- - - DC Monitoring - - -

Direct Current (DC) is a current flow that is usually going in one direction. Batteries are the most common and easiest to understand example of DC supply: mobile phones, laptops and automobile batteries can produce DC. Batteries can accept charge or be discharged. For charging, current will flow in a particular direction, and for **dis**charging, the current will flow in the opposite direction. 'Forward current' might be used to describe the current flow during typical operation of a device, and 'reverse current' might be used to describe the atypical state.

Alternating Current (AC), for comparison, typically alternates between positive and negative voltage, or forwards and reverse current, tens or hundreds of times a second. Just like how 'AC' can be used casually to means alternating voltage, DC can also be used to mean continuous positive or negative voltage, although it's usually prefixed with a V, as in +1.5VDC.

Direct Current (DC) measurement is also called **DC sensing**.

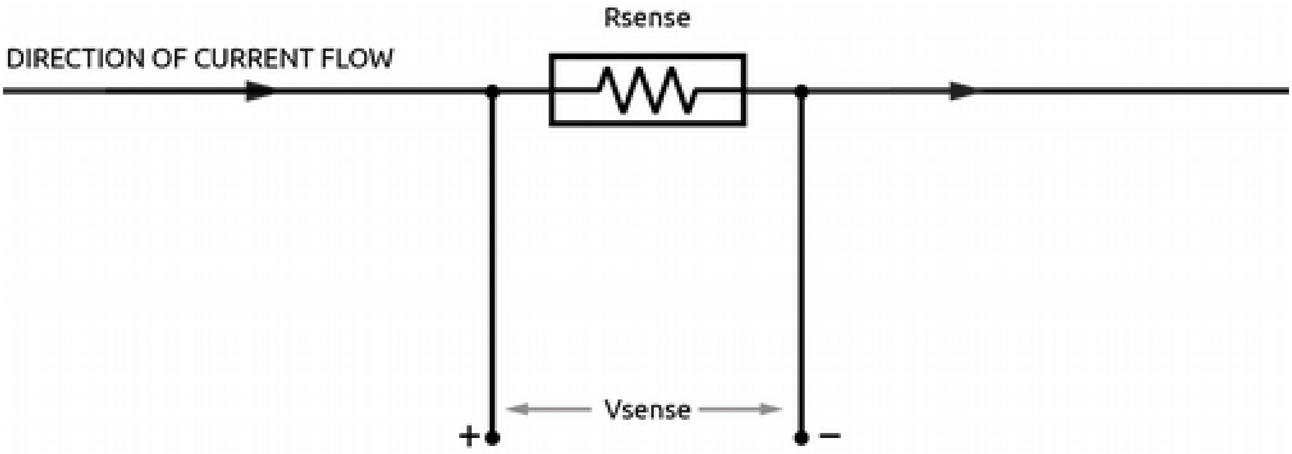
First, the two main types of DC sensing will be introduced. Then, the safety aspects of DC sensing, which are **more significant** than in AC measurement.

What’s covered here is measurement of direct current and voltage towards **digital** information. Analogue measurement methods exist and have been around, of course, for much longer, but won’t be covered in detail.

To monitor DC, a method has to be chosen from two main categories of technology - **shunt monitors** and **hall effect sensors**.

Shunt Monitoring

This method uses the **current sense resistor**, or **shunt**. These are typically low resistance, specially designed metal-alloy resistors, which maintain a fairly constant resistance value over a wide temperature range.

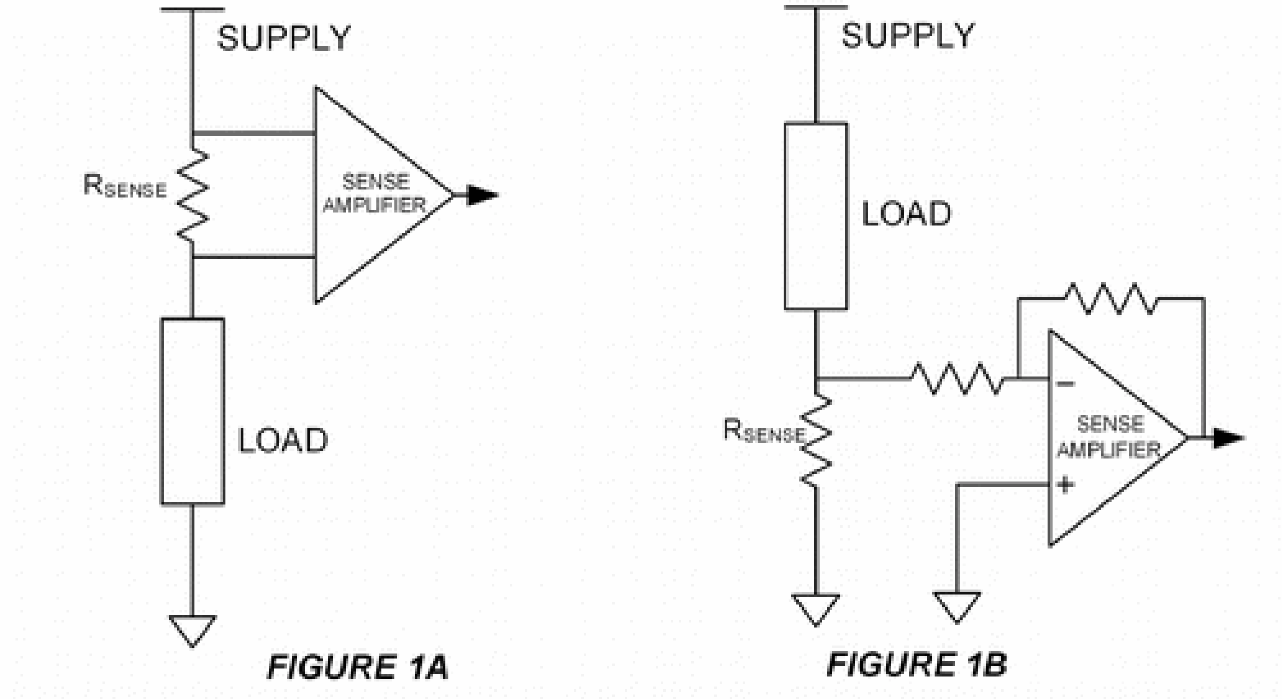


In this simple model, current flows through the shunt resistor and a small voltage is produced across it. The voltage drop is **proportional** to the current flow. **Vsense** is typically in the **millivolt** range. Many shunts are specified at a particular current range for a **50 or 100 mV** maximum sense output.

Image 1A
Soldered PCB Mounted Shunt. Credit: Ohmite
(around 50A max., around 20mm wide)

Image 1B
Panel Mounted Shunt. Credit: Murata Manufacturing
(around 500A max., around 100mm wide)

The next step is to **amplify** the millivolt signal coming from the shunt resistor. To select an amplifier we must understand **high-side** and **low-side** current sensing.



Credit : User ElectronS at https://electronics.stackexchange.com/

In figure 1A we have high-side sensing, and in 1B low-side sensing. Low-side has the advantage of cheap circuitry and simple implementation with standard op-amps. However the load circuit may be sensitive to the **offset ground** voltage cause by the small resistance of the sense resistor which has been located between the main circuit and ground, i.e. the load is not connected directly to ground.

High-side sensing allows the load circuit to be directly connected to ground, but requires a **differential common-mode amplifier**. This is an amplifier can can accept signals **at or above** the amplifier's supply voltage. Common-mode voltage means the input voltage range into the amplifier. When the common-mode input voltages are above the amp's supply voltage, this is called **over-the-top** sensing. High-side sensing has the important advantage of short-circuit detection. Look again at the diagram, and you can see that if a short-circuit fault appeared in a low-side configuration, it would not be detected, whereas in the high-side configuration it would.

The main advantages of shunt based sensing are versatility, easily selected current range, and accuracy.

Hall Effect Sensing

Hall effect sensing takes advantage of the magnetism produced by the current in a conductor. A small magnet is used to divert a tiny proportion of the flow of charge “sideways” from the main current conductor, or transversely to the magnetic field. The hall effect itself is the voltage being produced in the second conductor, it was discovered by Edwin Hall in 1879.

There are two main categories of hall effect sensors, open-loop or closed-loop.

Image 2A: Open-loop sensor

Image 2B: Closed-loop sensor

Hall effect sensors have the distinct advantage of in-built isolation from current carrying conductor of the DC system cable. In their open-loop form in particular, no break in the carrier cable is necessary for current measurement. This is very useful for not having to create or change any cable terminations.

The closed-loop form are almost always integrated circuits (ICs), ensuring the main current path comes in close proximity to the Hall magnet, these ICs are of course mounted onto PBC, which has the cable termination. Heat dissipation is designed into most of these IC types. However because of the heat dissipation issue IC hall effect current sensors tend not to measure above the range of 50 Amps, although 200A sensors are now available.

The main disadvantage is the set current range of the device, and the open-loop form will have a set cable size maximum also.

Other potential issues are accuracy, drift with temperature, sensitivity to magnetism and cost.

A trick with the open-loop form is to wind the cable through the aperture more than once, for example the reading from a 10A max cable can be doubled with an extra winding for a 25A max sensor, this simple trick makes larger open-loop devices more versatile, able to be used for lower-current cables.

The resistances of hall-effect sensors are typically very low, and are referred to as 'Rsense' just like shunts.

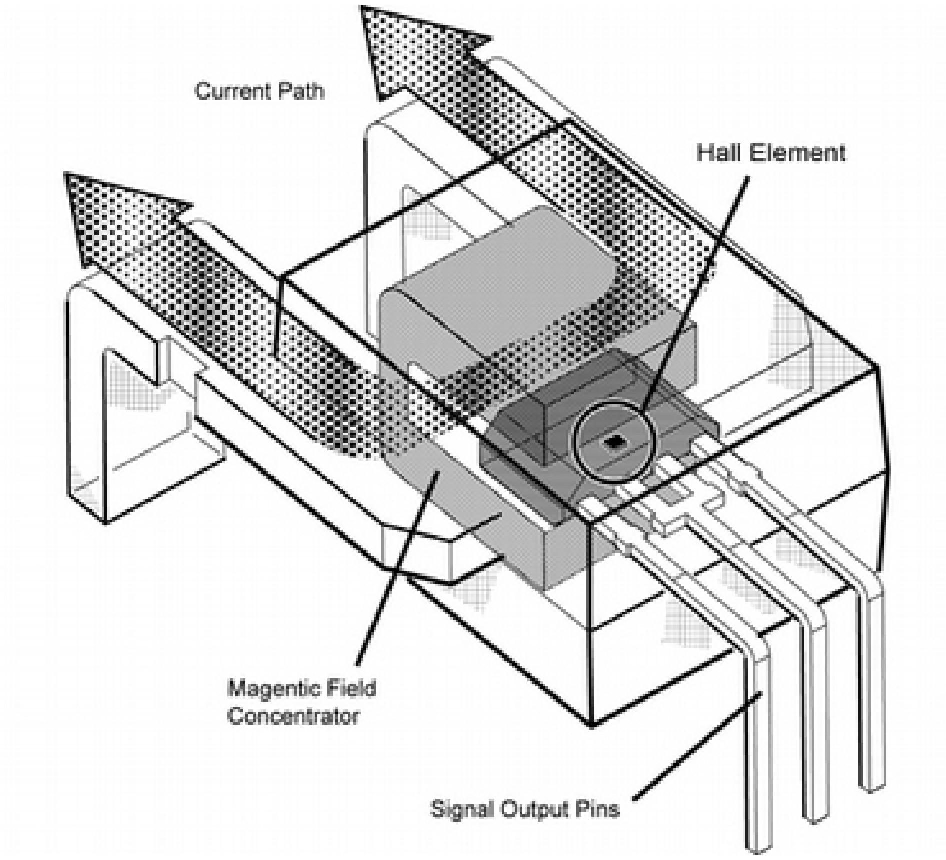


Figure 3 - High current Hall Effect current senson. Source: "https://www.allegromicro.com/en/Design-Center/Technical-Documents/Hall-Effect-Sensor-IC-Publications/Integrating-Hall-Effect-Magnetic-Sensing-Technology-Into-Modern-Household-Appliances.aspx"

Hall effect sensing has the general advantage of **common-mode isolation**, that is, isolation from the high-side positive voltages or floating voltage level of the conductor. In the safety section to follow this will be described in more detail.

Hall effect current sensing can have the advantage of simplicity, as the ICs can handle transients, isolation, amplification and error correction in one. The limitations are being overcome, so it's worth keeping an eye out on this field.

Examples of high current hall effect sensors are the AIMH021 and AIMH040 by Aim Dynamics.

Current Sensing Summary

There are a wide range of sensors that are capable of both shunt resistor and hall-effect based sensing.

Shunt based sensing is versatile, is fairly simple to implement and has a long history of applications. A wide range of methods are shown in Linear Technology's Application Note AN105.
http://www.analog.com/media/en/technical-documentation/application-notes/an105fa.pdf

Hall-effect type, especially open-loop, have potential for simple implementation of current **only** measurement and the associated cost-benefit. The common-mode and floating voltage isolation is also a great advantage.

Voltage Sensing

We've covered taking a current measurement. Now **voltage**.

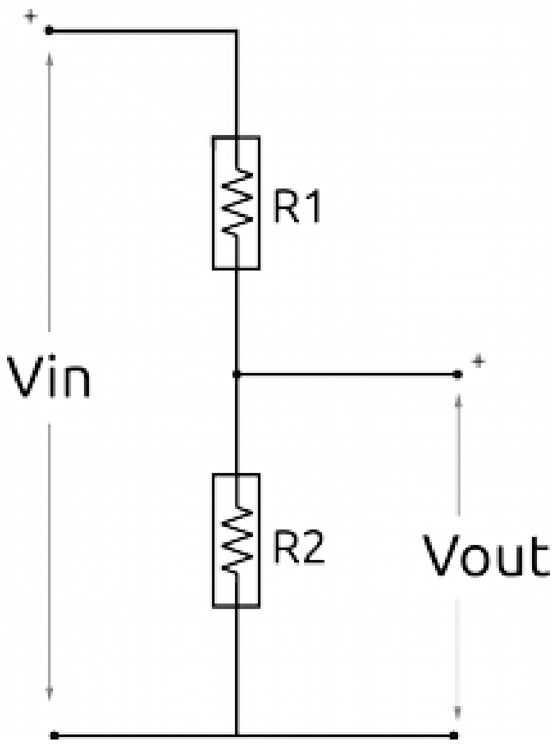
With DC, the cables must be physically altered to gain access to the voltage level. The cable must be tapped, crimped, bolted, soldered onto or screw-terminated to get the voltage reading.
Safety is obviously a part of this process.

The standard guidance in Europe is that anything above a working voltage of 75VDC is potentially harmful. This means that all work practice and installation of gear is done to never have to contact those voltages with one's body in any way.
Note that for generators (solar panels, wind turbines etc.) the floating voltage may be above the working voltage. Proceed with great caution with floating (non-earthed) generators.

A voltage sensor normally has **high impedance** in the mega Ohms, and may use a **buffer** and an **analog-to-digital converter** (ADC) to send the information digitally to the MCU.

Simple voltage divider:

A simple voltage measurement technique is the **resistor divider** or **resistor divider network**.



Here, the output is proportional to the input, and the ratio of (R1+R2) and R1.

$$V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}$$

First, the resistors must be selected for the target input and output range. Next, the values must be high enough to minimise current and heating effects, which could either create temperature based inaccuracies or simply blow one or both resistor. However, values too high can introduce noise to the next stage of the circuit.

The resulting situation from a high-resistance selection, for example a 1 Mega Ohm resistor at R1, is the low current output at Vout. If the resistor values have been selected such as to minimise power losses, then it’s likely that a high impedance output will be the case at Vout. This is important for analogue-to-digital converter (ADC) inputs.

ADCs normally require low-impedance inputs, this is because of the **sample-and-hold architecture** (**SHA**) of many ADCs. SHA requires that: 1. a small capacitor is charged in a defined time period, hence needing current available, and 2, the charge held long enough for analog-to-digital conversion to take place.

Buffered output/input:

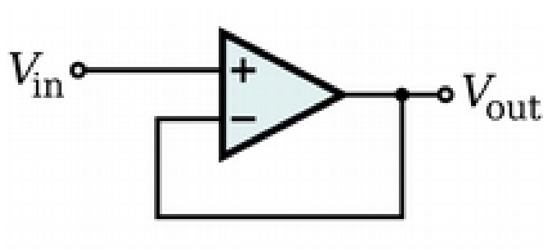


Figure 4A - Voltage follower diagram.

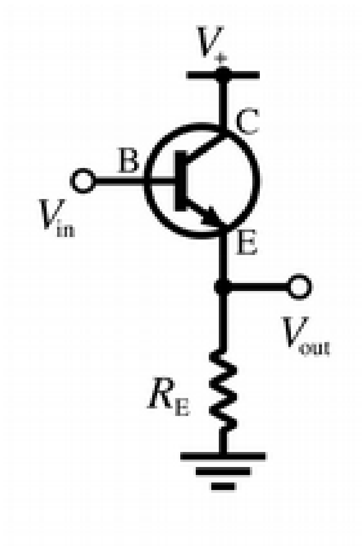


Figure 4B - Simple transistor buffer.

Therefore, we need a way to make available more current at Vout with a high resistance divider network. The way to do this is with a **buffer** or **voltage follower**. A buffer will take a voltage signal and can output it at a particular ratio, say 1:1 (no voltage amplification) while making available on the output side **greater current.** This provides the current necessary for the ADC input. A buffer in this case is usually a 1:1 amplifier, which takes an input voltage and outputs **the same** output voltage, with the added power of the amplifier's transistors, giving the output voltage **greater available current / lower output impedance**. More available current enables the ADC to sample **faster**, meaning greater accuracy. Common also are 1:8 buffers, meaning a **gain** of 8.

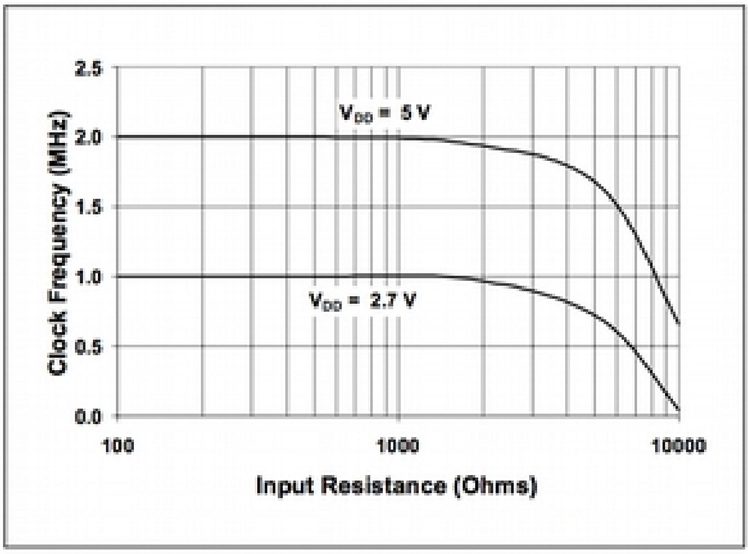


Figure 5 - Maximum Clock Frequency vs. Input Resistance (to maintain less than a 0.1 LSB deviation in Integral Nonlinearity from nominal conditions).

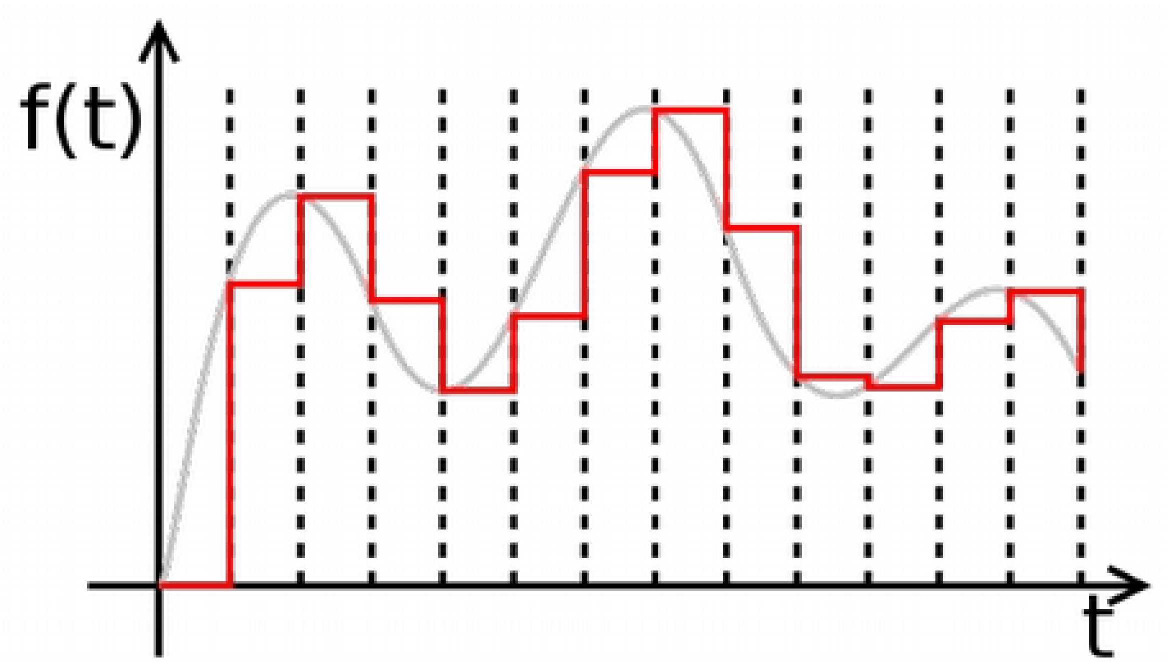


Figure 6 - Sample and hold for varying input: Obtained from en:User:Petr.adamek (with permission) and previously saved as PD in PNG format. touched up a little and converted to SVG by en:User:Rbj - en:Zeroorderhold.signal.svg, Public Domain, https://commons.wikimedia.org/w/index.php?curid=870310

Galvanic Isolation and DC Voltage Sensing.

Take solar panels as an example, we have a **floating** system. To get a reading of the voltage between the positive and negative current carriers, we need a **physical** connection to both positive and (floating) ground cables. We want to send this information to our **earthed** energy monitoring system: This introduces the problem of **isolation between the two ground potentials,** or **galvanic isolation**. For clarity, the ground of the solar panel side could be at a higher voltage than the ground of the earthed system side, if we imagine taking a cable from each side, and touching them together, we might get a nasty surprise.. despite them both being called 'ground'. This applies to safety of devices also, if we had an earthed laptop being connected via serial to a floating ground solar system the result would probably be a broken laptop, as a burst of current would flow through the laptop between 'floating ground' and true earth.

It is dangerous to the user to not have proper consideration of galvanic isolation in floating ground solar systems (or any floating generation system). Precautions such as *double isolation* or deliberate *earthing of a metal enclosure* containing whatever devices being installed might need consideration.

Really, it means the creation of two systems (possibly in one enclosure), where on one side is the isolated floating side taking our voltage measurement, and on the other side is the earthed side with our energy monitoring gear, laptops etc. being protected. We need to transfer information about our voltage reading and perhaps other information between the two sides. Information can be sent from one side to the other using RF or WiFi, optical analog isolation ICs, optical digital isolation ICs, or transformer (coil-coil) type devices, to name a few.

Here in our imaginary 2-system setup, one floating, one earthed, the problem is requiring two sources of power, one isolated from the other. In essence, to overcome this problem two separate independent power-supplies are needed for each side, one for the floating side, one for the earthed side. This often requires two separate power supplies on each side, however there is a switching power-supply topology which uses a transformer coil as the primary inductor, thus creating two voltage rails from one power-supply, one isolated from the main circuit which we can use for the other side of the system.

Common-ground of voltage sensors:

Here's another thing to consider with voltage sensing.
Voltage sensing in DC systems comes with a requirement that the sensor and system to be measured must share a **common ground**. This is often the case, but it's worth being aware of.

Here's why.

First, consider that a typical multimeter voltage sensor may have an input impedance of **10 Mega Ohm**. A floating system may have a **varying resistance to ground** in the order of **1000s of Mega Ohms**.

This means that an **earthed** voltage sensing device cannot accurately measure the voltage of a **floating** system because:

A. The resistance to earth of the floating system is **varying**; and
B. The relative resistance-to-ground would create a tiny voltage drop across the voltage sensor, unfeasibly small to amplify accurately.

The diagram below shows why measuring the voltage of either the positive or negative rail of a floating DC system would result in a reading of near zero. Effectively this means we cannot truly know the voltage of the floating side, without actually being connected directly to it.

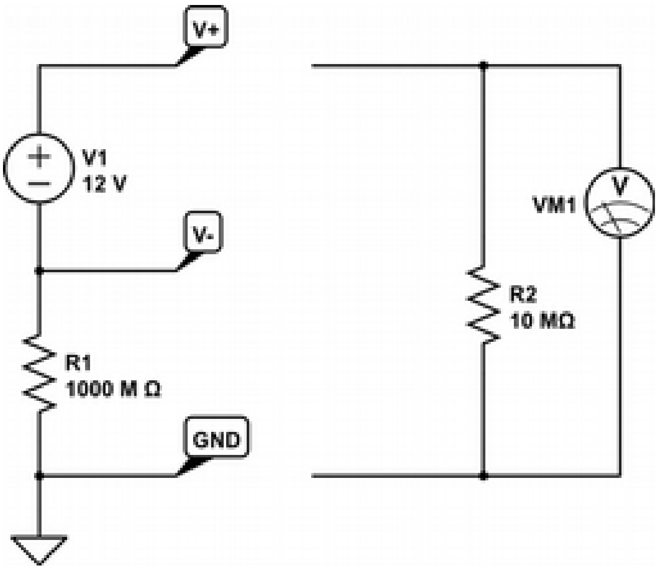


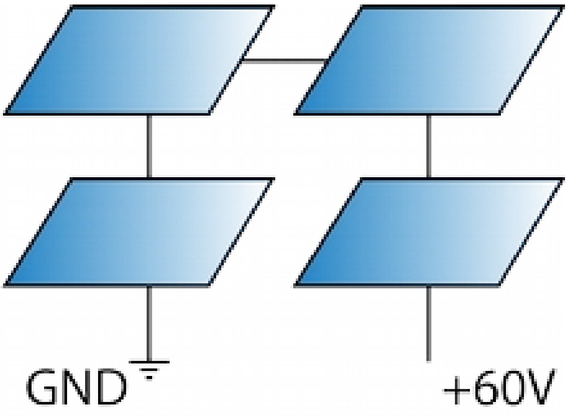
Figure 7 - Credit: Brian Drummond @ https://electronics.stackexchange.com/

Safety

To follow are several safety notes, all of which are much more apparent with DC monitoring than with AC. The shunt or hall effect device will be referred to below as the 'sensor'.

Floating systems:

Sometimes referred to as floating supply or floating ground, these are a major danger of any DC generation system and must be properly understood to protect people and equipment from injury and damage! An example of a floating ground is a non-earth solar PV array.
In a typical array we can expect voltage such in in the diagrams below:



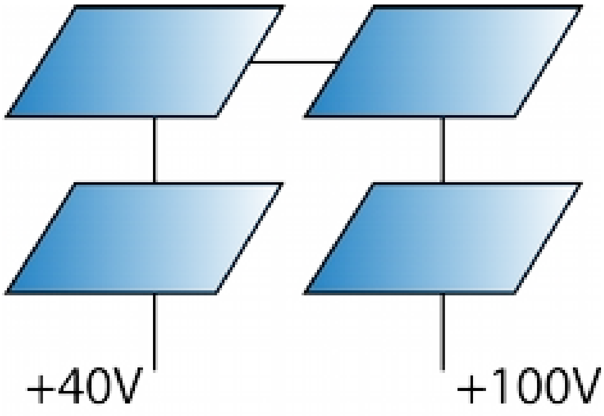


Figure 8A

Figure 8B

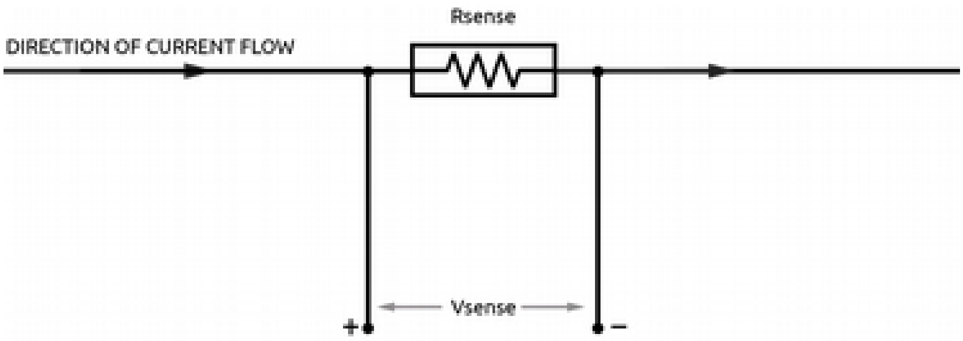
In figure 8A we have a safer system that's grounded to earth potential.
In figure 8B the system is floating, perhaps by design, or perhaps from a fault condition, ground has floated to +40VDC above actual earth. Consequently, the high-side rail has gone to +100VDC, dangerous stuff.
What's particularly dangerous about this situation is the charge buildup in the generator (panels) and metal chassis' surrounding the PV and equipment, meaning the available current is the generator charge + batteries (if any) + chassis charge buildup. So although +40VDC isn't a great deal, the available current is. If an earthed device was connected to a floating system like this, a huge amount a current would probably destroy the device(s) instantly and potentially start fires.

For DC generation systems that are non-isolated, a copper stake should ideally be driven into the ground and connected to a **single** point of the system, typically near the battery if there is one.

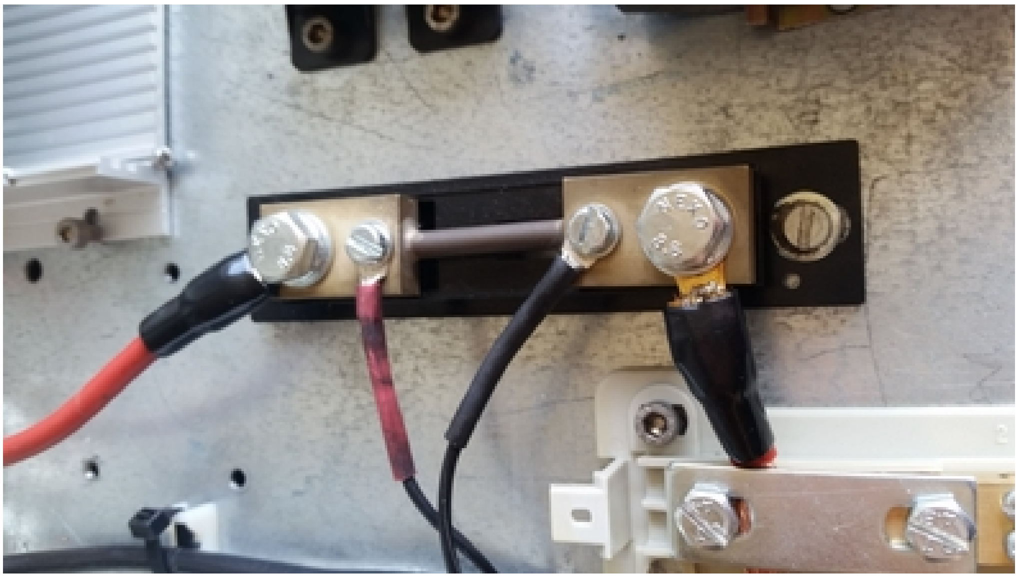
Earthing of generator systems can be either at the negative or positive pole. DC systems at 48VDC nominal are almost always positive grounded. This is because of the corrosion potential of copper at these voltages, the corrosion potential is the square of the voltage. Copper will corrode to a black oxide if charged positively for long enough, and be very difficult to work with.

Cables:

Unlike AC measurement, DC measurement often requires that cables are physically installed/cut/altered to accommodate the sensor. If we come back to our first diagram:



Rsense must exist in the main current path. The cable must be mounted either side of the shunt:



Photograph of a 100 Ampere manganin shunt showing the larger diameter current carrier and the small sense leads bolted on. The shunt is bolted onto the metal backing and is isolated from the backing due to the black plastic mounting.

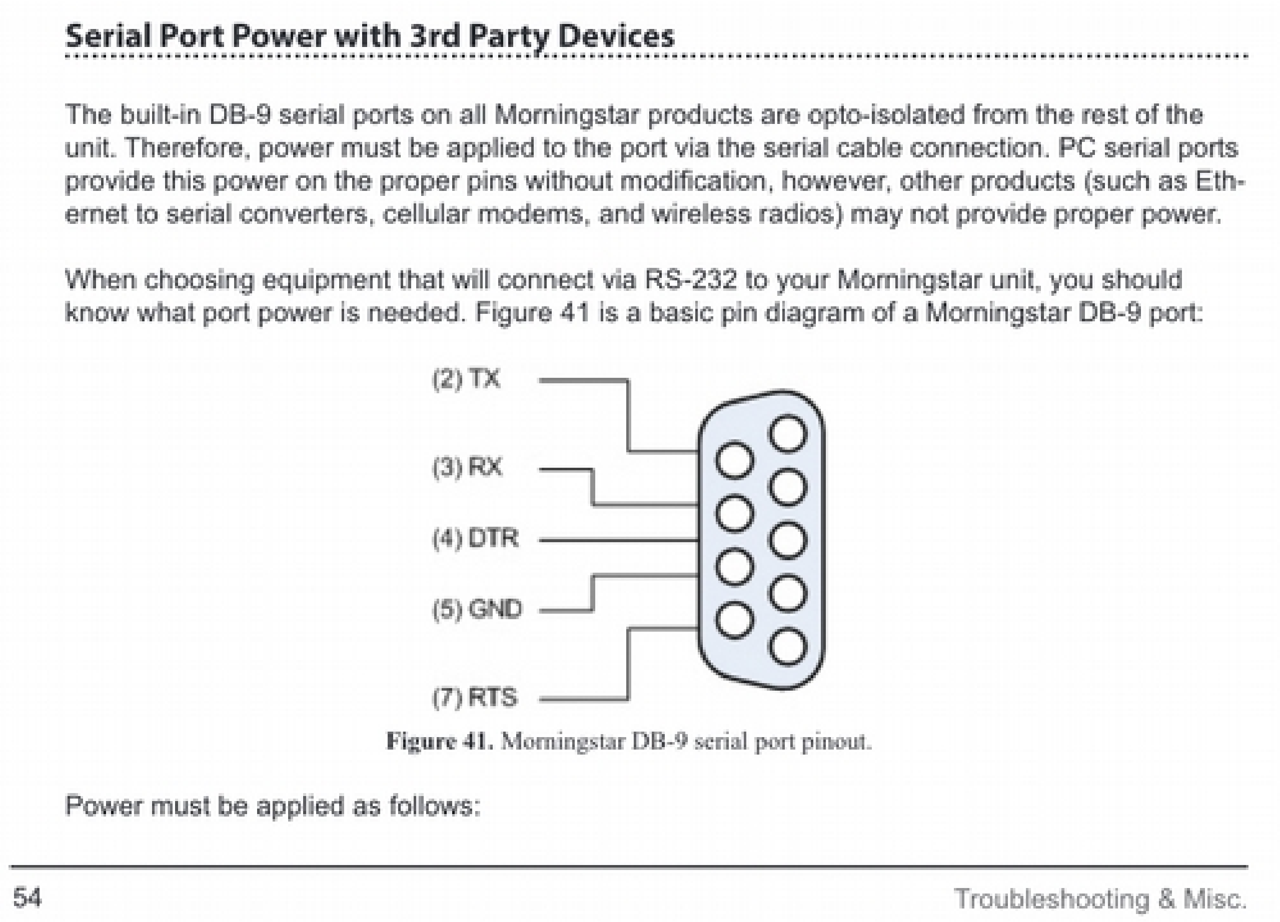
Heat:

The shunt resistance (Ohms) **and** heat dissipation rating (Watts) must be selected according to the expected current during normal operation (Amps). The shunts value can't be selected solely on it's Peak Current rating. Be sure to do your $P=I^2R$ calculations! The peak power rating of the shunt is chosen at 2 or 3 times the expected current.

A ready made calculator can be found at [this spreadsheet.]

Opto-isolation

Here’s an example extracted from a MorningStar solar charge controller, the RS-232 9-pin port requires power to operate the opto-isolators inside.



Serial Port Power with 3rd Party Devices

The built-in DB-9 serial ports on all Morningstar products are opto-isolated from the rest of the unit. Therefore, power must be applied to the port via the serial cable connection. PC serial ports provide this power on the proper pins without modification, however, other products (such as Ethernet to serial converters, cellular modems, and wireless radios) may not provide proper power.

When choosing equipment that will connect via RS-232 to your Morningstar unit, you should know what port power is needed. Figure 41 is a basic pin diagram of a Morningstar DB-9 port:

Figure 41. Morningstar DB-9 serial port pinout.

Power must be applied as follows:

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