Calibration of an industrial data acquisition system used in a solar heating plant

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Abstract. The use of data acquisition systems is essential when it is necessary to measure certain physical quantities involved in a particular process. The equipment must have a certain degree of reliability since all values taken by the acquisition system must be as close as possible to the values obtained by the measuring instruments. In this context, this article assesses the challenge concerning the calibration of data acquisition system used in solar heating plant, in order to determine the metrological reliability of the equipment. The calibration procedure consists of comparing the input signal from a calibrated signal generator, to the indicated value by the acquisition system. The difference between the two values is then treated statistically, resulting in an uncertainty analysis to be used for assessing the equipment reliability.

1. Introduction
The electric power market in Brazil is very competitive. For this reason, many thermoelectric power plants are constantly looking for new technologies aiming to reduce electricity generation costs. The solar heating plant consists of five independent 200 m² solar heating plants, each one for preheating one (8.7 MW) of the five selected engines and the fuel oil, out of the 38 engine thermoelectric power plant. In order to keep track of its performance, a data acquisition equipment is used for measuring the output electric current (4 to 20 mA), from temperature and pressure sensors, and frequency (Hz), from flow sensors, installed in selected positions of the hydraulic circuit.

In the thermoelectric power plant of this study, the thermal radiation absorbed by each solar heating system is used to complement the thermal energy necessary to heat the coupled engine and keep it ready for a quick start operation, by preheating the water that circulates between a steam boiler and the engine, thus saving fuel oil. Sometimes, when the water becomes hotter than what is needed because of the excess solar energy, the fuel oil is also preheated, thus improving the energy usage.

2. Operation
The data acquisition system consists of one independent module for each independent solar heating plant, totaling 5 independent modules. Each module has 10 analog input channels, 8 for temperature sensors and 2 for pressure sensors, and 4 digital signal frequency channels for flow sensors. Every 1/60 s, the module scans all channels. The measured values (mA or Hz) are then averaged over a 1 minute period and sent directly to a server, where they are stored in a file. Every hour, a coupled
monitoring software reads all values (every minute) and converts them into temperature, pressure or flow rate units. The results are then stored in another file for customer consultation.

3. Test procedures
The test procedure consists of comparing the output values of the data acquisition system and the reference instrument. Reference currents in the range of 4 to 20 mA, simulating the output from temperature and pressure sensors, were injected into the data acquisition system channels. Likewise, reference frequencies in the range of 0 to 100 Hz, simulating the output from flow sensors, were injected into the data acquisition system channels. All reference instruments had been properly calibrated by a Brazilian Calibration Network accredited laboratory.

During the tests, after the equipment having reached the steady state condition, a very stable reference current was injected into the data acquisition system, with its output integrated over a one minute period, simulating the system monitoring frequency. The average value between three consecutive outputs, when the maximum difference between each other was 1 μA, was considered to be the most probable output value from the data acquisition system. The measurement systematic error was calculated as the difference between the most probable value and the reference current. The maximum difference between the output from the data acquisition system during the tests and the most probable value was considered to be the type B uncertainty of current measurement.

The expanded uncertainty of temperature measurement, U, k = 2, by the data acquisition system, in the 4 to 20 mA output current range, was estimated by calculating the square root of the sum of the squares of three components, all of them converted to temperature units. (a) Type B expanded uncertainty of current measurement, U_{(a)}, k = \sqrt{3}, (b) Expanded uncertainty of converting probe resistance into temperature, according to [2], U_{(b)} = 0.20 °C at 20 °C, k = \sqrt{3}, and, (c) Expanded uncertainty of converting probe resistance into current, U_{(c)} = 0.002 mA (0.0125 °C), according to the manufacturer, k = 2.

\[
u = \sqrt{u_{(a)}^2 + u_{(b)}^2 + u_{(c)}^2}
\]

\[U = k \cdot u\]

A similar procedure was used for testing pressure probes, in the 4 to 20 mA output current range. When estimating the uncertainty of measurement, (b) Expanded uncertainty of converting probe output signal into pressure, U_{(b)} = 10 cm H₂O, obtained from probe calibration curve by the manufacturer, k = 2, and (c) Expanded uncertainty of converting probe signal into current, U_{(c)} = 0.002 mA (1.25 cm H₂O), according to the manufacturer, k = 2.

Likewise, a similar procedure was used to test flowmeters. When estimating the uncertainty of measurement, (b) Expanded uncertainty of converting probe frequency into flow rate, 1% of flow rate, obtained from the probe calibration curve supplied by the manufacturer, U_{(b)}, k = 2, (c) Frequency measurement resolution, 1 Hz (±0.17 m³/h), U_{(c)}, k = \sqrt{3}.

4. Results
During the tests, all electrical current and frequency data were converted into temperature, pressure or flow rate by the respective conversion curve.

| Table 1. Correlation points for conversion from electrical current or frequency to temperature, pressure and flow parameters. |
|---|---|---|---|---|---|
| Temperature | Pressure | Flow Rate |
| Point | mA | °C | mA | cm H₂O | Hz | m³/h |
| 1 | 4.0 | 0.0 | 4.0 | 0.0 | 19 | 3.5 |
| 2 | 20.0 | 100.0 | 20.0 | 1000.0 | 92 | 15.6 |
Figure 1 shows the temperature error measurement by 8 temperature channels in each of the 5 modules. It can be seen that for temperature values smaller than 20 °C the data acquisition system measures it with a large error. For larger temperature values, almost all errors are in the ± 0.3 °C range, which should be considered as a Type B uncertainty of measurement if no distinction is made between channels.

![Temperature measurement error](image1)

**Figure 1.** Temperature measurement error for channels in each module.

And figure 2 shows the current error measurement by 2 pressure channels in each of the 5 modules. It can be seen that for pressure values smaller than 200 cm H₂O (0.2 bar) the data acquisition system measures it with a large error. For larger pressure values, almost all errors stay in the ± 2 cm H₂O range, also considered as a Type B uncertainty of measurement.

![Pressure measurement error](image2)

**Figure 2.** Pressure measurement error for channels in each module.
The frequency error measurement captured by each flow channel of the 5 modules is shown in figure 3. As others parameters, almost all errors flow values are between ± 1 m³/h, considered as a Type B uncertainty of measurement.

**Figure 3.** Flow rate measurement error for channels in each module.

**Figure 4.** Expanded uncertainty measurement by temperature channels in each module.
Figure 5. Expanded uncertainty measurement by pressure channels in each module.

Figure 6. Expanded uncertainty measurement by flow rate channels in each module.

It can be seen that systematic error is larger than expanded uncertainty of measurement. If no distinction is made between channels, no correction can be made, and the maximum error in figures 1, 2 and 3, can be considered as a Type B uncertainty of measurement, which should be added to the calculated expanded uncertainty of measurement in figures 4, 5 and 6 by the root sum square method. If a smaller uncertainty value is required, the output from the data acquisition system must be
corrected by the systematic error measured in each channel, and the calculated expanded uncertainty of measurement are given by figures 4, 5 and 6. When in operation, if the measured values are not the same as those in the calibration, a linear interpolation between two neighbor points can be made. More precisely, a least square fit can be used as an interpolation scheme for estimating the most probable value and its uncertainty of measurement.

5. Conclusion
This paper presents a methodology for calibrating a data acquisition system with several channels. It includes estimating the most probable value as a function of a required uncertainty of measurement. (a) If there is no distinction between channels, no correction is made, and the uncertainty of measurement becomes large, (b) The reduction of the uncertainty of measurement requires the calibration of each channel, and, (c) interpolation scheme to be used when the measured point does not coincide with the calibrated points.

After correcting the output from the data acquisition system with calibration data, measurement value coincides with the most probable value to within the uncertainty of measurement, which shows the importance of differentiating sensor output value from the system readout. If no correction is made, results give a misleading information about the uncertainty of measurement with the sensors themselves.

The contribution of this paper is to include the uncertainty of measurement of data acquisition system, usually not considered in the uncertainty budget of the quantity being measured, thus better interpreting the results.

References
[1] ISOGUM 1998 Guia para a expressão da incerteza de medição
[2] IEC 60751 Standard, Edition 2.0 2008-07 Industrial platinum resistance thermometers and platinum temperature sensors
[3] Environmental Protection Agency M 2008 Data acquisition and information management QA Handbook. V II Section 14
[4] Jiannong W and Wei W The common data acquisition system based on arm9 2011 The Tenth International Conference on Electronic Measurement & Instruments (ICEMI 2011)
[5] Koutroulis E and Kalaitzakis K 2003 Development of an integrated data-acquisition system for renewable energy sources systems monitoring Renewable Energy 28 (Technical University of Crete - Chania, Greece) p 139-52

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