Internal resistance

A voltage value is always indicated on current and voltage sources, such as batteries, dynamos, generators, power supply units, and solar cells.

If you connect a load, such as a small light bulb, and measure the voltage drop across the load's resistor, you will find that this measured voltage is usually less than the indicated voltage. Why is that?
(Note: For the sake of simplicity, the following text will discuss only voltage sources, but it is understood to apply also to current sources).

Voltage sources have resistance themselves

The electrical resistance of a voltage source is called **internal resistance (**R_i). The internal resistance is caused by the nature of the voltage source itself.

- In a **battery**, for example, the internal resistance is caused by the resistance losses in the electrolytes that occur when energy is converted (chemical to electrical energy). Alkaline manganese AA batteries have a relatively low internal resistance. The internal resistance depends on the load duration. In a 1.5-volt AA battery, this resistance is approx. 0.01 ohm for a short duration and increases to approx. 1 ohm for longer durations.
- This is completely different in **solar cells**: In this case, the internal resistance is relatively high and depends greatly on the illuminance. In a 0.6V/150mV silicon solar cell, the internal resistance is up to 4 ohms in bright lighting. This is why the voltage drops significantly when a low-resistance load is connected.

Assuming the existence of internal resistance, a real voltage source can be illustrated with the following equivalent circuit diagram: An ideal voltage source (U_0) with constant voltage and a variable resistance R_i. The voltage that drops across this "equivalent circuit" is known as the terminal voltage (U_T), or the "real" voltage.

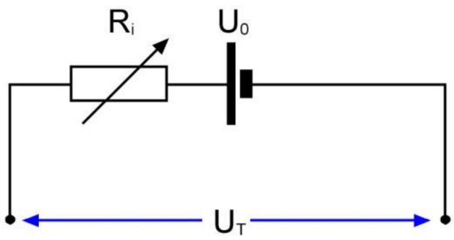


Fig. 1: Equivalent circuit diagram for a voltage source with internal resistance.

According to Ohm's law, the following relationship applies between voltage (U), current (I), and resistance (R):

$$U = R \cdot I$$

Together with Kirchhoff's voltage law, the following equation results for the terminal voltage (see Fig. 1):

$$U_T + R_i \cdot I = U_0$$

Properties of voltage sources

The following properties of a voltage source can be explained based on internal resistance:

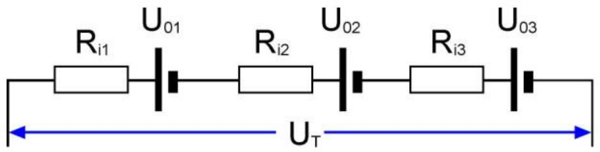
Property	Practical example
The higher the flowing current or the internal resistance of the voltage source is, the lower the **terminal voltage** will be.	A car with a partially discharged or rather old battery won't start in the winter. The internal resistance is so high that the terminal voltage is insufficient to turn the starter motor with enough power.
If no current is flowing (a load is not connected; this is called no-load operation), the terminal voltage is equal to the ideal voltage; this is referred to as **no-load voltage**.	This property is used, for example, to measure the voltage of a voltage source. The meter's resistance is so high that practically zero load current flows through the meter. The meter thus measures the no-load voltage. Some typical no-load voltages: Alkaline AA battery: 1.5 V 0.5V/150mA solar cell: 0.55 V
The maximum current that can be drawn from a battery, the **short-circuit current**, is limited by the internal resistance. This means that the current flow cannot reach infinite levels.	One example of such a short-circuit current is the 80 A (caution!) indicated for the alkaline AA battery (1.5 V). This current flows when a short circuit occurs with an approx. 1-mm thick copper wire. A 0.5V/150mA solar cell has a short-circuit current of 0.11 A.

Internal resistance for voltage sources connected in series and in parallel

From practice, we know that we obtain two, three, etc. times more voltage by connecting in series two, three, etc. batteries of the same type. If you need a higher current, you must connect the batteries in parallel.
How does the internal resistance behave in these cases? And do all voltage sources behave the same?

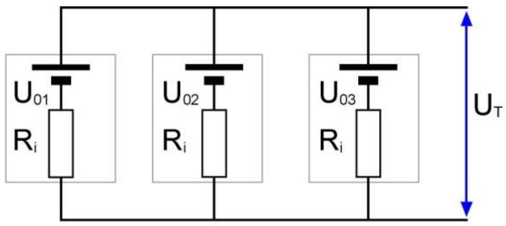
Battery

The internal resistance of an individual battery is constant.
If you look at the series circuit of batteries in the equivalent circuit diagram (see Fig. 2), it becomes clear that the internal resistances add up like the voltages, since they are also connected in series. Thus, in a series circuit with two batteries, the internal resistance doubles, etc. This increase in internal resistance results in a decrease in the short-circuit current.
Similarly, a parallel circuit (see Fig. 3) has a constant voltage at a lower total internal resistance. Thus, in a parallel circuit with two batteries, the internal resistance is cut in half, etc. This ultimately results in higher currents.



$$R_{i,\,total} = R_{i1} + R_{i2} + R_{i3}$$

Fig. 2: Equivalent circuit diagram for a series circuit of voltage sources. The total internal resistance is the sum of the individual internal resistances.



$$R_{i,\,total} = R_i / 3$$

Fig. 3: Equivalent circuit diagram for a parallel circuit of voltage sources. The total internal resistance is equal to the internal resistance of one voltage source divided by the number of connected voltage sources.

Example: If you connect a relatively low-power load to the AA battery, such as a solar motor (e.g., 0.3 V/4 mA), the voltage drop across the battery's internal resistance is low. By contrast, if you connect a more powerful motor or incandescent lamp, the voltage drop across the battery's internal resistance will be greater, and the useful output will drop.

Solar cell

The internal resistance of a solar cell depends on the structure, surface area, and material of the solar cell itself, but also on the illuminance.
To allow a comparison with a battery or accumulator, which we also assume is charged, we will consider the solar cell **at optimum lighting**.
The relationships that occur when solar cells are interconnected are similar to those of batteries. If you attach a load with a high resistance, e.g., an LCD clock, effectively the solar cell's total voltage will drop across the load. On the other hand, if you attach a relatively low-resistance motor to the circuit, most of the voltage will drop across the solar cell's internal resistance, and the useful output will drop. Depending on the type, electric motors need a certain minimum voltage and current. Many solar motors may start up at approx. 0.3 volts, but they need a relatively high amount of current. Compared to the solar motor's resistance, then, the solar cell's internal resistance is high and the motor does not turn at all or only very slowly when connected to a solar cell.
Therefore, in experiments with several solar cells and solar motors, you will often find that the parallel circuit delivers considerably more power and thus a higher motor speed than the series circuit. By contrast, **in lower lighting** the series circuit is often better for getting the motor to start at all. The reason for this is the fact that as the illuminance decreases, the solar cell's internal resistance

increases, and thus not only does the useful solar energy drop, but also the voltage at the load.

You will observe a similar situation for operation of light-emitting diodes with solar cells. Connecting the LEDs in parallel doesn't do any good even under optimum lighting; they won't light up as long as several solar cells are not connected in series and thus do not reach their minimum voltage.

Summary

The useful output of a current or voltage source always depends on the ratio of internal resistance and the resistance of the load.
Theoretically, the useful output is maximized when the load's resistance is equal to the source's resistance. In addition, depending on the type of load, there may be certain necessary minimum voltages or minimum currents.
In practical terms, we're working for example in a household electrical circuit with a relatively high load resistance. The voltage remains largely stable, and sufficient current is always available for the usual loads. The internal resistance of the "household electrical circuit" current or voltage source thus appears to play no role. However, if you were to attach loads with extremely low resistance, e.g., several radiators, the voltage would drop noticeably in the power grid (= internal resistance of the source), and the wiring would become hot and burn out. That's why there are fuses.
We observe these same laws in an individual solar cell, but in this case we're at the far low end of the power range of current and voltage sources. For this reason, relatively small changes have an immediate or clear effect when the load is connected. Since the individual solar cell delivers only relatively low voltage and current, several cells are interconnected into solar modules. Through a combination of parallel and series circuit, you can achieve voltages of approx. 36 V and 8 A per module. When many such modules are interconnected, they form a current and voltage source that is suitable for feeding (the alternating direct current) into the public grid.