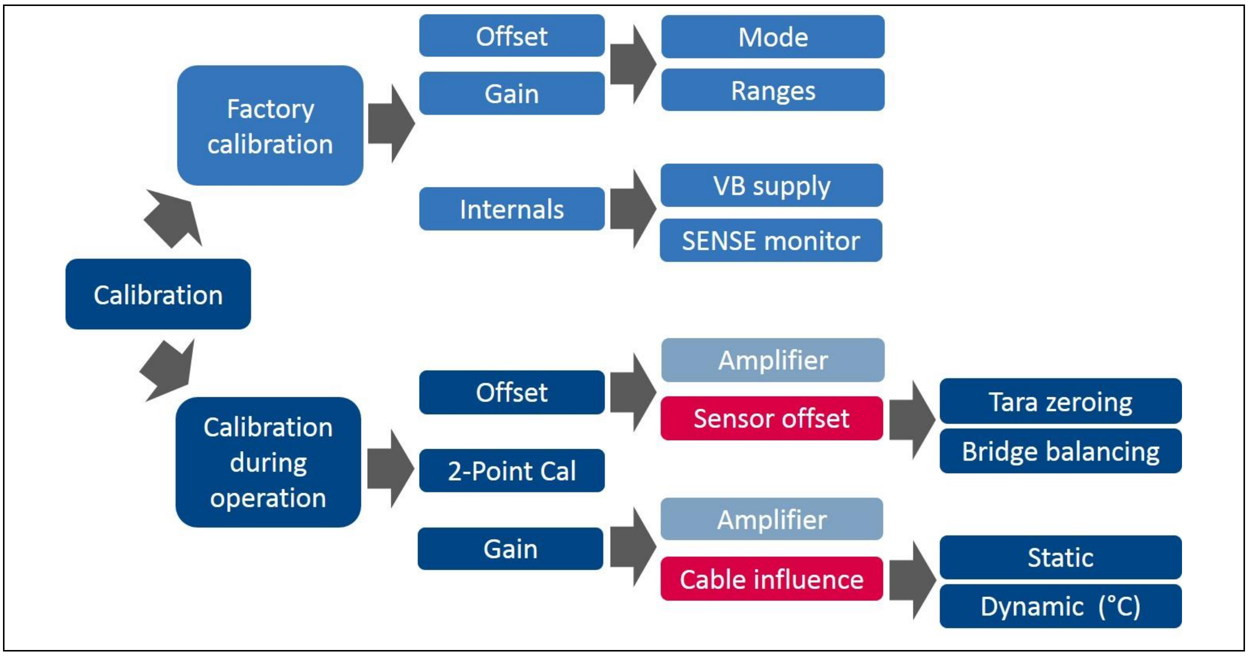
Calibration with Strain gauge and bridge measurements

Whitepaper January 2015 – Martin Riedel

Whoever is testing, expects their measurements to be precise and accurate. Thus, the value given by the measurement device must be consistent and close to the actual value. To ensure the accuracy and precision of a measurement device, it needs to be calibrated regularly. Without getting into the formal definitions and subtle differences between "balancing", "calibration" and "adjustment", the following categories can be distinguished:



Calibration: Concepts and classifications

Offset: Tara vs. Bridge balancing

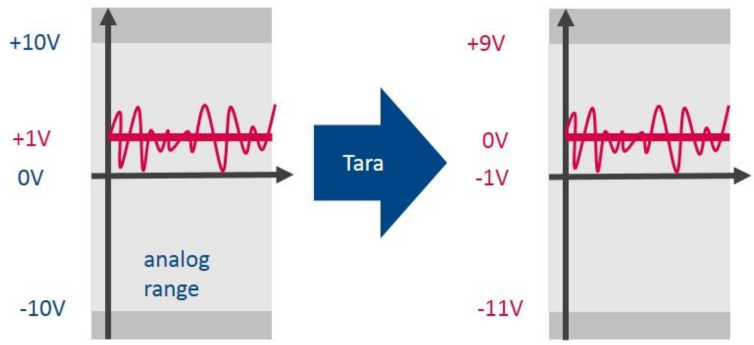
In contrast to the tare zeroing, used in the "simple" mode voltage, the bridge balance can compensate for very large initial values, which are even greater than the selected nominal measurement range itself:

For a bridge circuit, opposing deviations of the individual elements of 0.1% will cause an offset: **+/- 0.1% to → 1 mV/V bridge offset**. While quarter-bridge completion resistors are usually available with such initial precision, conventional strain gauges are typically specified for up to 0.3% production tolerance, resulting in 3 mV/V offset: **easily a multiple of the selected measuring range!**

Tara zeroing performs a simple rescaling, leading to individually different and asymmetrical measurement ranges. In contrast, bridge balancing is based on the provision, that the usable analog operating range of the amplifier is greater than the measurement range, selected by the user. Applying either analog or digital compensation, the effectively used range is then shifted symmetrically about the new "virtual" zero point.

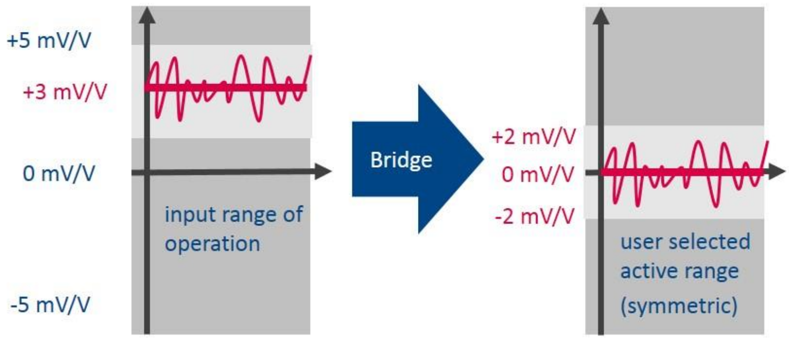
Tara zeroing

- Formal rescaling, only
- Results in individually distinct and asymmetrical ranges (e.g., -11V ... +9V)



Bridge balancing

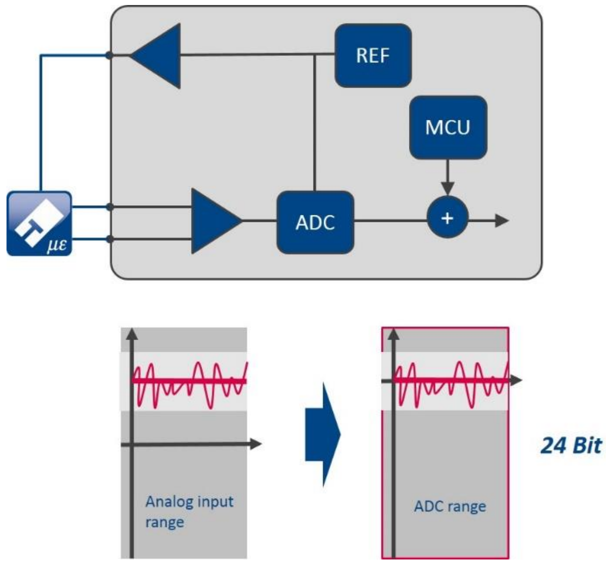
- Offset can be much larger than the selected measurement range!
- Compensation and offset shifting
- Results in uniform and symmetric ranges (e.g., +/- 2mV/V)



Modern digital concepts (such as imc systems) use high-resolution and stable 24-bit ADCs, having enough headroom to digitize the entire offset signal, yet still providing sufficient resolution to fully cover the (much smaller) actively used areas with abundant precision. Thus, the subtraction of the offset can be purely digital and realized absolutely free of drift.

Digital bridge balancing

- Requires ADC to acquire the entire analog input range
- Advanced concept, enabled and driven by modern ADC technology with 24 Bit
- Not depending on ultra-stable analog summing node – but based on stable ADC!



Stability of zeroing/balancing

The situation that bridge offset can take extremely large values, results in the fact, that stability of offset compensation is also determined by the *gain drift* of the system. As initial offset is increasing, it will not remain constant but is subject to gain drift. This possibly unexpected issue is illustrated by the following example:

Initial Offset to be compensated: ***2 mV/V*** @5V corresponding to ***10 mV*** absolute voltage
Gain drift: ***10 ppm / °C***
Resulting equivalent offset drift: 10 mV * 10 ppm / °C = ***0.1 µV / °C***

This “gain induced drift” is about the same order of magnitude as a typical input amplifier precision, in terms of its "direct" input stage offset drift.

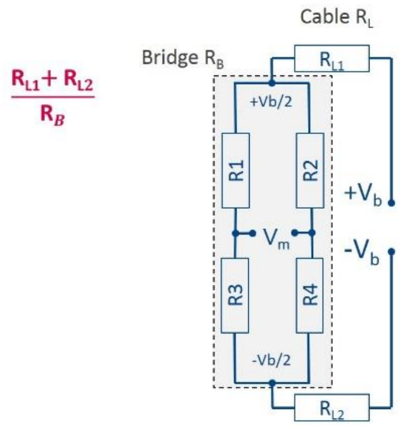
Gain error due to cable resistance

Cable resistances in the supply lines cause an attenuation of the excitation voltage that is actually effective at the remote sensor location: Following the basic resistive divider rule, the ratio of bridge impedance to the sum of the cable resistance is crucial. This "loss" can be compensated by applying additional “Kelvin sensing” leads (SENSE).

E.g.,: The thinnest wire customary in sensor instrumentation:
Copper size 0.14mm² (equivalent AWG26)

- ***0.14mm² == 130 mΩ / m***
- ***10 m*** lead wire, feed and return lead → double
- Worst case: low impedance bridge
  (120 Ω full-bridge → common in Europe…)
- Typical: 2 x 1.3 Ω / ***350 Ω*** →approx. 0.7%

10 m → *0.7 % Gain error*

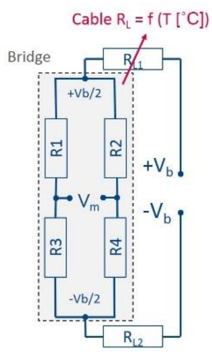


Dynamic temperature drift of cable resistance

Will it be sufficient to perform a one-time compensation of the static gain error prior to the measurement, i.e., after installation, or must the correction even be tracked during the running measurement operation? For outdoor test drive applications, temperature differences of 60 ° C could easily occur, for instance, when starting the test in the morning at -10 ° C, reaching 50°C in the midday heat…

The temperature coefficient of copper leads to a resistance drift of:

- Cu: 4000 ppm/°C (“TK4000”)
- ΔT = assumed ***60°C operating range***
- 4000 ppm * 60°C = 24 %
- Thus, the initially corrected gain error of 0.7 % will change by :
  0.7 % * 24 % = 0.18 % Gain drift (10 m cable)
  For longer cables, this can be even more relevant:
  1.8 % Gain drift (100 m cable)



Cable symmetry and single sensor lead (SENSE)

Cables and wires are manufactured from copper in a drawing process and can therefore be regarded as very well "matched"! As multiple leads are closely coupled in one common cable, even significant local heating will not degrade this perfect match!

Also, contact resistances of connectors do not essentially disturb the symmetry: Typical connectors specify a max. of 25 mΩ per contact. So even the coincidence of a corroded contact with an ideal one will only lead to:

Mismatching and gain errors: 25 mΩ / 350 Ω = 0.007 %

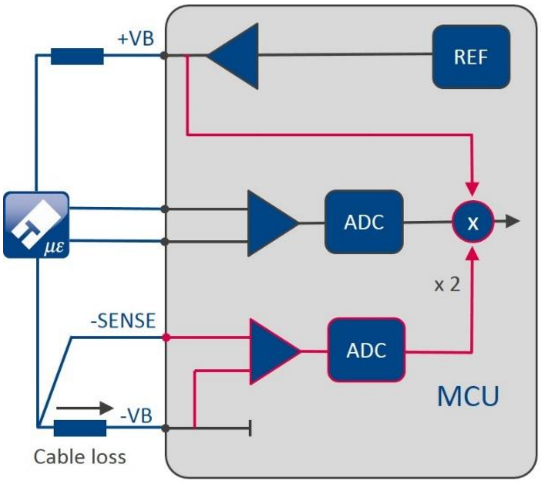
Thus: → ***one single SENSE lead is sufficient!***

imc systems accomplish compensation with a digital scheme:

The "basic" cable loss is detected by means of an additional measurement path and ADC, and mathematically compensated by twice the amount - ***continuously*** during operation!

Thus, dynamic compensation also accounts for temperature-induced drift of cable resistances.

In addition, even the local supply output (not yet attenuated) is directly monitored at the amplifier terminals VB, to even compensate for its residual tolerance.



Digital Single-SENSE compensation

Ratio-metric bridge measurements

In this way a perfect ratio-metric bridge measurement is achieved. Ratio-metric means that in terms of "mV / V → mV signal per V supply voltage", the bridge sensor always delivers a fraction of the supply voltage. Any attenuation of excitation supply can thus be compensated for by a purely computational gain correction. Actual "physical" adjustment of the voltage is to not even necessary! This avoids additional sources of error and stability issues associated with traditional analog control loop schemes.

Double SENSE

So then, are there cases, where double-SENSE lines would still be necessary or even useful? Besides very rare scenarios of asymmetrical cable resistances (see above), carrier frequency mode is one relevant case, where double-SENSE configuration is required to achieve accurately matched phase conditions.

Dynamic interference with half-bridge configuration

Moreover, double-SENSE configurations can be useful in rather "exotic" cases where it is expected that loose contacts or dynamic noise injection along the supply lines might occur - namely in half-bridge configuration. Why is this only an issue for half-bridge configurations?

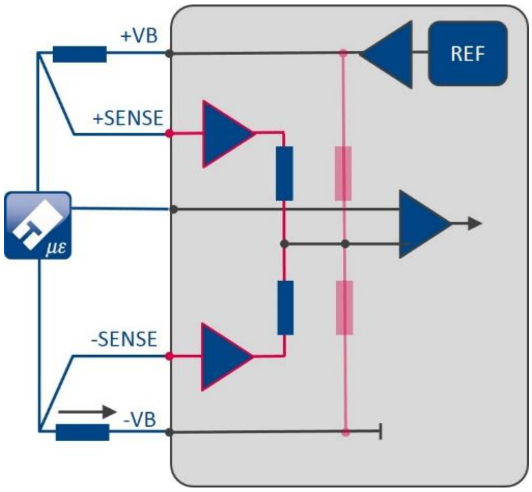
When using simple "single-SENSE", the internal half-bridge completion is always connected to the internal +/- VB node – a requirement to maintain symmetry.

Any noise coupling or dynamic disturbance along +/-VB will then only apply to the external (active) branch of the bridge, leaving the internal HB completion unaffected. While the corresponding gain errors are still insignificantly small, this can however lead to observable offset errors or signal artifacts.

Because these effects are dynamic in nature, they cannot be suppressed by (somewhat slower) arithmetic compensation.

Double-SENSE in contrast, allows for symmetric +/- SENSE signal feedback to drive the internal HB completion - Perfect for dynamic (analog) noise cancellation!

Dynamic disturbance with half-bridge configuration:



Dynamic noise injection or bad contacts on +/- VB

Conclusion: SENSE with imc bridge amplifiers

- imc systems are generally equipped with Kelvin sensing support (SENSE lines)
- Sense lead detects the actual effective supply voltage at the remote sensor
- Sense can be implemented with single or double wires:
    - Supply cables are symmetric: -> double Sense is usually not necessary
    - Economic single-SENSE is an important and unique selling point (USP) for imc-modules
    - Double SENSE for carrier frequency and rare cases of dynamic disturbances
    - The imc amplifier modules BR2-4 and UNI-4 offer both single and double SENSE: The software automatically detects the current wired configuration
- Arithmetic compensation of gain error - automatically in the background
- Dynamic adaptive compensation during active measurements even accounts for thermal drift

Quarter-bridge configuration

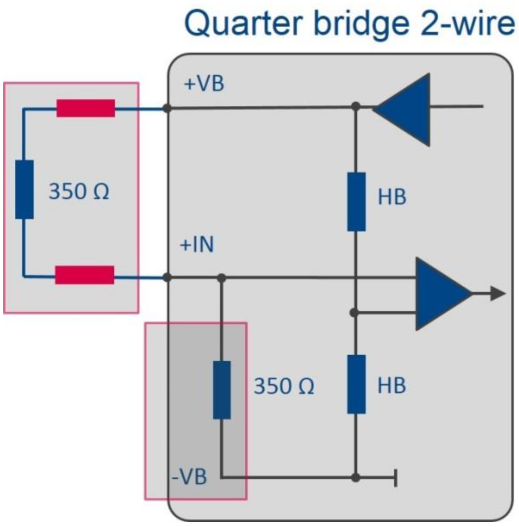
In quarter-bridge configuration, both the passive half-bridge completion and the lower quarter-bridge completion are accomplished internally in the amplifier. The strain gauge as the actual active fourth element is connected with two or three wires – afflicted with parasitic resistance.

First, the “primitive” 2-wire quarter-bridge circuit is presented. It is not really of practical importance since it has dramatic offset and drift problems, as shown in the following example:

2-wire

- Both wires are associated with upper branch of the bridge
- ***Cable***-resistance e.g., 2 * ***10 m***, 130 mΩ / m = ***2.6 Ω***
- ***Gain***-error: 2.6 Ω /350 Ω = ***0.7 %*** → ***still moderate***
- Offset-error: ¼ * R_K/R_B = ¼ * 0.7%
  ¼ * 7 mV/V = ***1.9 mV/V*** → ***dramatic!***
- Offset-drift: with Cu-Drift 4000 ppm / °C* 1.9 mV/V
  = ***7 µV/V / °C*** → ***FATAL!!***

→ This literally represents a thermometer:
135°C will drift the signal across an entire 1 mV/V range!!
135 °C * 7 µV/V / °C = 1 mV/V ***C***

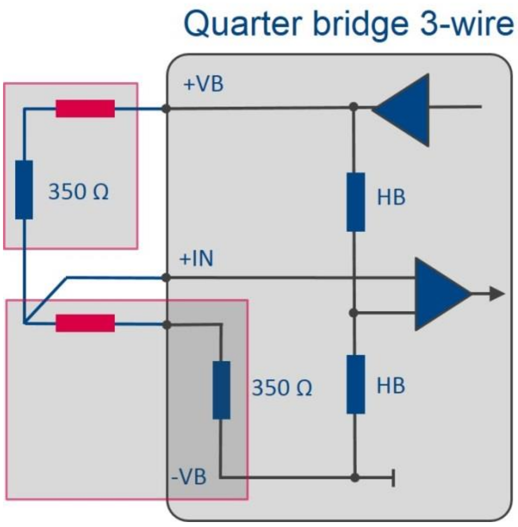


In contrast, 3-wire circuit avoids this offset error by symmetrically distributing the two cable portions between the upper and lower bridge arms – this is why it is almost exclusively used.

3-wire

- wires equally distributed: upper/lower branch
- no current flowing though wire #3
- ***Offset*** and thermal drift: → ***compensated***
- ***Gain***-error: e.g., (10m) 2.6 Ω /350 Ω = ***0.7 %***

→ ***moderate and “usually” uncompensated (see below…)***



For "conventional" bridge amplifier or relevant competitors, it can be stated:

The remaining "moderate" gain error, determined by the ratio of cable resistance to bridge impedance, will usually remain uncompensated. The basic 3-wire circuit does NOT take this factor into account!

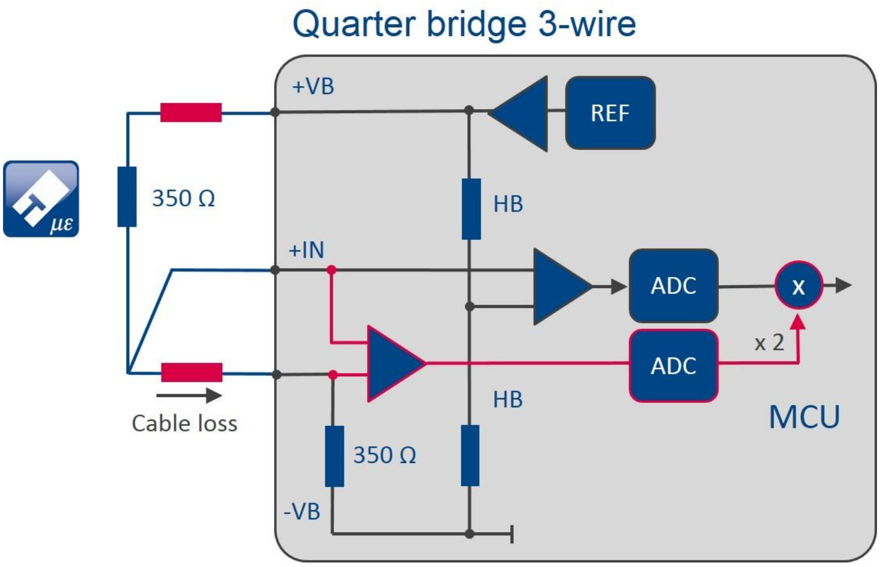
Residual gain error can typically be tackled by techniques such as "shunt calibration", in particular by shunting a calibration resistor in parallel to the internal quarter-bridge completion.

imc 3-wire quarter-bridge scheme (including gain compensation)

While offset stability, as the main property and benefit of the 3-wire circuit is state of the art and commonly used, ***imc systems additionally offer a unique full gain correction for 3-wire quarter bridge.***

This scheme is implemented by means of a separate auxiliary amplifier with ADC, to acquire the voltage drop along the "central" return line. Since this represents half of the total excitation loss, twice this value is used for an arithmetic gain correction.

Conclusion:
Thus, this gain tracking compensation supersedes any shunt calibration for quarter-bridge and is even superior due to its dynamic and adaptive abilities.



imc 3-wire quarter-bridge circuit with dynamic gain correction

Shunt calibration

But if, as has been shown here, gain error can fully be corrected- through SENSE leads (for full- and half-bridge) and even for quarter-bridge (especially with imc systems) - hence all external influences dynamically be compensated: then why would Shunt calibration be necessary?!

In deed, shunt calibration is merely intended only to simply check the measurement chain qualitatively: Forcing a signal step of i.e. 0.5 mV/V, to verify the setup and ensure that no cable breaks or faulty wiring exist.

If one wanted to correct the device’s “internal factors", that is, check or further improve the factory calibration of the amplifier modules (which, for example, are calibrated at imc to typ. 0.02%), one would need the high-impedance calibration resistors to be at least equally accurate. It is obvious, that leakage resistances in the GΩ range will soon set a limit to this. So it is clear that this attempt is not necessary or can even be counter-productive.

What remains, as relevant use cases for shunt calibration, are installations where extra SENSE lines have been omitted for simplicity and economic reasons. However, when attempting to determine cable impedance by shunt calibration in such cases, careful attention is required to take into account *all* relevant influences of cables, including those of the *measurement inputs*. It will be shown below, that this would in fact demand an extra lead wire to connect the shunt. On the other hand, this lack of extra wires (SENSE!) actually characterizes this case! Apparently a dilemma – but finally imc is offering a smart solution that effectively turns this “problem” into a feature!

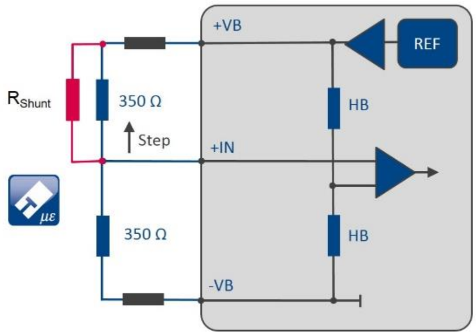
In what way are cable resistances distorting the shunt calibration? In *several* ways:

Connecting the parallel shunt directly at the strain gauge location creates a real signal change that is ***smaller*** than expected;

this is caused by the attenuation of bridge supply at the remote sensor, in consequence of ***cable resistance at +/- VB***.

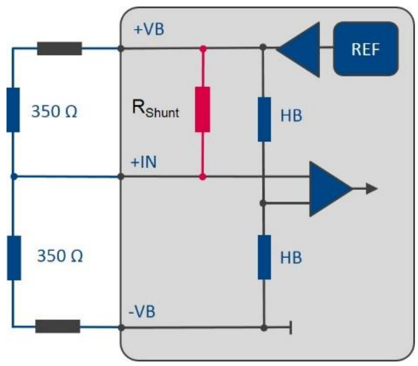
Alteration of step response: about $R_{cable} / R_{strain\ gauge}$
(e.g.,.: circa. 0.4 % at 1.3 Ω / 350 Ω)

Example: half or full bridge



However, since the shunt is not locally connected at the remote sensor, but instead is switched internally in the amplifier, the shunt is parallel to the sum of the strain gauge and cable.

The ratio of "Bridge to shunt" is thus greater than nominal. Thus, the real step is not smaller, but ***larger***.



Yet another, more drastic and even opposite distortion is caused by the ***cable resistance at the measuring input +IN***.

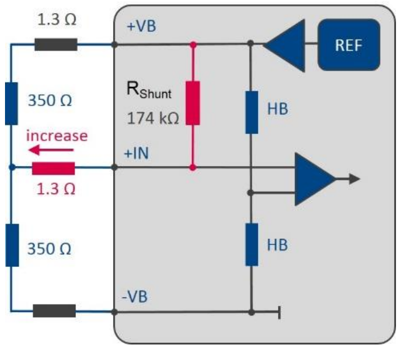
In this example, the 0.5 mV / V step is achieved with 174 KΩ (analogous to the quarter-bridge: = 1/4 * bridge/shunt)

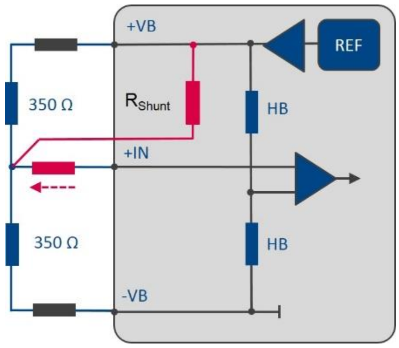
At first sight, the ratio cable / shunt is only 1.3 Ω to 175 KΩ, thus a negligible 8 ppm?
But this voltage divider acts upon the entire half-bridge voltage:

VB/2 * 8 ppm = 4µV/V

So instead of the expected attenuation, there is a further enlargement of the expected 0.5mV / V step by another 1%

This could be avoided by applying a separate lead wire for the calibration resistor. However, this additional line is usually not available!

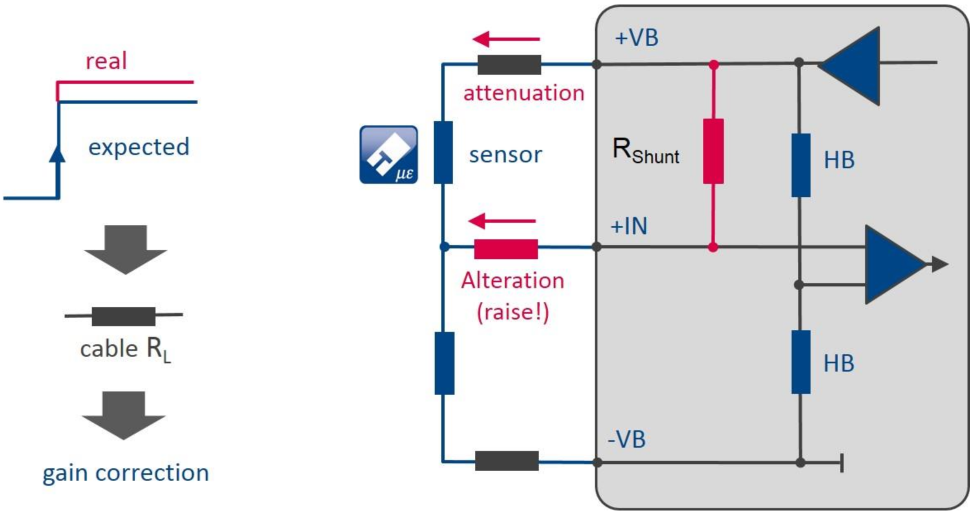




Cable compensation without SENSE – via shunt calibration

However, these different distorting influences can be represented and accounted for in a complete mathematical model. With the (realistic) assumption of symmetrical wires a (rather complex) formula can be derived, that allows the cable impedance (and resulting necessary gain correction) to be deduced from the observed distortion of the step response.

This function, a corresponding, automatic two-point calibration, constitutes yet another exclusive and unique feature of imc amplifiers!



Cable compensation without SENSE – via shunt calibration

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