PT100 FMMD analysis

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April 1, 2010

Abstract

The PT100, or platinum wire 100Ω sensor is a widely used industrial temperature sensor that is slowly replacing the use of thermocouples in many industrial applications below 600^oC, due to high accuracy[?].

This chapter looks at the most common configuration, the four wire circuit, and analyses it from an FMEA perspective twice. Once considering single faults (cardinality constrained powerset of 1) and then again, considering the possibility of double faults (cardinality constrained powerset of 2).

The analysis is performed using Propositional Logic diagrams to assist the reasoning process. This chapter describes taking the failure modes of the components, analysing the circuit using FMEA and producing a failure mode model for the circuit as a whole. Thus after the analysis the PT100 temperature sensing circuit, may be veiwed from an FMEA persepective as a component itself, with a set of known failure modes.

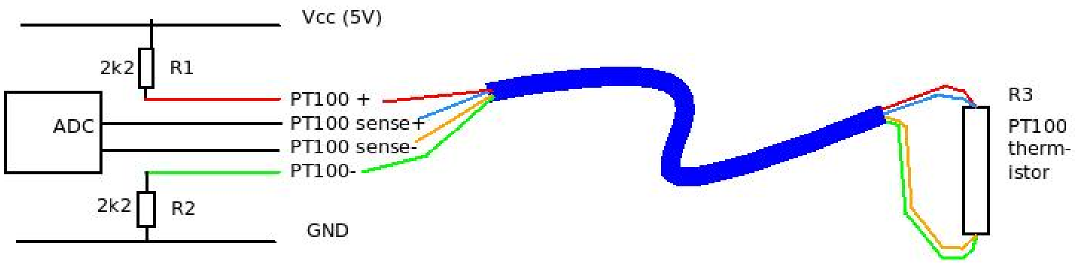

Figure 1: PT100 four wire circuit

1 Overview of PT100 four wire circuit

The PT100 four wire circuit uses two wires to supply small electrical current, and returns two sense volages by the other two. By measuring volatges from sections of this circuit forming potential dividers, we can determine the resistance of the platinum wire sensor. The resistance of this is directly related to temperature, and may be determined by look-up tables or a suitable polynomial expression.

The voltage ranges we expect from this three stage potential divider are shown in figure 2. Note that there is an expected range for each reading, for a given temperature span. Note that the low reading goes down as temperature increases, and the higher reading goes up. For this reason the low reading will be reffered to as *sense-* and the higher as *sense+*.

1.1 Accuracy despite variable resistance in cables

For electronic and accuracy reasons a four wire circuit is preffered because of resistance in the cables. Resistance from the supply causes a slight voltage drop in the supply to the PT100. As no significant

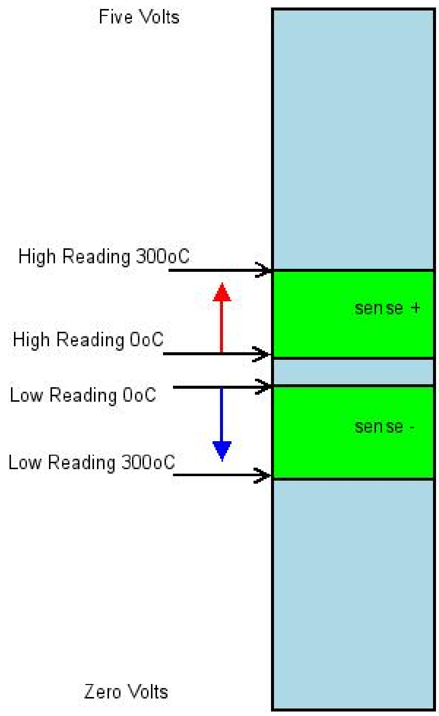

Figure 2: PT100 expected voltage ranges

current is carried by the two ‘sense’ lines the resistance back to the ADC causes only a negligible voltage drop, and thus the four wire configuration is more accurate.

1.2 Calculating Temperature from the sense line voltages

The current flowing though the whole circuit can be measured on the PCB by reading a third sense voltage from one of the load resistors. Knowing the current flowing through the circuit and knowing the voltage drop over the PT100, we can calculate its resistance by ohms law $V = I.R$, $R = \frac{V}{I}$. Thus a little loss of supply current due to resistance in the cables does not impinge on accuracy. The resistance to temperature conversion is achieved through the published PT100 tables[**?**].

2 Safety case for 4 wire circuit

This sub-section looks at the behaviour of the PT100 four wire circuit for the effects of component failures. All components have a set of known ‘failure modes’. In other words we know that a given component can fail in several distinct ways. Studies have been published which list common component types and their sets of failure modes, often with MTTF statistics [**?**]. Thus for each component, an analysis is made for each of it failure modes, with respect to its effect on the circuit. Each one of these scenarios is termed a ‘test case’. The resultant circuit behaviour for each of these test cases is noted. The worst case for this type of analysis would be a fault that we cannot detect. Where this occurs a circuit re-design is probably the only sensible course of action.

2.1 Single Fault FMEA Analysis of PT100 Four wire circuit

This circuit simply consists of three resistors. Resistors according to the DOD Electronic component fault handbook 1991, fail by either going OPEN or SHORT circuit [?]. For the purpose of this analyis; R_1 is the $2k2\Omega$ from 5V to the thermistor, R_3 is the PT100 thermistor and R_2 connects the thermistor to ground.

We can define the terms 'High Fault' and 'Low Fault' here, with reference to figure 2. Should we get a reading outside the safe green zone in the diagram we can consider this a fault. Should the reading be above its expected range this is a 'High Fault' and if below a 'Low Fault'.

Table 1 plays through the scenarios of each of the resistors failing in both SHORT and OPEN failure modes, and hypothesises an error condition in the readings. The range 0^oC to 300^oC will be analysed using potential divider equations to determine out of range voltage limits in section 2.

Table 1: PT100 FMEA Single Faults

Test Case	**Result sense +**	**Result sense -**	**General Symtom Description**
R_1 SHORT	High Fault	-	Value Out of Range Value
R_1 OPEN	Low Fault	Low Fault	Both values out of range
R_3 SHORT	Low Fault	High Fault	Both values out of range
R_3 OPEN	High Fault	Low Fault	Both values out of range
R_2 SHORT	-	Low Fault	Value Out of Range Value
R_2 OPEN	High Fault	High Fault	Both values out of range

From table 1 it can be seen that any component failure in the circuit should cause a common symptom, that of one or more of the values being 'out of range'. Temperature range calculations and detailed calculations on the effects of each test case are found in section **??** and 2.2.

2.2 Range and PT100 Calculations

PT100 resistors are designed to have a resistance of 100Ω at 0^oC [?],[?]. A suitable 'wider than to be expected range' was considered to be 0^oC to 300^oC for a given application. According to the Eurotherm PT100 tables [?], this corresponded to the resistances 100Ω and 212.02Ω respectively. From this the potential divider circuit can be analysed and the maximum and minimum acceptable voltages determined. These can be used as bounds results to apply the findings from the PT100 FMEA analysis in section 2.1.

As the PT100 forms a potential divider with the $2k2\Omega$ load resistors, the upper and lower readings can be calculated thus:

$$highreading = 5V.\frac{2k2 + pt100}{2k2 + 2k2 + pt100}$$

$$lowreading = 5V.\frac{2k2}{2k2 + 2k2 + pt100}$$

So by defining an acceptable measurement/temperature range, and ensuring the values are always within these bounds we can be confident that none of the resistors in this circuit has failed.

To convert these to twelve bit ADC ($\mathcal{ADC}_{12}$) counts:

$$highreading = 2^{12}.\frac{2k2 + pt100}{2k2 + 2k2 + pt100}$$

$$lowreading = 2^{12}.\frac{2k2}{2k2 + 2k2 + pt100}$$

Table 2: PT100 Maximum and Minimum Values

Temperature	**PT100 resistance**	**Lower**	**Higher**	**Description**
0 ^oC	100Ω	2.44V $2002\mathcal{ADC}_{12}$	2.56V $2094\mathcal{ADC}_{12}$	Boundary of out of range LOW
+300 ^oC	212.02Ω	2.38V $1954\mathcal{ADC}_{12}$	2.62V $2142\mathcal{ADC}_{12}$	Boundary of out of range HIGH

Table 2 gives ranges that determine correct operation. In fact it can be shown that for any single error (short or opening of any resistor) this bounds check will detect it.

3 Single Fault FMEA Analysis of PT100 Four wire circuit

3.1 Single Fault Modes as PLD

The component failure modes in table 1 can be represented as contours on a PLD diagram. Each test case, is defined by the contours that enclose it. The test cases here deal with single faults only and are thus enclosed by one contour each.

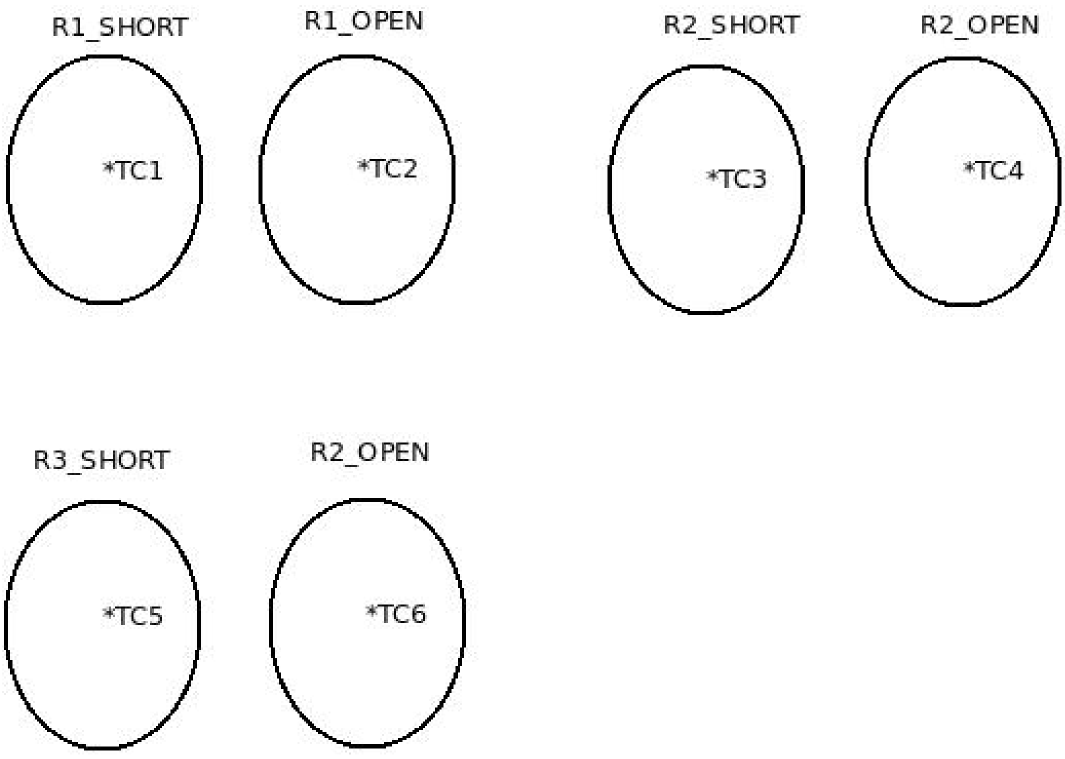

Figure 3: PT100 Component Failure Modes

This circuit supplies two results, sense+ and sense- voltage readings. To establish the valid voltage ranges for these, and knowing our valid temperature range for this example (0^oC .. 300^oC) we can calculate valid voltage reading ranges by using the standard voltage divider equation 1 for the circuit shown in figure 4.

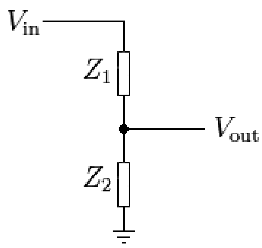

Figure 4: Voltage Divider

$$V_{out} = V_{in} . \frac{Z2}{Z2 + Z1} \tag{1}$$

3.2 Proof of Out of Range Values for Failures

Using the temperature ranges defined above we can compare the voltages we would get from the resistor failures to prove that they are 'out of range'. There are six test cases and each will be examined in turn.

3.2.1 TC1 : Voltages R_1 SHORT

With pt100 at 0^oC

$$highreading = 5V$$

Since the highreading or sense+ is directly connected to the 5V rail, both temperature readings will be 5V..

$$lowreading = 5V . \frac{2k2}{2k2 + 100\Omega} = 4.78V$$

With pt100 at the high end of the temperature range 300^oC.

$$highreading = 5V$$

$$lowreading = 5V . \frac{2k2}{2k2 + 212.02\Omega} = 4.56V$$

Thus with R_1 shorted both readingare outside the proscribed range in table 2.

3.2.2 TC2 : Voltages R_1 OPEN

In this case the 5V rail is disconnected. All voltages read are 0V, and therefore both readings are outside the proscribed range in table 2.

3.2.3 TC 3 : Voltages R_2 SHORT

With pt100 at 0^oC

$$lowreading = 0V$$

Since the lowreading or sense- is directly connected to the 0V rail, both temperature readings will be 0V.

$$lowreading = 5V . \frac{100\Omega}{2k2 + 100\Omega} = 0.218V$$

With pt100 at the high end of the temperature range 300^oC.

$$highreading = 5V$$

$$lowreading = 5V.\frac{212.02\Omega}{2k2 + 212.02\Omega} = 0.44V$$

Thus with R_2 shorted both readings are outside the proscribed range in table 2.

3.2.4 TC : 4 Voltages R_2 OPEN

Here there is no potential divider operating and both sense lines will read 5V, outside of the proscribed range.

3.2.5 TC 5 : Voltages R_3 SHORT

Here the potential divider is simply between the two 2k2 load resistors. Thus it will read a nominal; 2.5V.

Assuming the load resistors are precision components, and then taking an absolute worst case of 1% either way.

$$5V.\frac{2k2 * 0.99}{2k2 * 1.01 + 2k2 * 0.99} = 2.475V$$

$$5V.\frac{2k2 * 1.01}{2k2 * 1.01 + 2k2 * 0.99} = 2.525V$$

These readings both lie outside the proscribed range. Also the sense+ and sense- readings would have the same value.

3.2.6 TC 6 : Voltages R_3 OPEN

Here the potential divider is broken. The sense- will read 0V and the sense+ will read 5V. Both readings are outside the proscribed range.

3.3 Summary of Analysis

All six test cases have been analysed and the results agree with the hypothesis put in Table 1. The PLD diagram, can now be used to collect the symptoms. In this case there is a common and easily detected symptom for all these single resistor faults : Voltage out of range.

A spider can be drawn on the PLD diagram to this effect.

In practical use, by defining an acceptable measurement/temperature range, and ensuring the values are always within these bounds we can be confident that none of the resistors in this circuit has failed.

The PT100 circuit can now be treated as a component in its own right, and has one failure mode, **O**UT_OF_RANGE. It can now be represnted as a PLD see figure 6.

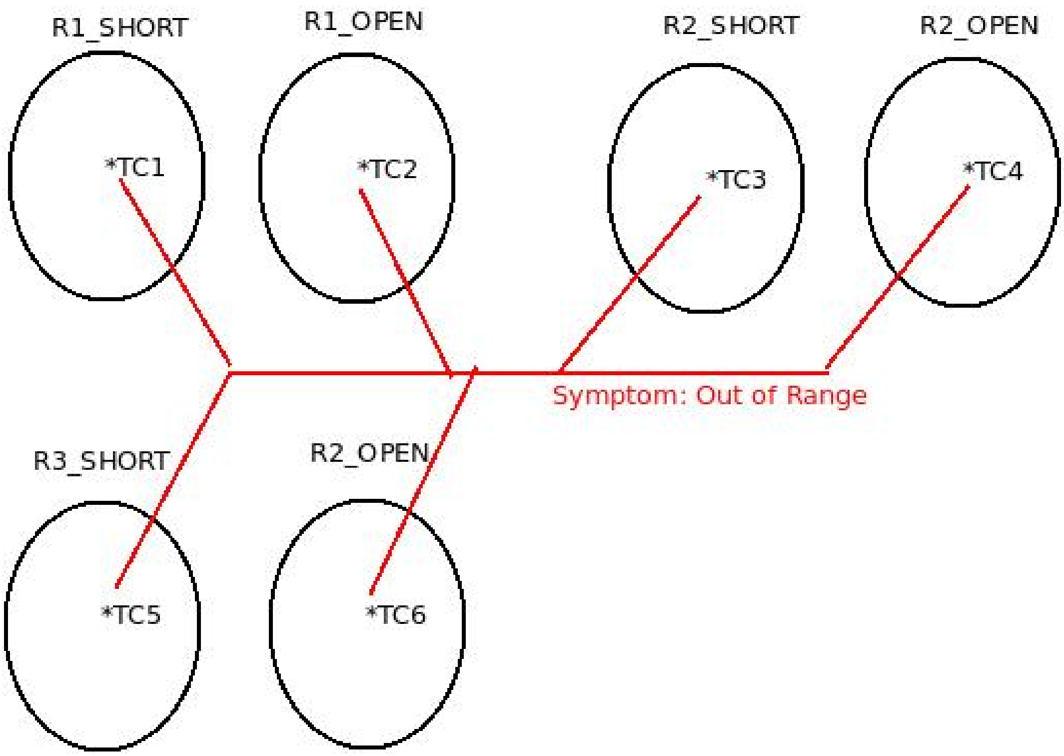

Figure 5: PT100 Component Failure Modes

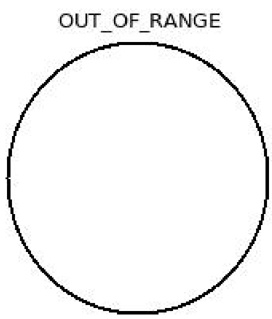

Figure 6: PT100 Circuit Failure Modes : From Single Faults Analysis

3.4 Mean Time to Failure

Using the MIL1991[?] specifications for resistor and thermistor failure statistics we calculate the reliability of this circuit. MIL1991 gives MTTF for a wide range of common components. It does not specify how the components will fail (in this case OPEN or SHORT). Some standards, notably EN298 only consider resistors failing in OPEN mode. FMD-97 Gives 27% OPEN and 3% SHORTED, for resistors under certain electrical and environmental stresses. This example compromises and uses a 90:10 ratio, for resistor failure. Thus for this example resistors are expevcted to fail OPEN in 90% of cases and SHORTED in the other 10%.

A standard fixed film resistor, for use in a benign environment, non military spec at temperatures up to $60^oC$is given a probability of 13.8 failures per billion (10^9) hours of operation. This figure is referred to as a FIT[1], Failure in time.

A thermistor, bead type, non military spec is given a FIT of 3150.

Using the RIAC finding we can draw up the following table (table 3), showing the FIT values for all faults considered.

Table 3: PT100 FMEA Single // Fault Statistics

Test Case	**Result sense +**	**Result sense -**	**MTTF per 10^9 hours of operation**
TC:1 R_1 SHORT	High Fault	-	12.42
TC:2 R_1 OPEN	Low Fault	Low Fault	1.38
TC:3 R_3 SHORT	Low Fault	High Fault	2835
TC:4 R_3 OPEN	High Fault	Low Fault	315
TC:5 R_2 SHORT	-	Low Fault	12.42
TC:6 R_2 OPEN	High Fault	High Fault	1.38

The FIT for the circuit as a whole is the sum of MTTF values for all the test cases. The PT100 circuit here has a FIT of 3177.6. This is a MTTF of about 360 years per circuit.

A Probablistic tree can now be drawn, with a FIT value for the PT100 circuit and FIT values for all the component fault modes that it was calculated from. We can see from this that that the most likely fault is the thermistor going OPEN. This circuit is 8 times more likely to fail in this way than in any other. Were we to need a more reliable temperature sensor this would probably be the fault mode we would scrutinise first.

The PT100 analysis presents a simple result for single faults. The next analysis phase looks at how the circuit will behave under double simultaneous failure conditions.

Notes:

[1]FIT values are measured as the number of failures per billion hours of operation, (roughly 1.1 Million years). The smaller the FIT number the more reliable the fault mode

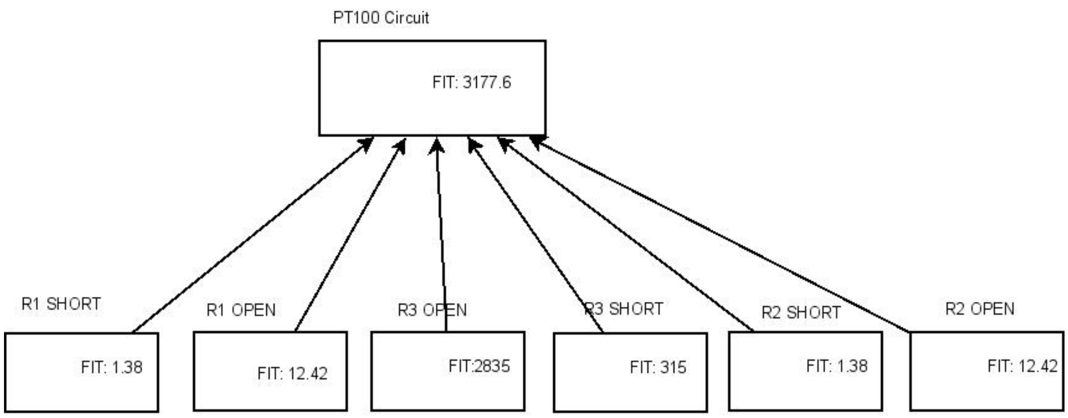

Figure 7: Probablistic Fault Tree : PT100 Single Faults

4 PT100 Double Simultaneous Fault Analysis

April 1, 2010