Current measurement with auto-ranging yields 180dB range dynamics
**White Paper**

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Measuring from 50 nA to 50A - continuous and with high-resolution

In the development and testing of devices and components with DC or battery supply, the examination and monitoring of operating currents is a very important topic. Anyone who measures currents that are determined by sophisticated power management, sleep modes, various active operating modes and their transitions, is faced with extreme range dynamics that can easily take conventional measurement technology to its limits. Here, auto-ranging can offer completely new possibilities, but also new challenges, in particular when applied to current measurement. imc Meßsysteme has implemented such a method in a measurement module that delivers acquired data via CAN bus for use in the laboratory or test stands.

Analysing complex on-board electrical systems in vehicles

Modern vehicles incorporate a rapidly increasing number of electronic components: from actuators for comfort features, lighting and entertainment systems, up to control units (ECUs) for powertrain components. Even the (seemingly) most trivial functions are being increasingly equipped with more intelligent and highly-complex control electronics. Vehicle development has to carefully address the topic of how these complex loads are interacting within the vehicle's battery-powered DC electrical system. For this purpose all involved devices and components are often installed in a "breadboard" arrangement in order to run through different operating scenarios and workflows.
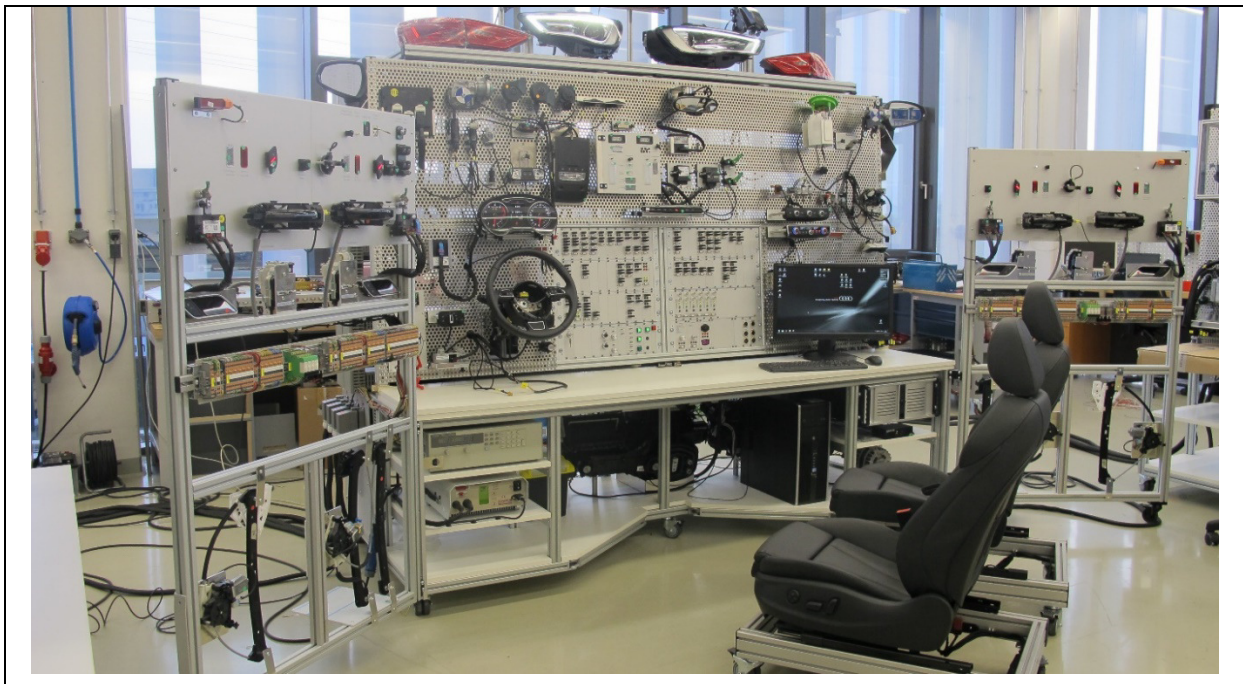
Figure 1: Analysing a complete vehicle electrical system on the "breadboard" arrangement

When systematically acquiring the individual operating currents in this setup, one is quickly confronted with exceptional requirements for measuring range dynamics. Leakage current in the nA range during sleep-mode and subsequent full-load operating currents are worlds apart, but nevertheless, these state transitions must be precisely and seamlessly acquired during a continuously running measurement.
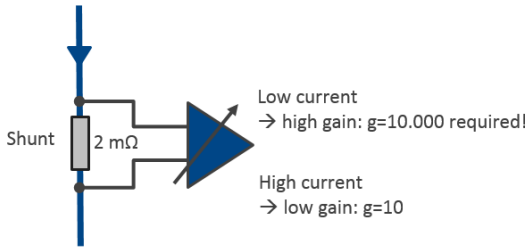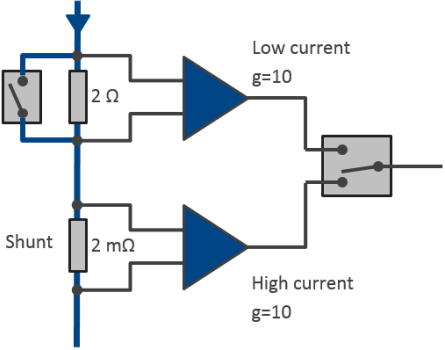
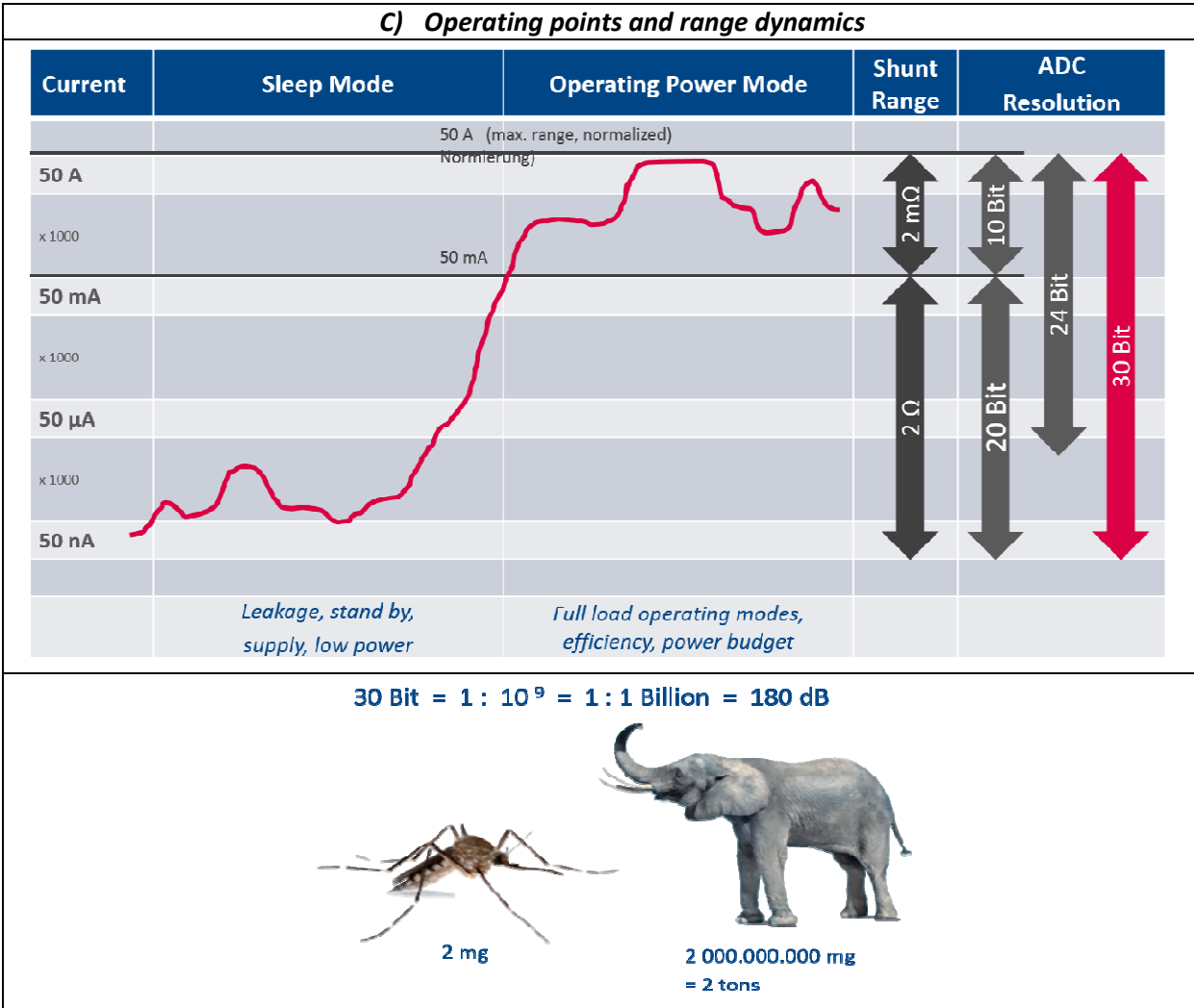## Dynamic auto-ranging during active measurement

Here, classical measurement technology reaches its limit. High-resolution ADCs with 24-bit, for example, already allow for considerable ranges to be covered with a fixed scale design, but for the described scenario, up to 30-bit range dynamics are required! Thus, adapted pre-amplification is needed. At first this is no surprise. However, the challenge is that this range selection must be automatically carried out during the running measurement depending on the actual measured current value, but without being able to anticipate its possible course. In addition, this switching process needs to be non-reactive: it is not allowed to have any influence on the load circuit or test object because it is exactly this transitional range that is also to be acquired and analyzed.

Adapting gain through shunt switching

In contrast to direct voltage mode, current sensing with a shunt resistor does not allow for a simple increase of pre-amplification: with only the extremely small signals available, one would simply "drown" with all of the noise. Therefore, with very small currents, the "gain" must result from an adapted high-impedance shunt that can deliver noteworthy voltage signals. This results in the rather demanding task of dynamically switching the shunt during the test without interrupting the load circuit.

Thus, two shunts are operated in series. The high-impedance one is bridged via a fast circuit breaker as soon as increasing current would raise the compliance voltage beyond a certain limit. The respective relevant voltage signal is then accordingly selected from the two measurement paths.

A) Limits of voltage gain	B) Shunt switching circuit
a) Fixed Shunt, limited by **power dissipation**! i.e. max. 2 mΩ, 50 A → 5W (I²*R) Shunt 2 mΩ Low current → high gain: g=10.000 required! High current → low gain: g=10	b) „Gain" through adapted shunt (1:1000) 2 Ω Low current g=10 Shunt 2 mΩ High current g=10
Voltage levels: **High** current: 2 mΩ * 50 A = 100mV → **g=10**, 1V ADC **Low** current: 2 mΩ * 50nA **= 0.1 nV** → g=10.000 for 1µV signal !	**Voltage levels:** **High** current: 2 mΩ * 50 A = 100mV → **g=10**, 1V ADC **Low** current: 2 Ω * 50nA **= 100 nV** → still manageable!

C) Operating points and range dynamics

Current	Sleep Mode	Operating Power Mode	Shunt Range	ADC Resolution
		50 A (max. range, normalized) Normierung)		
50 A			2 mΩ	10 Bit
x 1000				
		50 mA		24 Bit
50 mA				
x 1000				30 Bit
50 µA			2 Ω	20 Bit
x 1000				
50 nA				
	Leakage, stand by, supply, low power	Full load operating modes, efficiency, power budget		

30 Bit = 1 : 10^9 = 1 : 1 Billion = 180 dB

2 mg

2 000.000.000 mg = 2 tons

Figure 2: Fixed shunt vs. "gain" through adapted shunt – resulting range dynamics

30 dB range dynamics

When looking at the concrete dimensioning of the design, the dilemma to be solved becomes clear: the size of the sensor resistor (shunt) is the crucial parameter in circuit design. It must be large enough to supply significant voltage signals that aren't drowned out by noise and disturbance. On the other hand, the power dissipation increases by the square of operating current and thus imposes hard limits even with sophisticated heat management applied.

For an operating current (measuring range) of 50 A, the selected shunt may not be greater than approximately 2 mΩ and is already converting 5 W. At this upper operating point it supplies a mere 100 mV. This is a magnitude that is still well manageable and can be well processed by a 24-bit ADC (for example, with g = 10 for a 1 V ADC).

However, if one desires at the same time a measurement resolution of 50 nA with this configuration in order, for instance, to assess leakage currents, it soon becomes clear that the limits of physics are well exceeded here. Signals of 2 mΩ × 50 nA = 0.1 nV definitely have no chance to prevail over noise and parasitic thermovoltages, etc., even if they were to be "inflated" with an additional gain of, for example a factor of 1000, yielding 0.1 µV (**Fig. 2a**). The gain must therefore be generated from the shunt itself. This shunt's resistance of 2 Ω is increased by a factor of 1000 (shunt gain), but is only active at low currents. It is dynamically bypassed as soon as higher working currents (> 100mA) threaten to overload it, like shown in **Fig. 2b**.

Thus, a total range dynamic of about 30-bit results, i.e., a ratio of max. measurement range to min. resolution of 1:1 billion (10^9) (**Fig. 2c**).

The imc CANSAS-IHR module is based on this very concept: in a single unit, it provides two galvanically isolated auto-ranging measurement paths for acquisition of operating currents on loads that are supplied with up to 18V DC. Individual isolation allows the module to be placed at any location within the load circuit: high side or low side, on partial sub nets or entire system feeds.

Fast electronic solid state fuses will interrupt the test circuit safely and reversibly when overloaded. An optional switch allows an additional external laboratory instrument to be looped into the circuit.
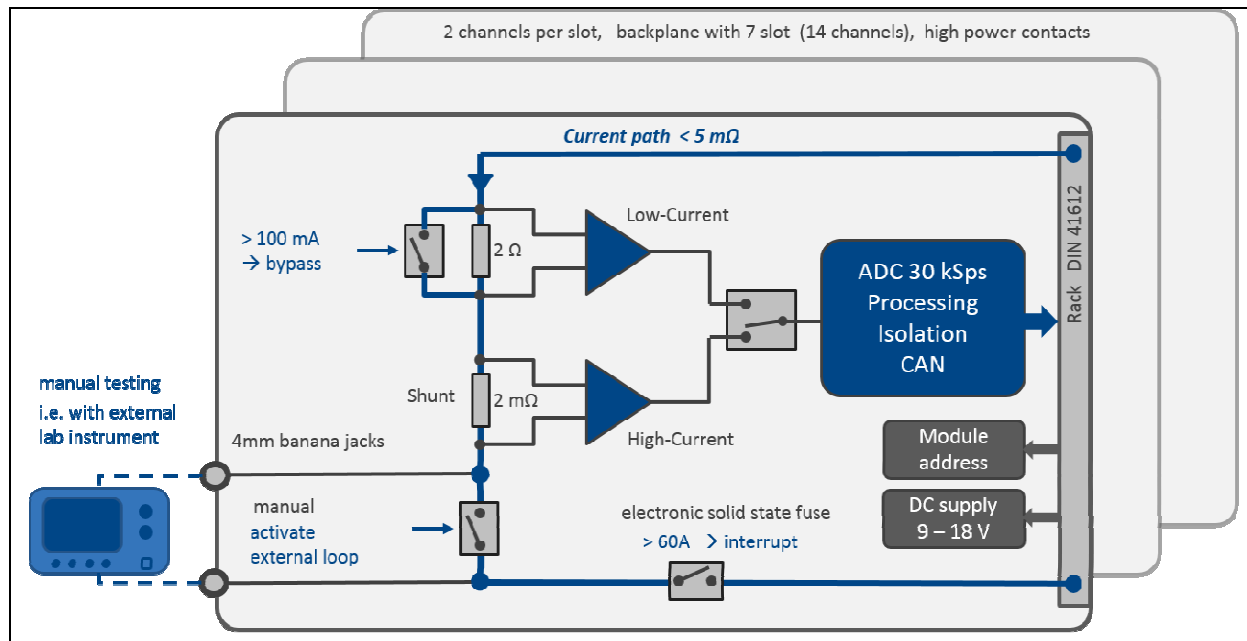

Figure 3: Modular test rack with 2 individually isolated channels per module (one channel shown)

The voltages at both shunts are digitized with 30 kSps and 24-bit and are automatically selected, scaled and calibrated by a processor. Outputs are provided via CAN bus with selectable data output rates from 1 Hz to 1 kHz.

In addition to the auto-scaled average values, minimum and maximum values are available. Regardless of the selected output rate, these are determined based on the internal 30 kHz data rate and refer to the selected output interval (which applies to the average values, too).

These modules can be inserted into a special 19" sub-rack that has a backplane equipped with multiple options of high-power contacts for wiring the test objects (push-in or soldered).
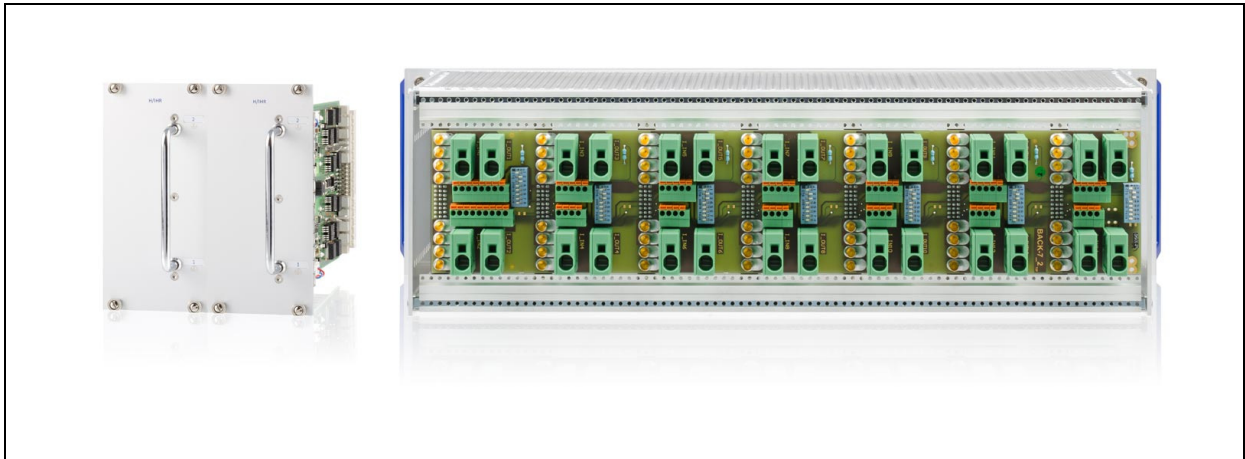
Figure 4: High-power connections on back of sub-rack

This allows for very flexible and extensive instrumentation of test stands and the acquired data can be recorded and evaluated with any CAN-based data logger or applications system.

In addition to this rack-solution for test stand applications, an alternative stand-alone version is also available. It contains two channels in an individual aluminum housing. It is ideally suited for spatially-distributed, as well as mobile applications.

Figure 5: imc CANSAS-IHR as a stand-alone module for distributed installations

| *imc CANSAS-IHR high-resolution current measurement module* |
| :--- |
| • *Galvanically isolated* current measurement with shunts |
| • Test objects: loads supplied with up to *18V DC* |
| • 2 shunts with dynamically switched current path (*bypass*) at high current flow |
| • Automatic and dynamic range selection: *auto-ranging* |
| • Resulting *30-bit* range-dynamics: 50 nA - 50A |
| • Acquisition and output of *average* and *min/max* |
| • Output rate selectable at intervals of *1 Hz*/10 Hz/*100 Hz*, internal processing/acquisition with 30 kHz |
| • Data rate up to 1 kHz with a static measuring range (50A, without auto-ranging) |

Switching dynamics

The switching action of the shunt has to react much faster than would be necessary for the actual measurement: Suddenly increasing current must instantaneously short-circuit the high-impedance shunt in order to not only to prevent it from burning up, but also to avoid an excessive peak of compliance voltage. As an (albeit transient) voltage drop in the load circuit ("droop"), this would influence, or even "disconnect", the load components to be tested.

Therefore, the activation of the shunt bypass is controlled by a fast comparator, but resumed activation of the high-impedance shunt is only permitted with a delay (**Fig. 6**). The combination of level hysteresis (switching threshold) with the temporal hysteresis of the fast activation (< 1 µs) and slower deactivation (< 1 ms) of the bypass guarantees safe and stable state transitions.
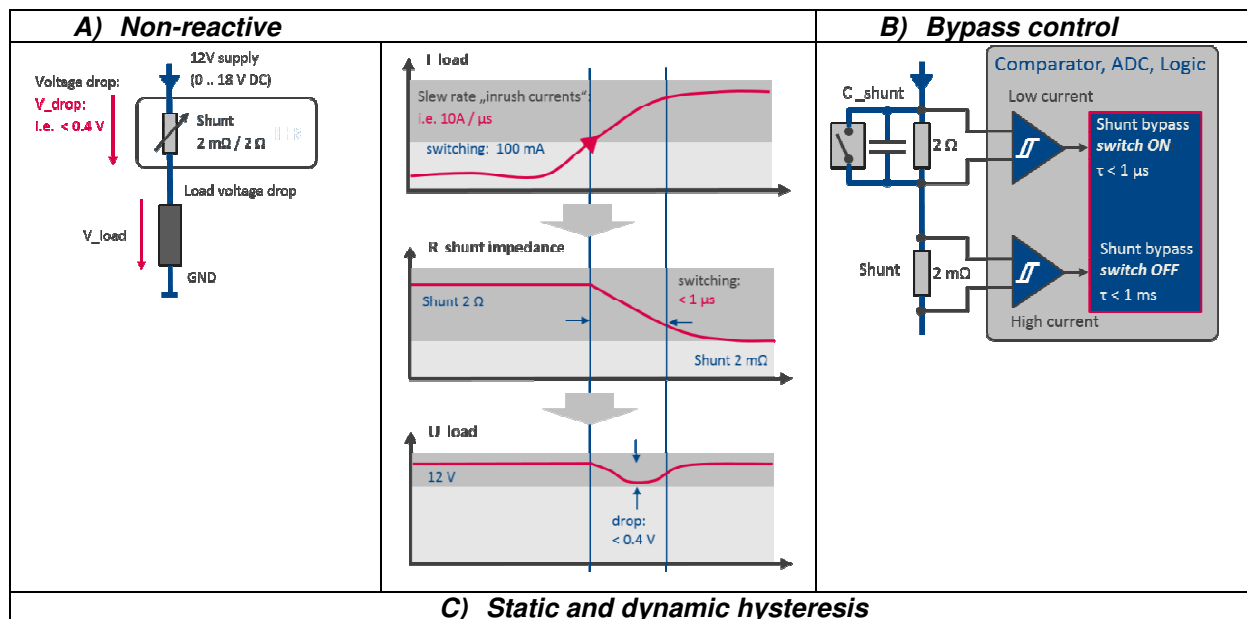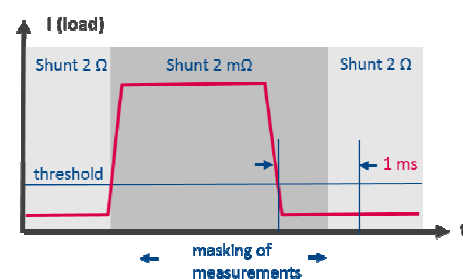

A) Non-reactive		B) Bypass control
	C) Static and dynamic hysteresis	
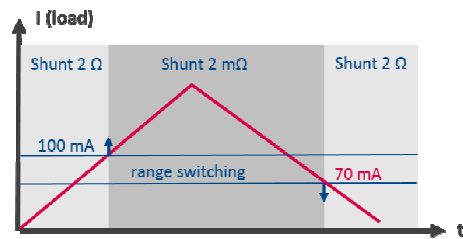
Figure 6: Dynamic shunt switching

Thus, even with fast rising current transients (inrush, surge) of 10 A/μs, virtually non-reactive switching is still guaranteed that limits voltage drops across the load to about 400 mV. An appropriate capacitance across the shunt also helps to flatten the voltage transients in the transition zone until the comparator reacts (**Fig. 7**). The concept is thus also suitable for measuring test objects with a highly dynamic behavior.
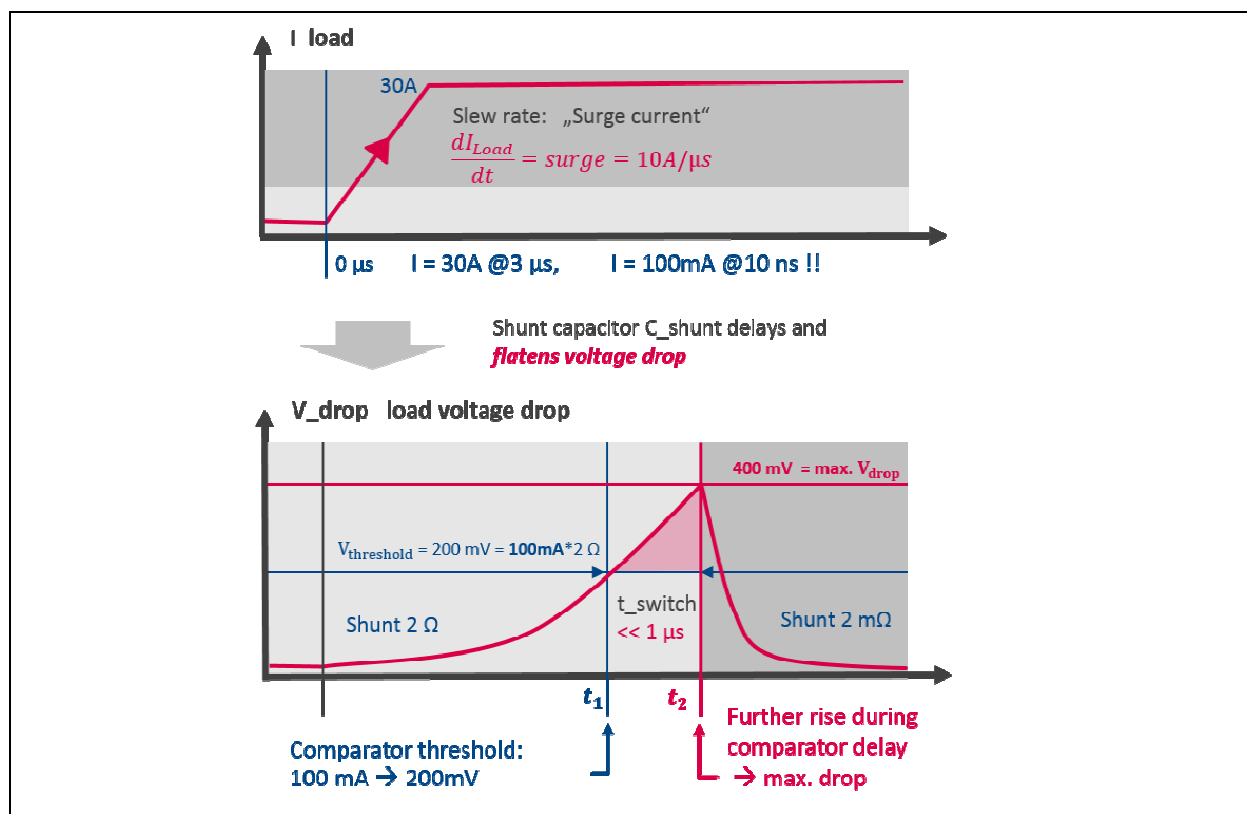
Figure 7: Maximum voltage drop across the load in case of surge currents

The hysteresis dead times, as well as the settling times of the parallel measurement paths (ADC) that have to be masked out, limit the meaningful data output rates to 100 Hz. However, it is also possible to disable the auto-range shunt switching in a "fixed mode" and then to use a maximum data rate of 1 kHz.

Is auto-ranging a universal solution?

Basically, auto-ranging methods are helpful in particular in the applications described here, which concern separated work areas that are traversed in succession and in which one also remains (**Fig. 8b**). Then use can actually be made of the fact that small signals are processed optimally with low noise and adapted gain, resulting in a real gain in usable data resolution.

However, auto-ranging is not a cure-all that will necessarily be of advantage in any measurement situation. In the case of periodic signals, for instance, which are analyzed in the frequency domain by means of FFT, the following should be borne in mind:
While the "inner part" of the signal range, i.e., the sections of small amplitudes, are optimally re-solved with adaptive gain (for example, g = 1000), this low-noise level is effective only in a compara-bly small portion of the total time, namely a respective 1/1000 along the time scale (**Fig. 9**). That means, the background noise (noise floor) of the FFT, will still be dominated by the signal-to-noise ratio (SNR) of the coarse measuring range. Consequently, such auto-ranging will only have negligible benefit for SNR of the spectral data.

A further essential prerequisite for auto-ranging is that the fine or "zoomed" range must be symmet-ric around zero. To benefit from extended resolution, signals need to move around the zero line of the unipolar or bipolar signal range, because we are not concerned here with AC coupling, but with an adapted linear gain. While that is the case for the described type of current measurement, it does not apply in quite different applications such as bridge measurements using strain gauges, because in that case, the signal is typically afflicted by a large initial offset that needs to be compensated.
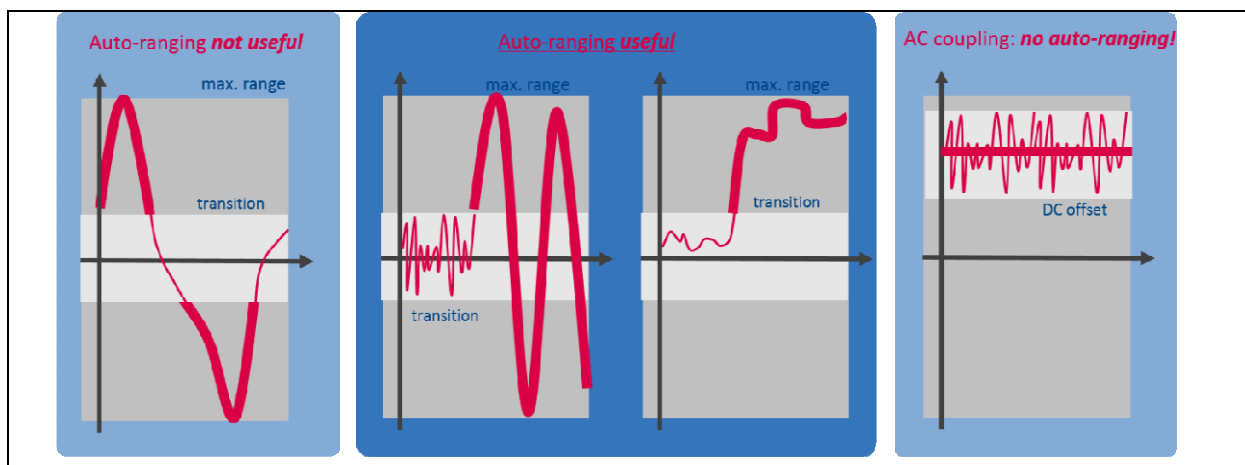
Figure 8: When is auto-ranging useful?
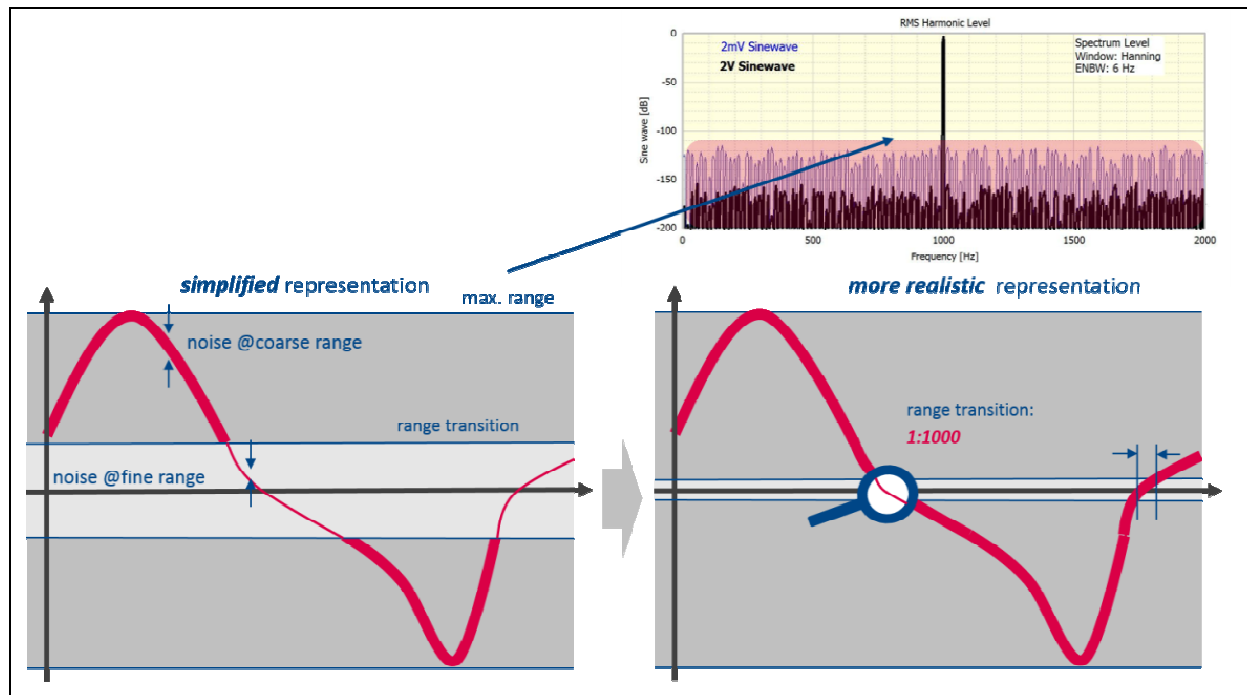
Figure 9: Limited use of auto-ranging for periodic signals

What can current measuring with auto-ranging achieve?

Where?

- Extreme range dynamics (full-power vs. sleep-mode)
- Power-Up tests of components and systems
- Demarcated work areas/operating points
- Limited use for periodic signals

How?

- Dynamic range adjustment during active measurement
- Continuous data acquisition
- No interruption in the load circuit (non-reactive)

imc

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