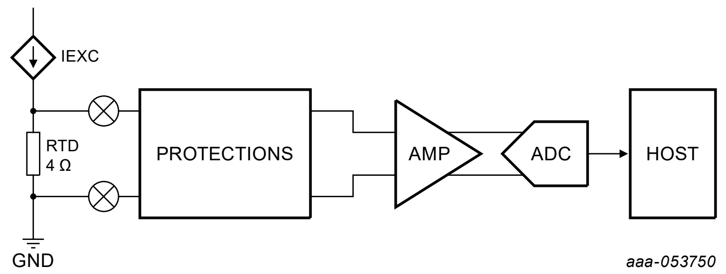

Figure 1. Simplified measurement block schematic

The measurement system should not introduce significant errors. The voltage must be read with low offset and gain error, and the current generator should have high impedance. Also, to avoid multiple calibrations at different temperatures, the measurement system performances must be stable even when its temperature changes.

1.2 Common system requirements

RTDs are used when a precise temperature measurement is required. Compared to thermocouples, RTDs have higher performance repeatability with lower drift as they age.

The Pt100 resistance goes as low as approximately 18 Ω at –200 °C and reaches approximately 390 Ω at 850 °C. The Pt1000 ranges from 180 Ω to 3.9 kΩ in the same temperature range.

The accuracy in the resistance measurement is translated in the accuracy of the measured temperature. For example, for a Pt100, if a ±1 °C accuracy is required, its resistance must be measured with an accuracy of ±0.385 Ω.

While the measurement system is not exposed to the same temperature as the RTD, a temperature range from –40 °C to 70 °C is a common requirement in the market. A low temperature drift of the measurement system in the range of tens of ppm per °C is also required.

1.3 RTD wiring

RTDs are connected to the measurement system with long wires that are plugged into the screw connectors. These wires have their own resistance and, when the injected current flows through them, this creates a voltage drop that is measured by the system. In some installations, the wire length is a range of hundreds of meters. The corresponding resistance depends on the wire section that is typically between 12 AWG and 26 AWG, therefore determining a wire resistance from a few ohms to tens of ohms.

To overcome the wire resistance error, a few RTD wiring configurations are possible: 4-wire, which is the most precise, 3-wire, and 2-wire.

In the 4-wire configuration, the wiring resistance has no impact because the current injection and the measurement occur in two different wire pairs. In the 3-wire configuration, the wire resistance is canceled with special techniques, assuming all 3-wires have the same resistance. In the 2-wire configuration, it is not possible to cancel or compensate for the error. This configuration is used when the resulting measurement error can be accepted by the system.

1.4 Protection

Because the measurement system may be hundreds of meters away from the measurement point, these wires are exposed to voltage surges of a few kilovolts, in general, caused by lightning.

The measurement system must be protected on such occasions. A typical protection consists of a transient voltage suppression diode (TVS) that can absorb the energy.

Another required protection is related to the possibility that the 24 V DC source voltage, which is the most common source used in industrial systems, is applied by mistake to the RTD measurement system screw connectors at the first installation of the system or during maintenance. In this case, a protection device such as a Zener diode must be inserted to protect the measurement unit.

2 RTD measurement solutions with NAFE13388/NAFE73388

2.1 Introduction to NAFE13388/NAFE73388

The NAFE13388 and NAFE73388, its high-speed version, are highly configurable industrial-grade multichannel universal input analog front-ends (N-AFE) that meet high-precision measurement requirements. The NAFE13388/NAFE73388 family of products is designed to measure any input voltage and currents typically used in the industrial market, such as ±10 V, ± 0 mA to 20 mA, RTDs and thermocouples.

The device integrates low-leakage, high-voltage fast multiplexers (mux), low-offset and low-drift programmable gain amplifier (PGA) and buffers, high data-rate 24-bit sigma-delta ADC, precise voltage and current excitation source, and low-drift voltage reference. The digital data are read by the host MCU/MPU through the SPI interface.

The current excitation source is designed for RTD measurement featuring a low-temperature drift of 4 ppm/°C typical and an impedance in the range of hundreds of kilo-ohm. The low-temperature drift characteristics of the N-AFE allow getting a typical unadjusted error of ±0.002 % of full-scale reading at room temperature and ±0.05 % in the temperature range from –25 °C to 105 °C after onboard calibration. These characteristics allow the devices to meet the most stringent requirements of RTD measurement systems.

The excitation current also provides a 65 nA current value setting, which allows implementation of open-wire detection of RTDs.

The NAFE13388/NAFE73388 input pins are diode-protected internally for electromagnetic compatibility (EMC) and miswiring scenarios.

3 RTD configurations with NAFE13388/NAFE73388

3.1 4-wire RTD

The 4-wire RTD is the most precise measurement configuration because it is based on a force/sense principle. The current is forced through two wires of the RTD and the resulting voltage is measured on the other two wires. However, it is also the most onerous because it requires four wires of the RTD and more connections to the system resources.

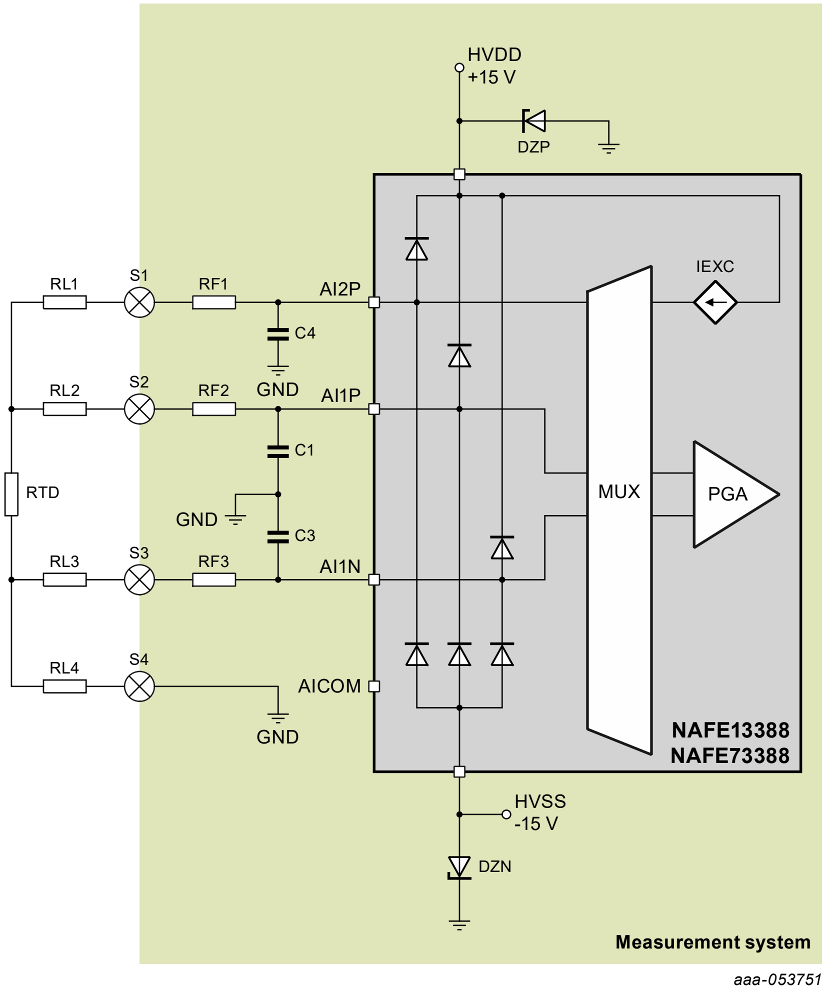

Figure 2. 4-wire RTD configuration

Figure 2 shows the typical 4-wire configuration using NAFE13388/NAFE73388. RL1, RL2, RL3, and RL4 are the wire resistances, while RF1, RF2, and RF3 and C1, C2, and C3 form the antialiasing filter.

Table 1 shows the values of the components and the excitation current setting that is used as an example to describe the different configurations. A current excitation of 500 μA determines a self-heating of 0.01 °C of the RTD in the worst case of the smallest RTD.

Table 1. Example of requirements for 4-wire configuration

Component	Value
RTD	Pt100
IEXC	500 µA
Wire resistances ($RL_{1,2,3,4}$)	50 Ω
System operating temperature	–40 °C to 70 °C
Measurement accuracy at room	±0.05 °C
Measurement accuracy over temperature (-40 °C to 70 °C)	±1 °C
Temperature drift	±50 ppm/°C

Table 2. Component values for 4-wire RTDs with NAFE13388/NAFE73388

Component	Value
RF1, RF2, RF3	2.5 kΩ
C1, C2, C3	1 nF
HVDD	15 V
HVSS	–15 V
DZP, DZN	28 V Zener diode

3.1.1 Elements affecting precision

The excitation current flows through the AI2P pin, the RF1, RL1, RTD, and RL4. Because of the 1 GΩ input impedance of the input channels, any mismatch between RL2+RF2 and RL3+RF3 does not affect the measurement accuracy significantly because the current flowing into the input pins is low.

Based on the above consideration, the resulting RTD resistance measurement is then given by:

Equation 2: $R_{RTD} = \frac{V_{RTD}}{IEXC}$

By analyzing Equation 2, the accuracy in the RTD measurement is then given by the accuracy in the voltage reading and in the current excitation. A common procedure to get a high-accuracy measurement is to do zero-scale and full-scale calibration. A 0 Ω and a precise resistance value, close to the RTD maximum resistance, are inserted between S2 and S3 contact points and the resulting voltage readings are corrected by using the NAFE13388/NAFE73388 digital-calibration registers (gain and offset). However, this procedure allows to get the required accuracy at the ambient temperature of the measurement unit only.

At higher or lower temperatures, the system is subjected to additional errors. A common procedure is to have a low-temperature coefficient resistor as a reference for the ADC.

The NAFE13388/NAFE73388 has been designed to implement a ratiometric measurement technique with a low-temperature drift both on the voltage reading channel and on the current excitation. This allows a single calibration point at ambient temperature only without the need for a low-temperature coefficient reference resistor.

So, the total temperature drift introduced by the NAFE13388/NAFE73388 is given by the gain, offset, and current excitation drifts.

As reported in the NAFE13388/NAFE73388 data sheets[2] , the typical gain drift is ±1 ppm/°C. The offset drift is calculated by dividing the value in volts reported in the data sheet by the RTD voltage at the maximum temperature, which is 0.195 mV, so it contributes 0.1 ppm/°C. The excitation drift is ±4 ppm/°C, therefore determining a typical total temperature drift of ±5.1 ppm/°C, which goes to ±17.3 ppm/°C when considering the maximum values.

Table 3. Gain and offset Input temperature drift

Symbol	Parameter	Min	Typ	Max	Unit
GD	Gain drift	-	±1	±2	ppm/°C
OD	Offset drift	-	±0.02	±0.075	µV/°C
IEXC-D	Output current drift	-	4	15	ppm/°C

By considering the operating temperature range defined in Table 1, the total error is then 0.15 °C in the typical case and 0.49 °C in the worst case, therefore meeting the target of ±1° C.

3.1.2 Protection

As shown in the circuit of Figure 2, the NAFE13388/NAFE73388 do not require additional components at the inputs for surge protection. For example, a 1 kV surge pulse at the S2 pin determines a current of 400 mA (1 kV/2.5 kΩ) flowing into AI1P and passing through the internal diode connected to VDD. These internal diodes have been designed to handle a pulsed current of 0.5 A, so the pulse does not damage the NAFE13388/NAFE73388. The resulting voltage spike is then clamped by the Zener diode DZP. The same applies for negative surge voltages that are going through the VSS path.

The NAFE133388/73388 protection architecture allows improvement of RTD measurement accuracy, as well.

For example, the SMBJ33CA is a common protection device available from different semiconductor companies and commonly used to protect the inputs of an RTD system. The SMBJ33CA has a maximum specified leakage current of 1 µA. Figure 3 shows a typical connection of the TVS. The leakage current is sunk from the excitation current on the S2 and S3 connectors. In this case, the excitation current is set at 500 µA, but 1 µA won't go through the RTD. Rather, it goes to the TVS connected to the S2, while the leakage current on S3 has no effect. The TVS determines an error of 0.2 % (1 µA/500 µA).

At room temperature, this error can be corrected by the calibration procedure that compensates for the missing 1 µA.

The leakage current of the TVS determines another type of effect, which is the voltage drop caused by the leakage current on the wire resistances. This effect cannot be compensated for by calibration because the wire resistances are not part of the measurement system when it is calibrated in the manufacturing line. However, also referring to Figure 3, the two voltage drops V_{RL3}, V_{RL2} cancel each other if the leakage current is the same between the two TVSs, and the two wire resistances are also the same.

Equation 3: $V_{(INP\text{-}INN)} = V_{RL3} + V_{RTD} - V_{RL2}$

When the temperature of the system changes, the leakage current increases, so whatever value has been used during the calibration at room temperature, it is no longer valid. Assume an increase of around 100 nA when the temperature goes from 25 °C (calibration temperature) to 100 °C. This current, which is now not flowing through the RTD, determines an error of 0.05 °C in the measurement.

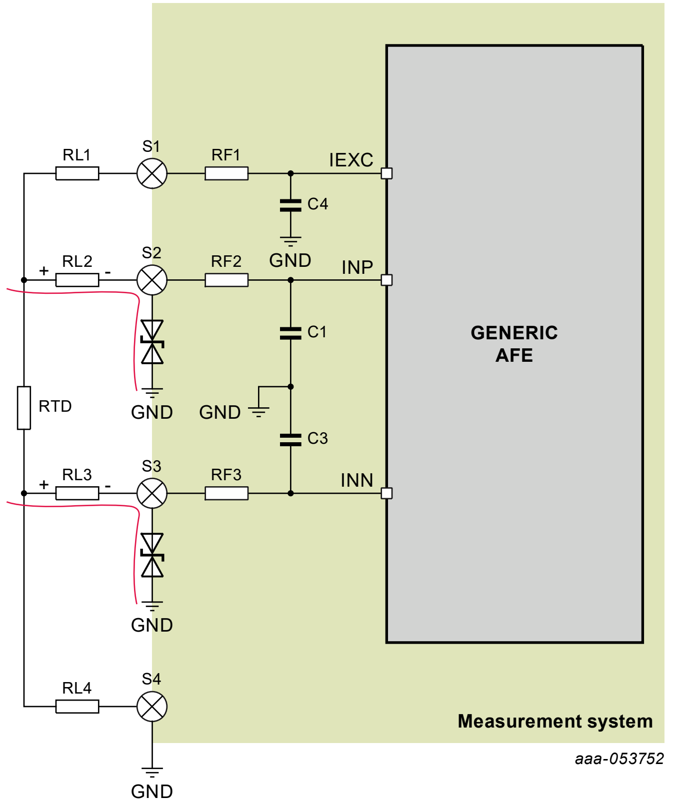

Figure 3. TVS and leakage current path

As a second effect, a 10 % mismatch in the leakage between the two TVSs determines a voltage drop on the wire resistor of 100 nA x 50 ohm = 5 uV equivalent to another 0.03 °C error in RTD measurement.

In summary, the presence of the protection TVS determines an error close to 0.1 °C, which represents 10 % of the target maximum error.

The NAFE13388/NAFE73388 integrated protection diodes have a leakage of 100 pA in the range from –40 °C to 85 °C. This value has a negligible effect on the excitation current flowing through the RTD both at room and at higher temperatures.

However, since this leakage current is now flowing through the filter resistances, the effect of voltage drop must be considered:

Equation 4: $V_{LEAK} = I_{LEAK} \cdot (RF2 + RW2)$

Where

I_{LEAK} = 100 pA;

RF2 = 2.5 kΩ;

RW2 = 50 Ω (maximum wire length);

The resulting value is 0.26 μV, which represents 0.0005 % of the 50 mV generated by a 500 μA excitation current through the Pt100 at 0 °C. This is translated to 0.001 °C, which is below the requirement that has been set.

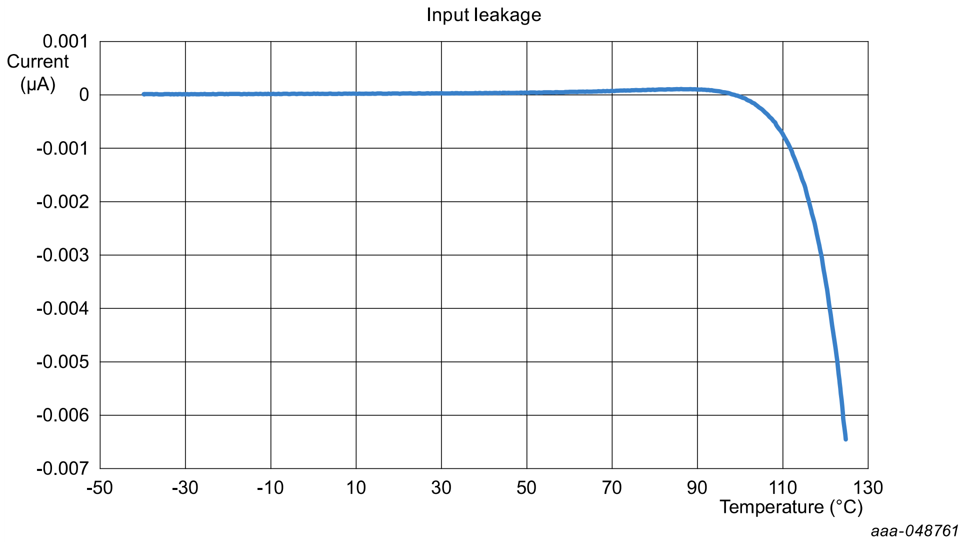

Figure 4. NAFE13388/NAFE73388 Input leakage current

3.2 3-wire RTD measurement

The 3-wire configuration is the most common because it gives a good balance between precision and complexity.

With the NAFE13388/NAFE73388, it is possible to implement the 3-wire configuration either using a dedicated pin for the excitation current or using one of the differential inputs as an excitation source pin. In the first case, three pins of NAFE13388/NAFE73388 are used, while in the second case, two pins are used. The three-pin connection gives the best accuracy, while the two-pin configuration allows measuring up to four RTDs with a single chip.

3.2.1 Configuration using dedicated excitation pin of NAFE13388/NAFE73388

By using a 3-wire RTD with a dedicated pin for the current excitation, the resulting measurement accuracy is very close to the 4-wire configuration.

Figure 5 shows the reference schematic for this configuration. The current is injected through the AI2P pin and flows through RF1, RL1, RTD, and RL3 to ground. The RTD voltage measurement is taken between the AI1P and AIN pins.

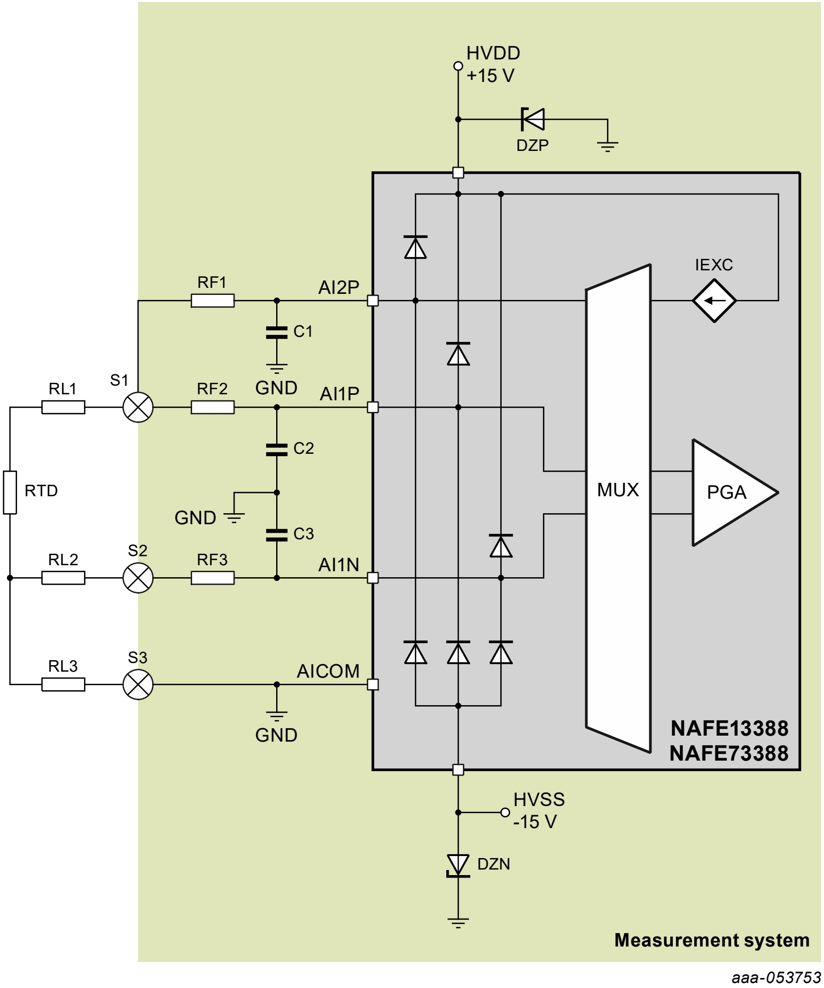

Figure 5. 3-wire RTD with dedicated excitation pin

Consider the various contributions to the measured voltage. As done in the 4-wire configuration, the voltage drop given by the input and leakage current related to the AI1P and AI1N pins can be ignored.

Equation 5: $V_{(AI1P\text{-}AI1N)} = I_{EXC} \cdot (RL1 + R_{RTD})$

Equation 5 shows that the measurement is strongly affected by the RTD wire resistances. The internal multiplexer of NAFE13388/NAFE73388 can do measurements between any input pins including ground and a dedicated pin for pseudo-differential measurement named AICOM.

To reduce the error of Equation 5, the NAFE13388/ NAFE73388 is programmed to measure the voltage between AI1N and AICOM (or GND if AICOM is used for other purposes), which is given by:

Equation 6: $V_{(AI1N\text{-}AICOM)} = I_{EXC} \cdot RL3$

By assuming RL1 ≈ RL3, which is a common assumption in 3-wire RTD measurements, and since the excitation current is sourced by the same current generator used in the measurement of V(INP-VINN), V(AI1P-AI1N) can be corrected by subtracting the result of (VAI1N-AICOM) thus getting the contribution of the RTD resistance only as in the 4-wire configuration.

Equation 7: $V_{(RTD)} = V_{(AI1P\text{-}AI1N)} - V_{(AI1N\text{-}AICOM)} = I_{EXC} \cdot R_{RTD}$

However, because the system needs two measurements instead of one, any unadjusted error in the measurement is accounted twice, so a lower accuracy than a 4-wire measurement can be expected.

The NAFE13388/NAFE73388 simplifies the above procedure thanks to its embedded programmable state machine, which can store 16 different configurations for mux, PGA gain, excitation current, gain, and offset calibration pairs. The 16 configurations are also linked to the corresponding digital data that has been read. The system is then able to offer 16 logical channels that the host MCU has to configure just once at the startup, and then it gets the readings without any additional transaction on the SPI bus, except for the reading command.

In the above case, the logical channel 0 (LCH0) is configured to measure the voltage between AI1P and AI1N, while logical channel 1 (LCH1) is configured to measure the voltage between AI1N and AICOM.

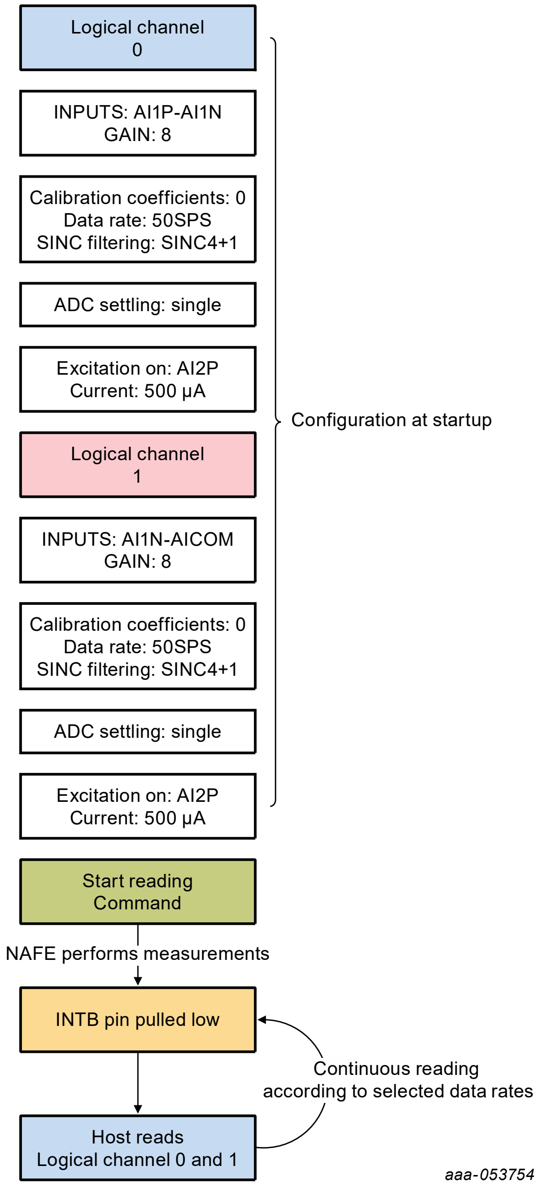

Figure 6. Logical channels configuration for 3-wire RTD

Once the two measurements are done, the NAFE13388/NAFE73388 advises the MCU that the data are ready through its interrupt pin (INT). The MCU reads them all at once and applies the subtraction of Equation 7 to get the corrected RTD voltage value.

3.2.2 Configuration using shared excitation and reading pin

Because all the pins of NAFE13388/NAFE73388 can be used as input and/or current excitation, it is possible to use the same pin to both inject current and measure voltage. This is shown in Figure 10. The current generator IEXC is now routed to the AI1P pin through the internal mux.

The main advantage of this configuration is, by using two inputs of the NAFE13388/NAFE73388, up to four different 3-wire RTDs can be measured with one chip. The disadvantage is now the excitation current passes across the RF2 and RL1 resistor, therefore determining a voltage drop that is measured by the reading channel.

The voltage between AI1P and AI1N is now given by:

Equation 8: $V_{(AI1P\text{-}AI1N)} = I_{EXC} \cdot (RF2 + RL1 + R_{RTD})$

Also in this case, performing the second measurement described in Equation 6 to get the value of I_{EXC} · RL3, assuming RL1 = RL3, and subtracting the known value of I_{EXC} · RL1 from Equation 8, the following equation can be written:

Equation 9: $V_{(AIP\text{-}AIN)} = I_{EXC} \cdot (RF2 + R_{RTD})$

The voltage across the RTD is still affected by the RF2 contribution. The NAFE13388/NAFE73388 flexibility is of help in removing this factor in the equation as done for RL1.

The IEXC current generator is now routed to AI1N and the voltage between AI1N and AICOM is also measured:

Equation 10: $V_{(AI1N\text{-}AICOM)} = I_{EXC} \cdot (RF3 + RL2 + RL3)$

Assuming again RL2 = RL3 and being I_{EXC} · RL3 is already measured, it is possible to calculate the voltage drop given by RF3 only:

Equation 11: $V_{(RF3)} = V_{(AI1N\text{-}AICOM)} - 2 \cdot I_{EXC} \cdot RL3 = I_{EXC} \cdot RF3$

If RF3 and RF2 are chosen to be of the same type or a matched resistor pair is used, assume RF2 ≈ RF3 and subtract I_{EXC} · RF2 from Equation 9, therefore obtaining the voltage given by the RTD only.

Also, any absolute value difference between RF2 and RF3 at room temperature is compensated during the calibration procedure, leaving uncorrected just the temperature mismatch of the two resistors.

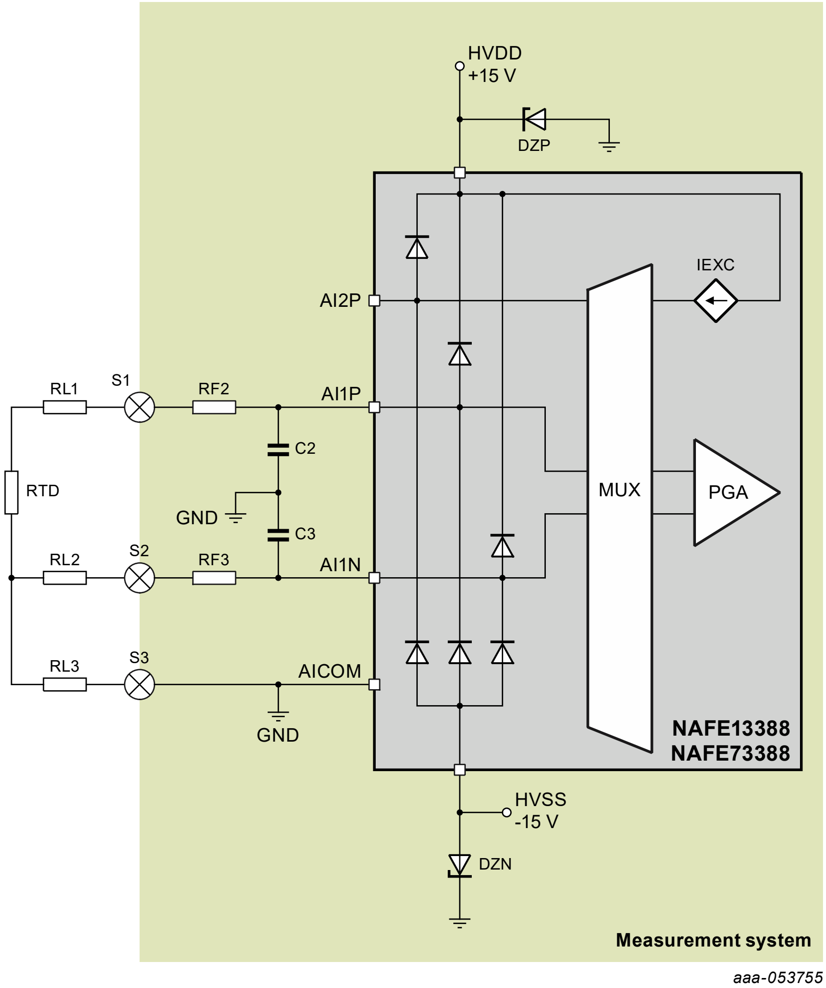

Figure 7. 3-wire RTD with shared excitation pin

3.3 2-wire RTD measurement

The 2-wire RTD measurement is the simplest one, but also the least accurate. As seen in the 3-wire RTD configuration, the NAFE13388/NAFE73388 allows two possible connections: one with a dedicated excitation pin and one with a shared excitation and reading pin. In multiple RTD systems, one NAFE13388/NAFE73388 can measure up to four different RTDs using dedicated excitation pins, while it can measure up to eight RTDs with shared pins.

3.3.1 Configuration using dedicated excitation pin

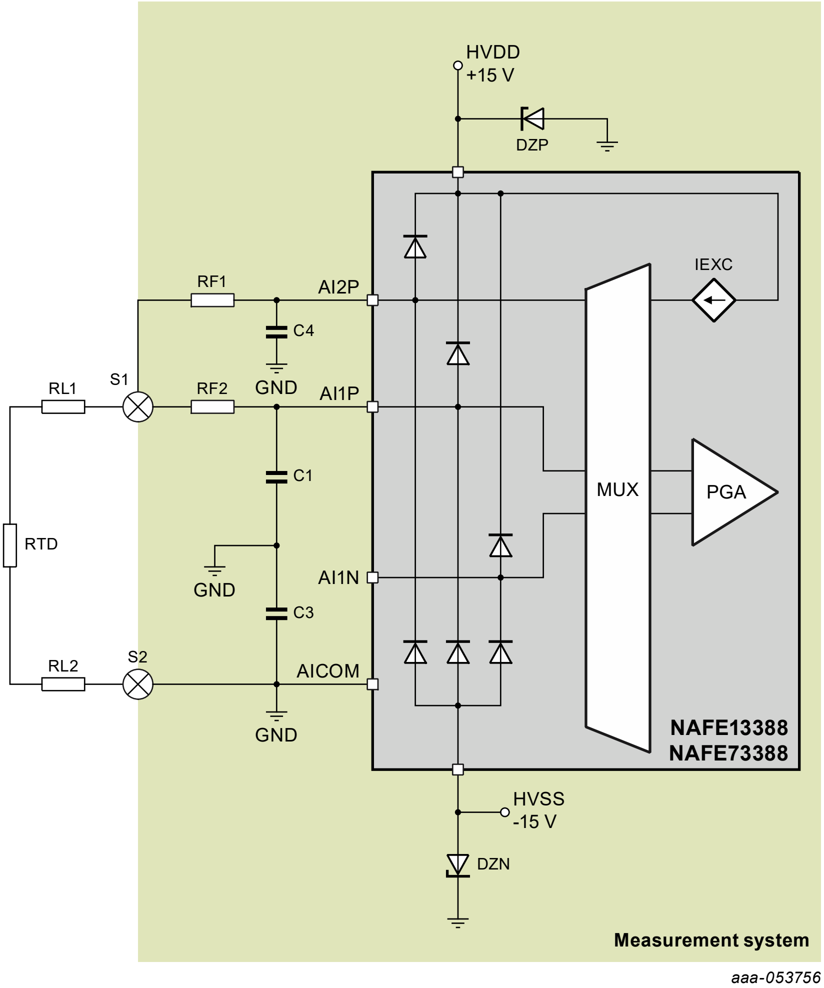

Figure 8. 2-wire RTD with dedicated excitation pin

The current generator IEXC is routed to the AI2P pin through the internal mux. The resulting voltage is measured between AI1P and AICOM. Assuming again no current is flowing into AI1P and AICOM thanks to the high-impedance value of the input stage, the voltage measured results from the following:

Equation 12: $V_{(AI1P\text{-}AICOM)} = I_{EXC} \cdot (RL1 + R_{RTD} + RL2)$

This time there is no way to estimate or measure the wire resistance RL1 or RL2. So, the resulting voltage measurement contains the error given by those resistors.

However, to minimize the impact of these resistors, it is recommended to have R_{RTD} >> RL1. So a Pt1000 RTD with short wire connection is a configuration where the error can be acceptable.

3.3.2 Configuration using shared excitation and reading pins

This configuration is the most efficient in multiple RTD measurement systems.

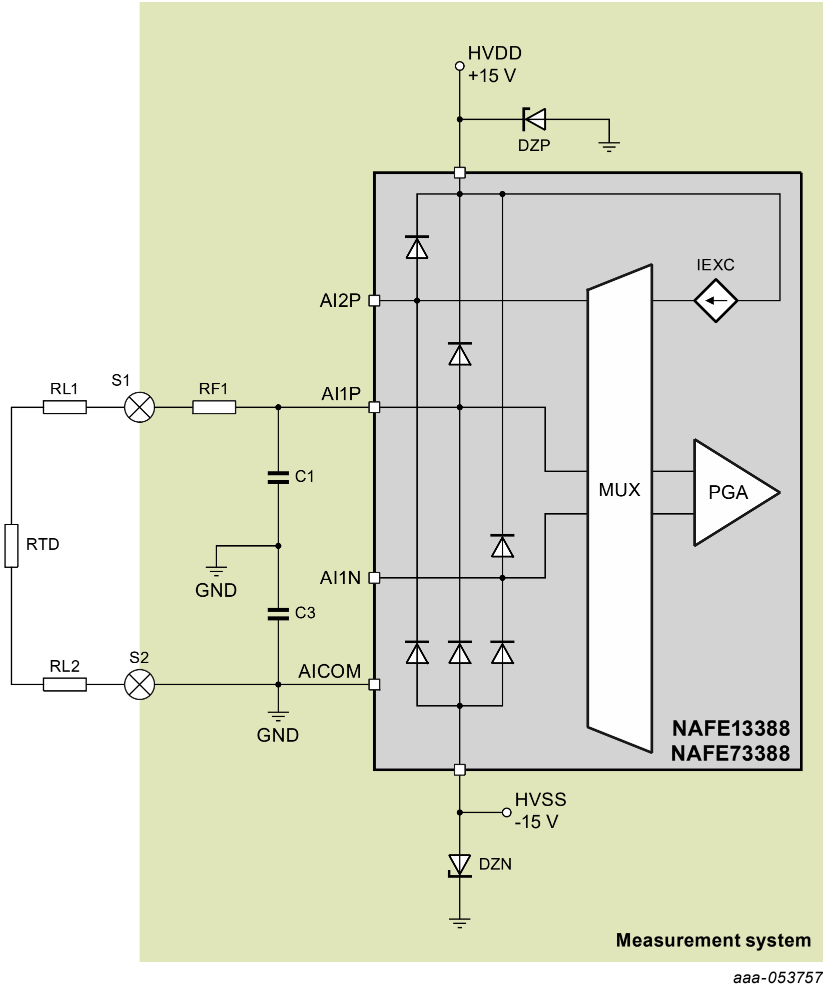

Figure 9. 2-wire configuration with shared excitation and reading pins

The current generator is routed to AI1P and the resulting voltage is measured between the same AI1P and AICOM.

The resulting measured voltage is given by:

Equation 13: $V_{(AI1P\text{-}A1COM)} = I_{EXC} \cdot (RF1 + RL1 + R_{RTD} + RL2)$

As in the 3-wire RTD with the shared excitation pin, now the resistor of the antialiasing filter RF1 takes part in the voltage measurement. Performing a calibration procedure at a given temperature t0, the impact of RF1 is canceled. At a different temperature of the system, the variation of RF1 creates an additional error. It is recommended then to select a low-temperature drift resistor in order to match the system requirements in terms of accuracy.

4 Configuration for software configurable 2-, 3-, 4- wire RTD measurement

Because of the software configurability of NAFE13388/NAFE73388, all the above-described configurations can be implemented with the same hardware design.

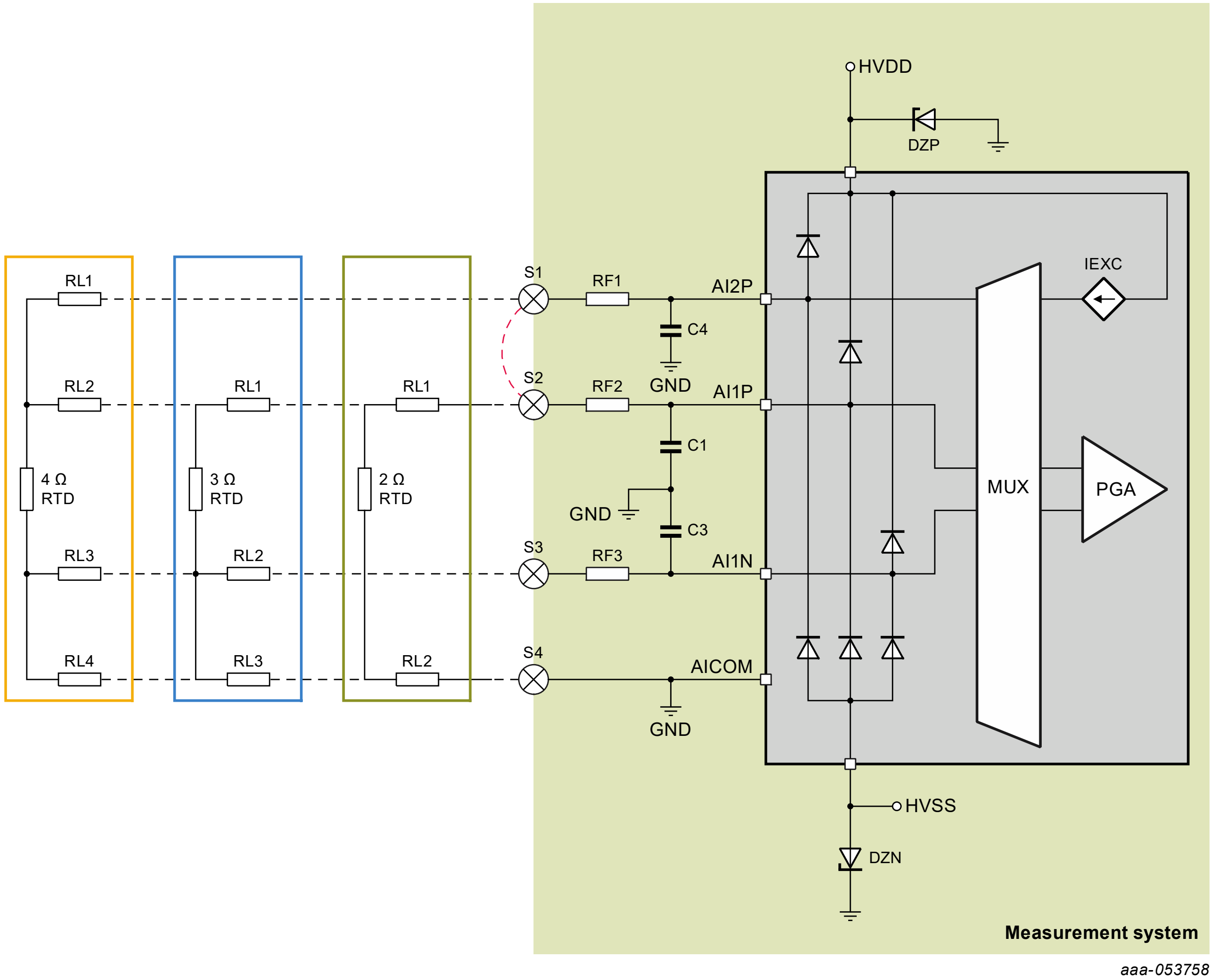

Figure 10. Software configurable RTDs connection

Each of the NAFE13388/NAFE73388 input pins is connected to a screw terminal. By configuring the NAFE13388/NAFE73388 registers through its SPI, the current excitation can be routed to any of the screw terminals and the related voltage reading can be done to any input pair. Some configurations need an additional jumper on two screw terminals to be implemented (red line in Figure 10). Figure 10 shows the connections for RTD1 indicated in Table 4.

Table 4. Multiple RTD configurations with one NAFE13388/NAFE73388

Short name	RTD configuration	# of RTDs	IEXC pin	Voltage reading pins
4w	4-wire	3	RTD1: AI2P RTD2: AI4P RTD3: AI2N	RTD1: AI1P-AI1N RTD2: AI3P-AI3N RTD3: AI4N-AICOM
3wA	3-wire/dedicated IEXC	3	RTD1: AI2P RTD2: AI4P RTD3: AI2N	RTD1: AI1P-AI1N RTD2: AI3P-AI3N RTD3: AI4N-AICOM
3wB	3-wire/shared IEXC	4	RTD1: AI1P RTD2: AI2P RTD3: AI3P RTD4: AI4P	RTD1: AI1P-AI1N RTD2: AI2P-AI2N RTD3: AI3P-AI3N RTD4: AI4P-AI4N
2wA	2-wire/dedicated IEXC	4	RTD1: AI2P RTD2: AI3P RTD3: AI2N RTD4: AI3N	RTD1: AI1P-AICOM RTD2: AI4P-AICOM RTD3: AI1N-AICOM RTD4: AI4N-AICOM
2wB	2-wire/shared IEXC	8	RTD1: AI1P RTD2: AI2P RTD3: AI3P RTD4: AI4P RTD5: AI1N RTD6: AI2N RTD7: AI3N RTD8: AI4N	RTD1: AI1P-AICOM RTD2: AI2P-AICOM RTD3: AI3P-AICOM RTD4: AI4P-AICOM RTD5: AI1N-AICOM RTD6: AI2N-AICOM RTD7: AI3N-AICOM RTD8: AI4N-AICOM

For example, in order to implement the configuration 3wA, S1 and S2 need to be shorted so the current can flow on one of the three wires of the RTD. Also, in the event some pins of NAFE13388/NAFE73388 are free, they can be used for mixed configuration. For example, in case of 4-wire RTD, the pins AI2N and AI4N can be used for another 2-wire RTD in 2wA configuration.

5 Summary

The NAFE13388/NAFE73388 family of products allows a designer to implement a fully integrated RTD measurement system. Because of integrated protections, the accuracy performances are not affected by external protection components' leakage and temperature drifts.

The high-precision, low-drift integrated current excitation source gives flexibility to the measurement system. In 3-wire RTD, one current injection path is used instead of the two matched current sources used in other solutions. This feature gives the possibility to optimize the system according to the required specifications with up to eight RTDs supported by one NAFE13388/NAFE73388.

The large Common mode voltage range allows for the use of large resistors in the current path without limiting the current generators headroom. Also, there is no need for a bias resistor to precisely convert the RTD voltage to the voltage range of the input channel.

6 Revision history

Table 5. Revision history

Rev	Date	Description
AN14127 v2.0	04 December 2024	• Updated references to equations throughout. • Updated Figure 3. • Updated Legal information.
AN14127 v.1.0	18 January 2024	Initial version

7 References

[1] Relation Temperature vs. Resistance According to IEC60751 / ITS-90

[2] NAFE13388 NAFE13388/NAFE73388 data sheets

[3] American Wire Gauge (AWG) standardized wire gauge system

Legal information

Definitions

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