Voltage measurements of hybrid engines

White Paper

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Introduction

Hybrid engines are gaining increasing importance in the automotive world. This kind of propulsion comprises both a conventional internal combustion engine and an electric motor. The power supply for the electromotor and the energy recovery from the braking process involve batteries which can typically have voltages of many hundred Volts. Measurement of individual, cascading cell voltages present a measurement engineering challenge. While the cell voltages are typically only a few Volts, connecting the cells in series produces a high voltage level on the basis of which the cell voltage must be measured. This whitepaper indicates what to look for in performing such measurements and helps in selecting the appropriate measurement amplifier. The topic is approached from the standpoint of the user and not of the developer.

What is common mode voltage (CMMR)

The following simple example is meant to illustrate what common mode voltage means. When considering a voltage source consisting of 3 V cells, where one wishes to measure the voltage of the cell whose negative terminal is at 300 V, then the measurement amplifier's negative input is at 300 V and its positive input at 303 V.

The common mode voltage U_{cm} refers to the mean value of the voltages at the amplifier inputs. In the example shown (Fig. 1), the common mode voltage is U_{cm} = 301.5 V. The measurement amplifier now has the task of correctly measuring the voltage applied between its plus and minus terminals, without becoming influenced by the common mode voltage.

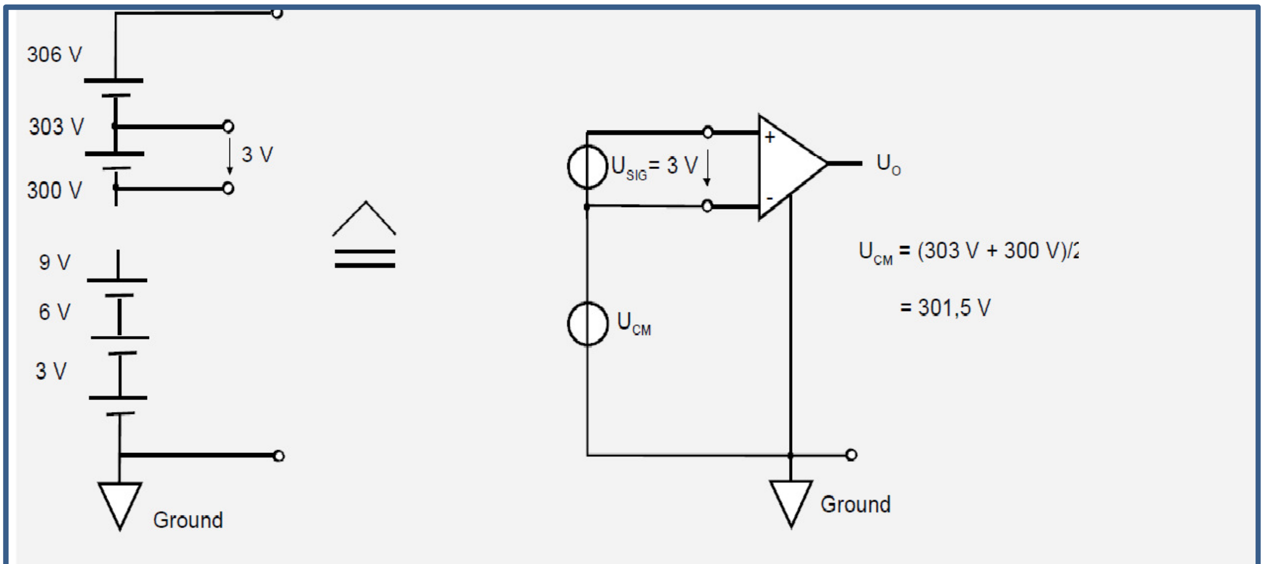
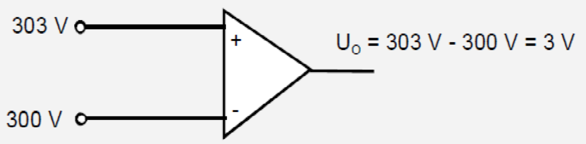


Fig. 1: Emergence of common mode voltages at a battery

As the example in Fig. 2 shows, the difference would have to be determined with an extremely small uncertainty in order to be able to measure the 3 V with adequate accuracy. With amplifiers, the capability to suppress common mode voltages is referred to as CMRR (Common Mode Rejection Ratio). The resulting output voltage U_O in this case is given by:



The U_{CM} = 301.5 V must be eliminated. If the differential amplifier (subtractor) has an uncertainty of only 0.1%, this would mean an error of approx. 0.3 V. In reference to the 3 V range, this is a relative error of 10%!
The suppression of U_{CM} is called CMRR.

Fig. 2: The differential amplifier subtracts the voltages between the plus and minus inputs

$$U_0 = U_{SIG} + U_{CM}/CMMR.$$

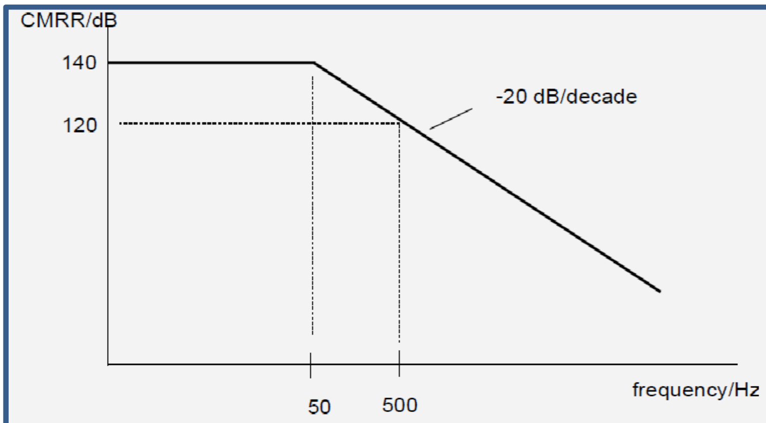
Good amplifiers suppress common mode voltages by 120 dB (factor 10^6); very good ones reach up to 140 dB (factor 10^7). Note, however, that this CMRR is mostly specified only for 50/60 Hz. Typically the CMRR decreases as the common mode voltage's frequency increases.

This deserves special note, since hybrid drives have besides the DC battery an inverter connected between it and the electromotor, which it controls. If the common mode voltage comes from the inverter, then it is possible to assume that the frequencies present in the inverter lie in the kHz range and the CMRR for such signal is substantially lower. For instance, the CMRR in the diagram above is only 80 dB at 50 kHz.

Isolated amplifiers

With measurements of high voltages, isolated amplifiers are very common. On the one hand, it is necessary to avoid damage to the measurement apparatus, and on the other hand, protection of personal safety is to be ensured. Especially high common mode voltages such as those occurring in hybrid car batteries can be dangerous for humans coming in contact with them.

Among isolation amplifiers, one distinguishes between those which have block isolation and such where each channel is insulated individually. Fig. 4 illustrates block isolation



The CMRR decreases at 20 dB/decade. This means that for a 10-fold higher frequency the CMRR decreases by a factor of 10 (20 dB).

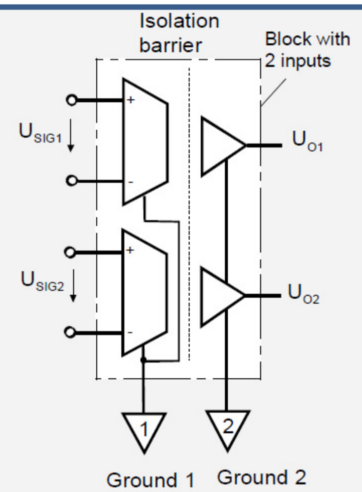
Fig. 3: CMRR as a function of the frequency

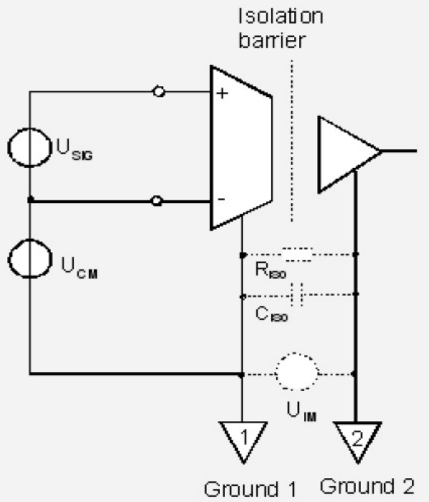
for two channels. The input voltage U_{SIG1} and U_{SIG2} each are referenced to Ground 1. For instance, none of the four input lines have a voltage differential to Ground 1 higher than 10 V. Suppose instead that a voltage differential of 1000 V is permitted between Grounds 1 and 2 (isolation voltage). This kind of arrangement forces the user to consider whether connect Ground 1 one of the two inputs, or whether to let Ground 1 to “float” without a reference point. After all, the sensors the user wishes to connect, which output the voltages U_{SIG1} and $_{USIG2}$, typically have only two and not three connection lines. There is no universally applicable and satisfactory answer regarding how to connect Ground 1. But it is often more convenient to fix Ground 1.

tion barrier. Between Grounds 1 and 2, there may be an additional voltage U_{IM} present which may not exceed the isolation voltage specified in the technical specifications. Suppression of the voltage U_{IM} is stated in the spec sheets under IMR (Isolation Mode Rejection). In such a case, the resulting output voltage is given by

$$U_0 = U_{SIG} + U_{CM} / CMRR + U_{IM} / IMR$$

If the channels are set up with individual isolation, which is of course associated with higher costs (every channel needs a separate power supply), then the amplifier’s minus input can be connected with Ground 1. This wiring is performed by the manufacturer and the user needs not be concerned with it. When there are





U_{IM} = Voltage difference between Ground 1 and Ground 2
R_{ISO} = Parasitic isolation resistance
C_{ISO} = Parasitic capacitance

Fig. 4: Block isolation with two inputs

Fig. 5: Model with block isolation

In order to understand the situation with block-isolated amplifiers, the image at right (Fig. 5) illustrates a model applied to one channel.

On the side of the measurement source, whose voltage U_{SIG} is coupled to Ground 1 via the common mode voltage U_{CM}, the previous statements apply. In the measurement amplifier itself, electrical separation is achieved by magnetic or optic coupling, for example, which provides the desired insula-

multiple channels, then each channel is electricallyseparated from each other channel and all of them are separated from Ground 2. In this case, the amplifier is employed in so-called single-ended mode.

As a result, no common mode voltage can emerge on the amplifier’s input side and the resulting output voltage U_A is given by

$$U_0 = U_{SIG} + U_{IM} / IMR$$

So for isolated amplifiers, the IMR is analogous to CMRR in unisolated amplifiers. For individual and block isolation, note that ideal isolation between the grounds is only present for DC voltage differences.

While the parasitic isolation resistance can be quite high ($10^{12}\ \Omega$), the influence of the parasitic capacity C_{ISO} is not to be neglected in the case of high frequencies. If one assumes, for example, a low capacitance of only 10 pF an, then for a signal frequency of f = 1 MHz the resulting capacitive resistance is $XC = 1/(2\ \pi\ f\ C_{ISO}) = 15.9$ kΩ. In practice this means that the isolation effect decreases with higher frequencies.

Isolation voltage equals test voltage?

The spec sheets for isolated amplifiers from various manufacturers contain many terms whose meanings can puzzle the user. On the one hand there is the isolation voltage U_{ISO} (maximum permitted voltage U_{IM}), which is the maximum which may be applied between the grounds, and on the other hand there is the test voltage U_{test}. The manufacturer inspects each channel before release with a test voltage which is significantly higher than the isolation voltage to be withstood. In compliance with American UL standards, this test voltage U_{test} is

$$U_{test} = 2\ U_{ISO} + 1000\ V$$

where the voltage needs to be applied for 60 s and there is a tiny current which may not be exceeded. With regard to human safety, the protection classes CAT I through III are defined, which each require different test voltages.

Isolated does not necessarily mean problem-free

Next, a brief example involving temperature performed with a thermocouple will illustrate how interference problems due to potential differentials can occur even in isolated measurement. Observe Fig. 6

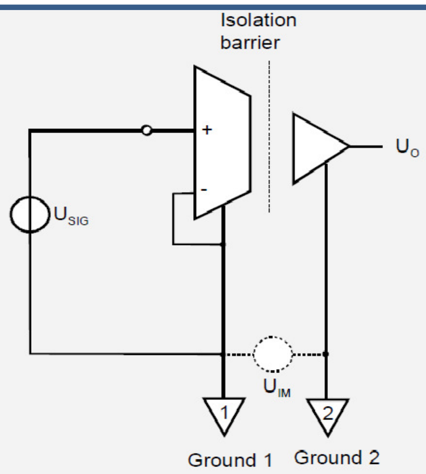


Fig. 6: Individually isolated channel

For example, a thermocouple is to be conductively coupled to an electronic component in a hybrid vehicle's inverter. Thus, there is a voltage U_{IM} between the two grounds, which can fluctuate very quickly. In such cases, a slew rate of multiple 100 V/µs are not rare. To make the effects clear, this example assumes that the voltage U_{IM} has a slew rate of dU_{IM}/dt = 100V/µs. The capacitance between the thermocouple and Ground 2 should have a value of only C = 5 pF. Thus the resulting current through the capacitor, assuming that U_{IM} drops almost completely to zero across the capacitor, is given by

$$\mathbf{i_{GL} = C\ dU_{IM}/dt = 5\ pF\ 100V/\mu s = 0{,}5\ mA}$$

If a value of 1 Ω is assumed for the resistance (R_L corresponding to a cable length of approx. 1 m), then the resulting voltage drop is 0.5 mV. Considering that a Type K thermocouple generates a voltage of approx. 40 µV/K, this voltage drop across R_L already corresponds to a measurement error of more than 10 K, since at the isolated amplifier's input the sum of the voltages from the thermocouple plus the voltage drop across R_L is measured.

The fact that in practice the problem described mostly only occurs in moderated form is due to there also being a resistance and a capacitance on the thermocouple's (+ amplifier input's) upper lead. If both RC combinations were equal, then the effects would be substracted when the difference is taken in the amplifier. Unfortunately with thermocouple are made of different materials with vastly different resistance properties.

However, the problem described does not only occur with isolated amplifiers. Even with non-isolated differential amplifiers, any common mode voltage present can produce similar effects.

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