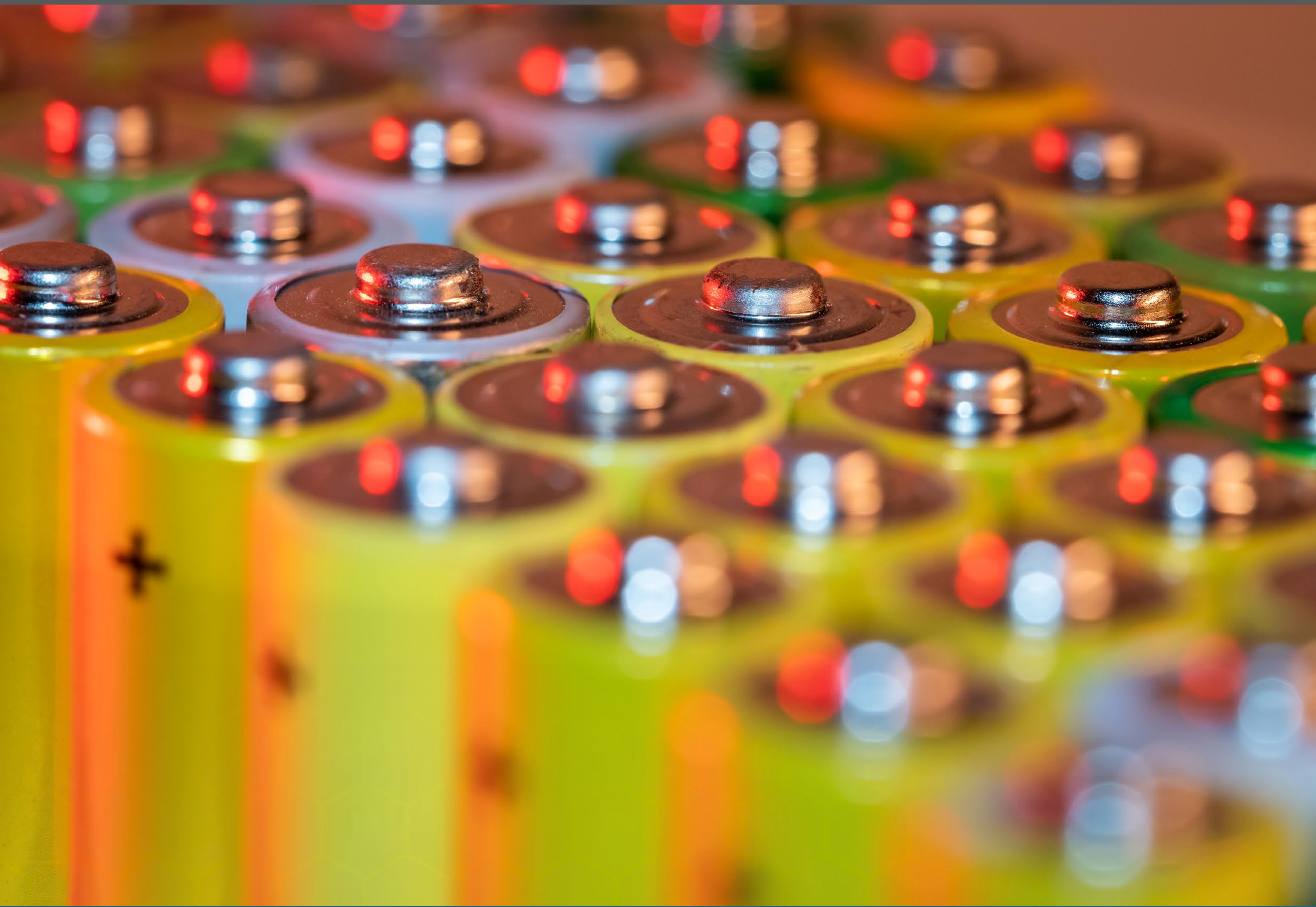
MATRIX | ELECTRICAL MACHINES



BATTERY SIMULATOR

CP1166

Inspiring The Next Generation Of Engineers

www.matrixtsl.com

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Operating the Battery Simulator

The Battery Simulator

The Matrix Battery Simulator is a DC power supply that simulates the operation of an electrochemical battery. We will use this to learn about the use and characteristics of different types and configurations of batteries. As well as understanding batteries on their own, we will study their application as part of an electrical machine.

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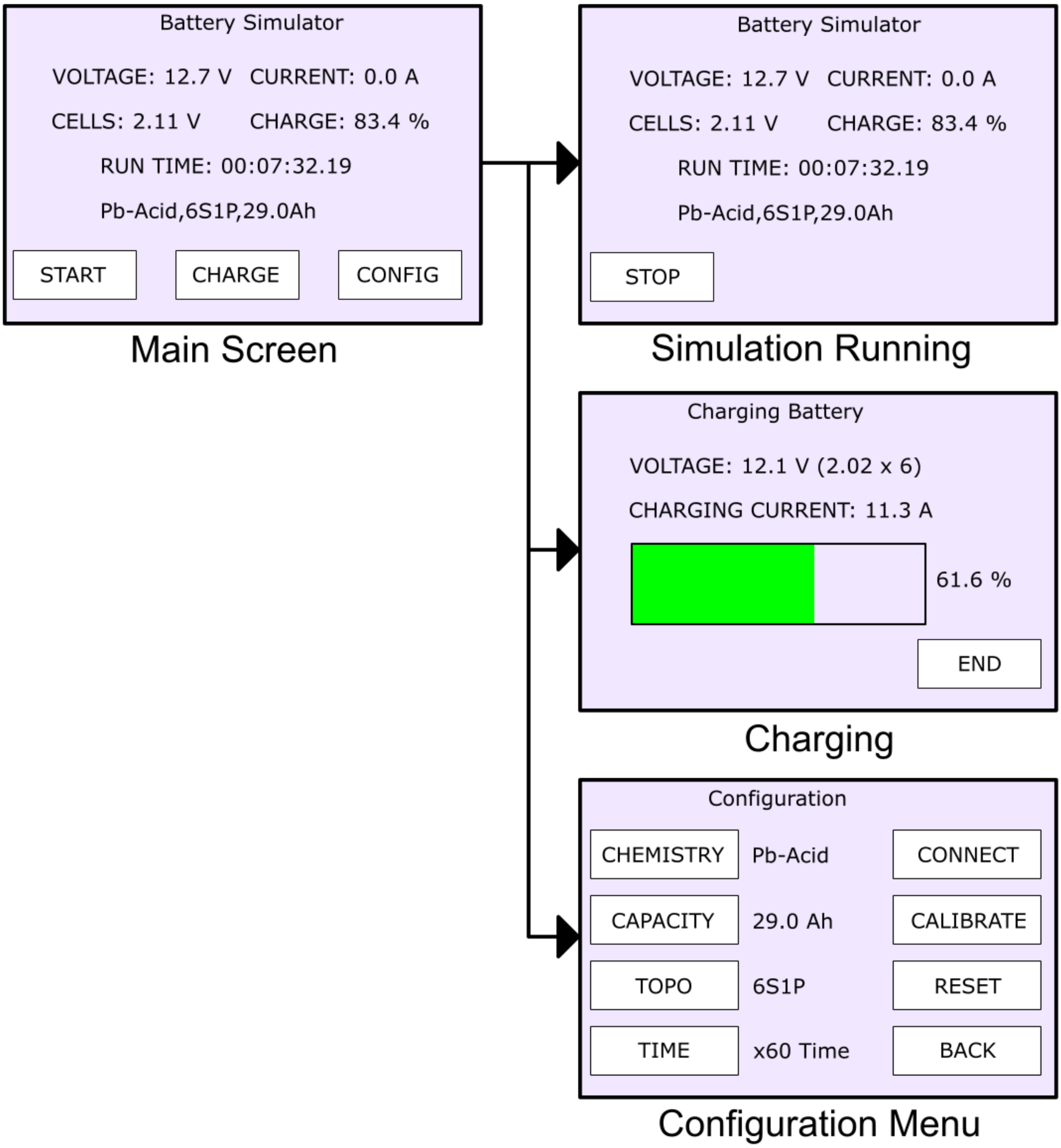
Operating the Battery Simulator

The battery simulator can be controlled using the touchscreen on the front panel or the FlowCode Application available on the Matrix website. See the manual for more details on how to control and configure the device.



From the main screen, the simulation can be started and stopped, the simulated battery can be charged and the configuration menu can be accessed.

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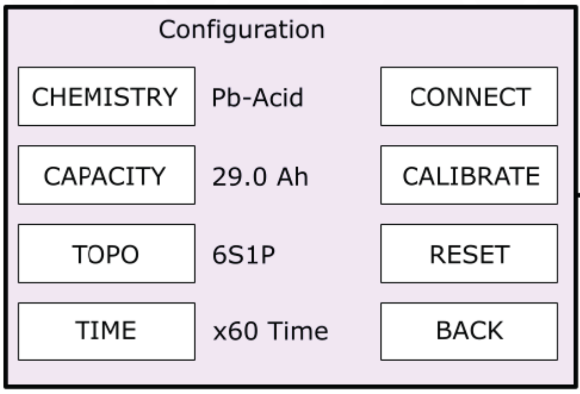
Operating the Battery Simulator



Configuration Menu

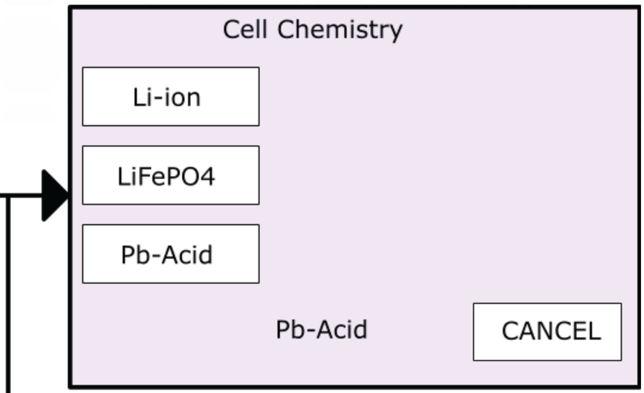
The configuration menu enables the battery and simulation to be configured.

The cell chemistry can be lead-acid (Pb-acid), lithium-ion (Li-ion) or lithium-iron-phosphate (LiFePO4). Each chemistry behaves differently and its characteristics will be investigated.

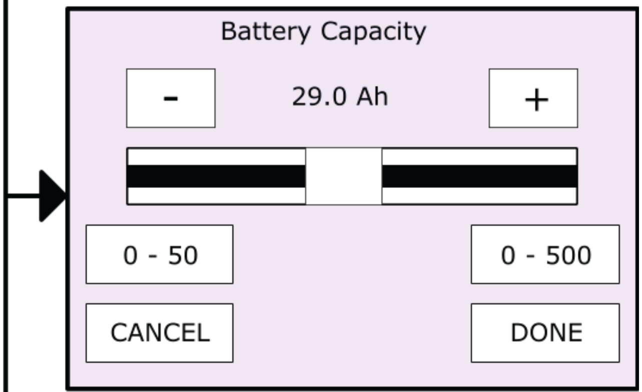
The capacity of the simulated battery can be adjusted. This will affect the amount of energy that can be delivered before the battery voltage drops and the simulation switches off.

The topology of the battery can be chosen. Simulated cells can be connected in series or in parallel. The selected topology is represented by a code consisting of the number of series cells followed by the letter ‘S’, followed by the number of parallel strings and then the letter ‘P’. For example, twenty cells arranged in four parallel strings with five series cells in each string would be written as 5S4P.

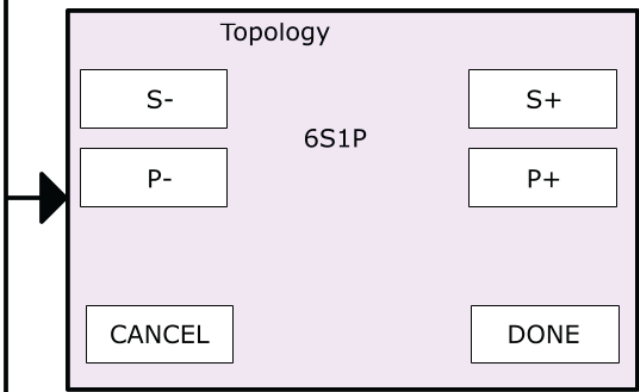
All of these screens are described in more detail in the operating manual.



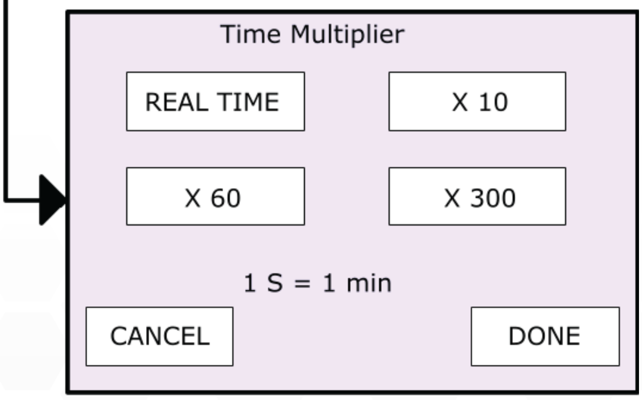
Cell Chemistry



Battery Capacity



Battery Topology



Time Multiplier

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Note About Test Loads

The battery simulator is able to supply power to other components in the Electrical Machines range providing a simulation of a battery powered system. For testing the behaviour of a battery in isolation it is convenient to use resistors.

Before connecting a resistor to the battery simulator, it is important to check the power rating of the resistor. When a battery or voltage supply is connected to a resistor, the power dissipated by the resistor can be calculated using the formula: -

$$P = V^2 / R$$

Where P is power in watts, V is voltage and R is resistance in ohms. The power rating of the resistor must be greater than or equal to the power dissipated.

If the power dissipated is close to the maximum rating of the resistor then it will get warm.If it exceeds the maximum rating then the resistor can overheat and be damaged.

Worked examples: -

1. A ten-ohm resistor has a power rating of 100 W. What is the largest voltage that can safely be used?

We can rearrange the rule above: -

$$V^2 \leq P_{max} \cdot R$$

Since R is 10 and P_{max} is 100, it follows that V^2 must be less than or equal to 1000 so the greatest voltage allowed is √1000 = 31.6 V.

2. What resistor would be required to draw four amps from twenty volts.

We can calculate the resistance required using Ohm's law.

$$R = V / I$$

The resistance is 20V / 4 A = 5Ω. Using either $P = V^2 / R$ or $P = V \cdot I$, we get a minimum power rating of 80W. The resistor must have a power rating of 80W or greater.

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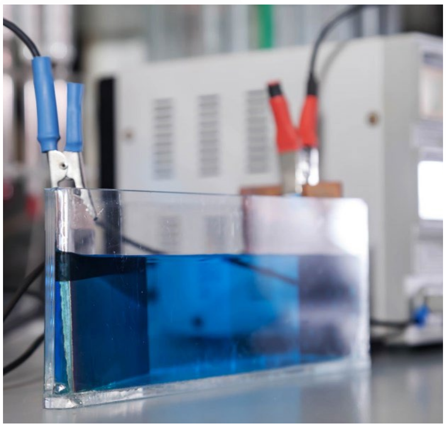
WORKSHEETS

Worksheet 1 – Battery Chemistries



A battery is made up of electrochemical cells that convert stored chemical energy into useable electrical energy. A chemical reaction within the cell generates a voltage between the terminals. This voltage is then able to provide electric current to power a circuit.

Each cell has a positive terminal and a negative terminal. Electric current flows out of the positive terminal, does its work within a load and returns to the negative terminal. Rechargeable batteries can also convert electrical energy back into stored chemical energy. When charging, current is forced into the positive terminal. The characteristics of a battery are determined by the chemical composition.
Three different chemistries are simulated, lead-acid (Pb-acid), lithium-ion (Li-ion) and lithium-iron-phosphate (LiFePO4). In this worksheet, we shall begin characterising the three types.

Over to you:

From the home screen, touch the CONFIG button to enter the configuration screen.
Set the topology to 1S1P, one single cell. Set the chemistry to Pb-acid.
Return to the home screen and touch START. Record the output voltage.

Stop the simulation and go back to the configuration screen. Change the chemistry to Li-ion. Start the simulation and again record the output voltage.

Finally measure the output voltage of a LiFePO4 cell.

So What?

As well as differing in cell voltage, the chemistries have other differences that make them suitable for different applications.

Challenge

As well as the three chemistries available in the simulator, there are many other battery chemistries. Research and see how many types you can find. Where are the different types used?
It is possible to create a battery by pushing two dissimilar metals into an orange or similar fruit. Research how to do this and try it. What voltage does it produce?

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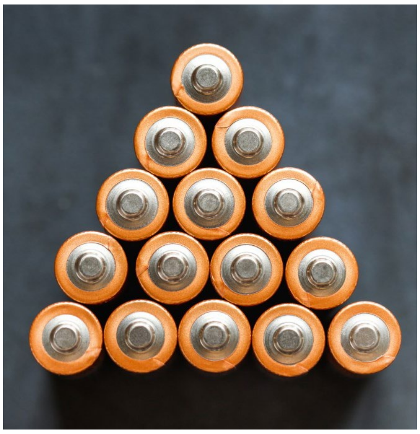
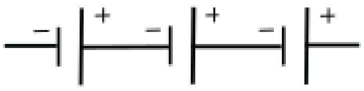
WORKSHEETS

Worksheet 2 – Batteries in Series and Parallel



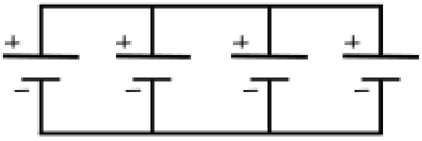
In many applications, a single cell does not produce sufficient voltage or current. If we want more, then we can wire the terminals of two or more cells together. This way they work together. In this worksheet, we shall investigate the two ways of wiring cells: series and parallel.

To wire cells in series, the positive terminal of one cell is wired to the negative terminal of the next. This can be repeated with as many cells as required. When we describe a battery with cells wired in series, we write the number of cells followed by the letter 'S'.



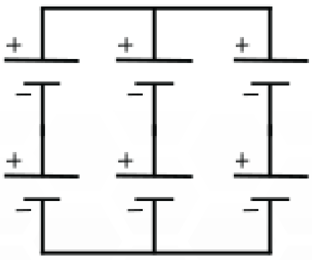
Three Series Cells, 3S

To wire cells in parallel, the positive terminals of the cells are connected together. The negative terminals are separately connected together. When we describe a battery with cells wired in parallel, we write the number of cells followed by the letter 'P'.



Four Parallel Cells, 4P

We can create a battery using a combination of the two methods. First a number of cells are wired in series. A number of chains of series cells can then be connected in parallel. To describe such a battery, we write the number of cells in each series chain, the letter 'S', the number of chains in parallel and then the letter 'P'. For example, "3S4P" describes a battery with four parallel chains of three series cells each.



Three Parallel Chains of Two Series Cells, 2S3P

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When combining series and parallel connections, it is important to make sure that every chain connected in parallel has the same number of series cells. Think of it like placing a platform on columns of building blocks. You can have any number of blocks in each column and any number of columns. However, the columns must all be of equal height otherwise the platform would not be level.

The battery simulator takes care of connecting cells for us. We only have to tell it how many series cells we want in each chain and how many chains to connect in parallel.

Over to you:

In the configuration screen, select the Pb-acid chemistry. Set the topology to 2S1P, two cells in series. Start the simulation and record the output voltage. Change the topology to 4S1P, four cells in series, and again record the output voltage.

Fill in output voltages in the table in the student handout for the series and parallel combinations up to six cells in series and four cells in parallel. Plot voltage against number of parallel cells on a graph. Also plot voltage against number of series cells.

So What?

When cells are connected in series, the total voltage is increased. This allows batteries to be constructed that have a higher voltage than an individual cell. When cells are connected in parallel, the voltage remains the same. One reason for connecting cells in parallel is to increase capacity. In the next worksheet, we shall investigate another advantage.

Challenge:

Research topologies of different batteries and why they are used. For example, a car starter battery is described as a "12 volt, lead-acid Battery", how might this be constructed? Why might a torch or remote control require two AA batteries?

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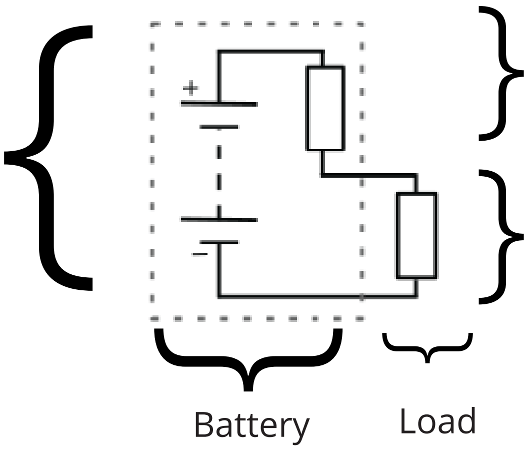
An ideal battery would provide a constant voltage in all conditions. In a real battery, the output voltage drops as the current increases. This makes it appear as if the battery contains an internal resistance that forms part of the electric circuit.

Full (OpenCircuit) voltage of the battery.
V_0



Voltage drop across internal resistance
Vi = I·Ri

Voltage across load is reduced by the voltage across the internal Resistance.
$V_L = V_0 - V_i$

We can calculate the internal resistance of a battery. First we measure the open-circuit voltage of the battery, this is the voltage with no load connected. With no load, there is no current and therefore no voltage drop across the internal resistance. (In reality, a multimeter draws a very small current but it is small enough that it can be ignored.)

Next we connect a load and measure the output voltage and current. The voltage across the internal resistance is considered to be the difference between the open circuit voltage and the loaded output voltage. The same current flowing through the load is also flowing through the internal resistance. From Ohm's law we can calculate the internal resistance: -

Internal Resistance = (Open-circuit Voltage – Loaded Voltage) / Load Current

$$R_i = (V_0 - V_L) / I$$

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Over to you:

Set the chemistry to lead-acid and configure the topology to be six cells in series 6S1P. This gives a nominal 12-volt battery. Start the simulation and measure the open-circuit output voltage.Attach a load and measure the output voltage and current with the load attached. Calculate the internal resistance.

A ten-ohm resistor is adequate for this experiment but for more accurate results a load of around three-ohms should be used. Check that the power rating of the resistor used is sufficient. See page 6 for details of how to calculate power rating. Be careful when handling the resistor as its surface can become hot during use!

Change the topology to be twelve cells in two parallel sets of six in series, 6S2P. Repeat the experiment and calculate the internal resistance in this configuration. Change the topology to be 24 cells in four parallel sets of six in series, 6S4P. Again, measure the internal resistance.

Change the chemistry to lithium ion. As the cell voltage of Li-ion batteries is higher than lead acid, we only need three cells to construct a nominal 12-volt battery. Repeat the experiment with the configurations 3S1P, 3S2P and 3S4P.

Change the chemistry to lithium iron phosphate and repeat the experiment with the configurations 4S1P, 4S2P and 4S4P.

So What?

Internal resistance is a serious limitation in practical battery applications. This is especially so in high current applications. Putting cells in parallel reduces the effect of internal resistance. The effective internal resistance is the resistance of one cell divided by the number of cells.

The cells that are simulated in the battery simulator are uniform for each type of chemistry. In real batteries, the internal resistance is governed by the geometry of the electrodes. Battery designers must take this into account when designing batteries for specific applications.

Challenge

Consider some real-world applications of batteries. In what applications would internal resistance be a serious consideration? In what applications would it be less important?

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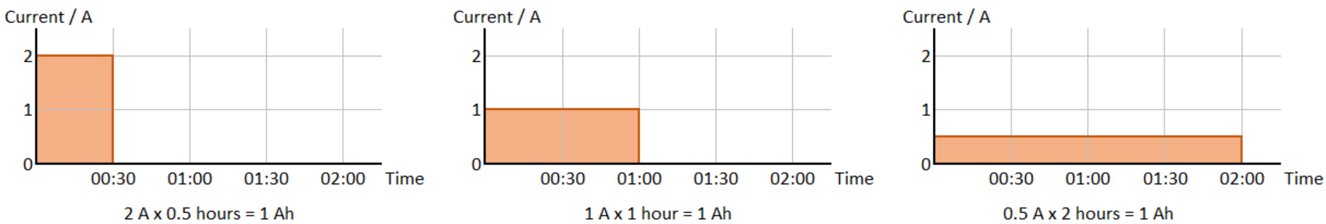
Worksheet 4 – Battery Capacity

The function of a battery is to store energy. The capacity of a battery is measured in amp-hours (Ah). A one amp-hour battery is capable of providing a current of one amp for a period of one hour before it is fully discharged. The same battery could provide two amps for half an hour. It could equally provide half an amp for two hours.



Simplified Graphs of Current against Time

The capacity in amp-hours is the product of multiplying the current by the time that the battery is able to provide that current. This is the same as the area under the graph of current vs time. In the above graphs, the areas are all the same, one amp-hour. In a real application, the current could change over time but the area under the graph would still equal the battery capacity.

Over to you:

Configure a 10S1P lead-acid battery with a capacity of 1 Ah. In the configuration screen, select TIME and set the time multiplier to x60. This will make the simulation run 60 times faster than real life so one hour of simulation time will take one minute of real time.

Connect a resistor of around ten ohms to the output of the simulator. Check that the power rating of the resistor is sufficient.

When started, the output current should be around two amps. With the time multiplier set to x60, it should only take half a minute to simulate half an hour of discharge. Watch the remaining charge indicator and when it gets to 50%, record the output current. When it reaches 0%, fully discharged, and cuts off, record the simulated time shown.

Repeat the experiment with 5S1P and 2S1P batteries. The different battery voltage will cause different currents and thus different discharge rates.

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So What?

A fully charged battery holds a certain amount of charge. A higher current uses this charge more quickly and the battery runs flat sooner. A lower current uses this charge more slowly and the battery will supply this current for a longer time.

Challenge:

1. In theory, the three experiments should each have shown that the simulated battery provided exactly one amp-hour of charge. How accurate are your results? Can you think of a way of improving the experiment?
2. Find capacity ratings of common batteries. For example automotive batteries, mobile phone batteries or power banks and general purpose rechargable batteries. Sometimes the capacity of a battery is given in watt-hours (Wh) or milli-amp-hours (mAh). Can you explain how to convert these to amp-hours? Hint: Remember that 1 A is 1000 mA. Also remember that power in watts is voltage multiplied by current.

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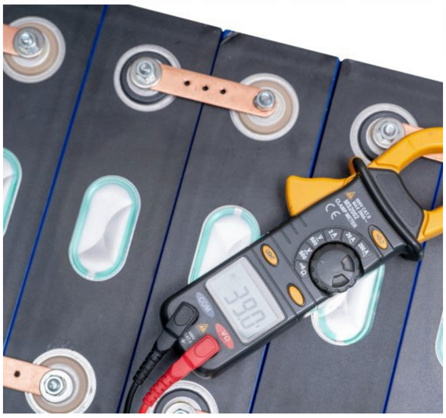
WORKSHEETS

Worksheet 5 – Battery Discharge Curves



In the previous worksheet you may have noticed that the output voltage varied. An ideal battery would provide a constant voltage from full charge until completely discharged. In reality, as the energy stored in a battery is used, its output voltage reduces. The different chemistries will reduce by different amounts. In this worksheet we will investigate how each chemistry behaves.

Over to you:

Set the time multiplier to x60, this simulates one hour of discharge in one minute. Set the battery capacity to 2 Ah. Set the chemistry to Pb-acid and the topology to 6S1P. Start the simulator and connect a ten ohm resistor to the output.

Record the output voltage straight after connecting the load. Wait until the remaining charge in the battery drops to 90% and record the output voltage again. Record the voltage every time the charge drops by another 10%. Fill in the table in the student handout.

Change the chemistry to Li-ion and the topology to 3S1P. Repeat the experiment, filling in the next column of the table.

Change the chemistry to LiFePO4, the topology is still 3S1P. Fill in the last column.

Plot these results on a graph.

So What?

Designers of electrical systems must account for the drop in voltage as batteries discharge. This ranges from making sure that a battery-powered clock continues to function as its single AA battery drops a fraction of a volt to designing electric vehicles so that their full performance is available over the full range of their batteries.

In the search for new battery technologies, the drop in voltage is something that researchers must consider. A battery that lost most of its voltage near the beginning of its discharge would not be very useful.

Challenge

A battery-powered electrical system is able to measure the current that it draws from its battery and also has a built-in clock to measure time. Can you explain how the system might use these two measurements to estimate how much charge is remaining in the battery.

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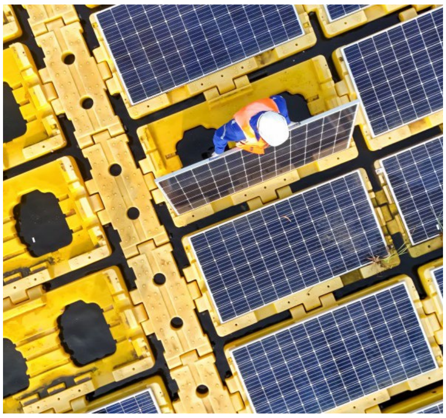
WORKSHEETS

Worksheet 6 – Battery Discharge Behaviour



So far, we have seen that batteries have a voltage that varies over the course of their discharge. We have also found that batteries exhibit an internal resistance. An obvious question is: does the internal resistance change over the discharge? The answer is that it does and in this worksheet we shall investigate how it varies for each of the chemistries.

Measuring the internal resistance is a little more involved than simply measuring the output voltage. Recall from the earlier worksheet that measuring internal resistance requires measuring both load voltage and open circuit voltage. Fortunately, the discharge of the battery will pause if the load is disconnected giving time to write down the voltage.

Over to you:

Set the configuration as follows: -
Chemistry: lead-acid
Topology: 6S1P
Capacity: 2 Ah

Set the time multiplier to x60. Start the simulation and record the open circuit voltage. Connect a ten-ohm load and record the voltage and current.

Wait for the charge to drop to 90%, record the voltage and current. Disconnect the load and record the open-circuit voltage.

Reconnect the load and wait for the charge to drop to 80%. As before, measure the load voltage and current and the open-circuit voltage. Take measurements every time the charge drops by 10%. After the discharge is complete, calculate the internal resistance at each point and plot both the open-circuit voltage and the internal resistance on a graph.

So What?

The increased internal resistance results in a lower voltage under load and reduced efficiency, especially when driving higher currents. The power lost due to the internal resistance can also cause heating in the battery. This is something that designers of electrical systems must account for.

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Worksheet 5 – Battery Discharge Curves

After taking charge out of a battery it must be put back in. Just as the discharge behavior of a battery follows well-defined patterns, the charging must as well. The difference with charging is that is driven by the external charging circuit. Batteries must be charged in the correct manner otherwise they may be damaged or even explode.

Battery chargers must be suited to the type of battery that they are charging. The Battery Simulator Box can simulate charging each of the three chemistries. In general, a charger will provide a constant current for a certain time and then switch to a constant voltage until the battery is fully charged. Depending on the type of battery chemistry, the charger will then either switch off or provide a float charge to maintain the battery at 100%.

Over to you:

Configure the battery to be six lead-acid cells in series. Configure the capacity to be 1.0 Ah and set the time multiplier to x60. Start the simulator with a test load and run until the charge is used up and the simulation cuts off.

With the battery fully discharged, touch the charge button to start charging. At 20 minute intervals (20 seconds in the real world), record the battery voltage, charging current and state of charge as shown on the screen.

At the beginning, the battery charges quite quickly. Around 80% the charger switches to constant voltage mode and charging is slower. At this point, it is possible to stop charging, change the time multiplier to x300 and then resume charging. Readings can now be taken every hour (12 seconds in the real world).

Once the battery is fully charged, stop the charger and plot the readings on a graph. Change the chemistry to Li-ion and repeat the test.

Repeat the test again, this time with the chemistry set to LiFePO4.

Challenge

In the battery simulator, all the cells that make up a battery are in perfect balance. In a real battery, cells can get out of balance. Certain cells in a series chain may be more discharged than others. To restore balance to the cells during charging, more sophisticated chargers use a battery management system (BMS). Research these and explain how they work.

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STUDENT HANDOUT

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Worksheet 1 – Battery Chemistries

Cell Voltage for Pb-acid = ... Volts

Cell Voltage for Li-ion = ... Volts

Cell Voltage for LiFePO4 = ... Volts

Challenge:

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WORKSHEETS

Worksheet 2 – Batteries in Series and Parallel

Voltages of series and parallel combinations: -

Series / Parallel	1S	2S	4S	6S
1P				
2P				
4P				

Challenge:

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Worksheet 3 - Internal Resistance

Battery	Open-circuit Voltage	Load Voltage	Load Current	Internal resistance
Pb-acid 6S1P				
Pb acid 6S2P				
Pb acid 6S4P				

Battery	Open-circuit Voltage	Load Voltage	Load Current	Internal resistance
Li-ion 3S1P				
Li-ion 3S2P				
Li-ion 3S4P				

Battery	Open-circuit Voltage	Load Voltage	Load Current	Internal resistance
LiFePO4 4S1P				
LiFePO4 4S2P				
LiFePO4 4S4P				

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Challenge:

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Worksheet 4 - Battery Capacity

Battery	Output Current at 50%	Simulated time to full discharge	Current X time = Capacity Ah
10S1P			
5S1P			
2S1P			

Challenge:

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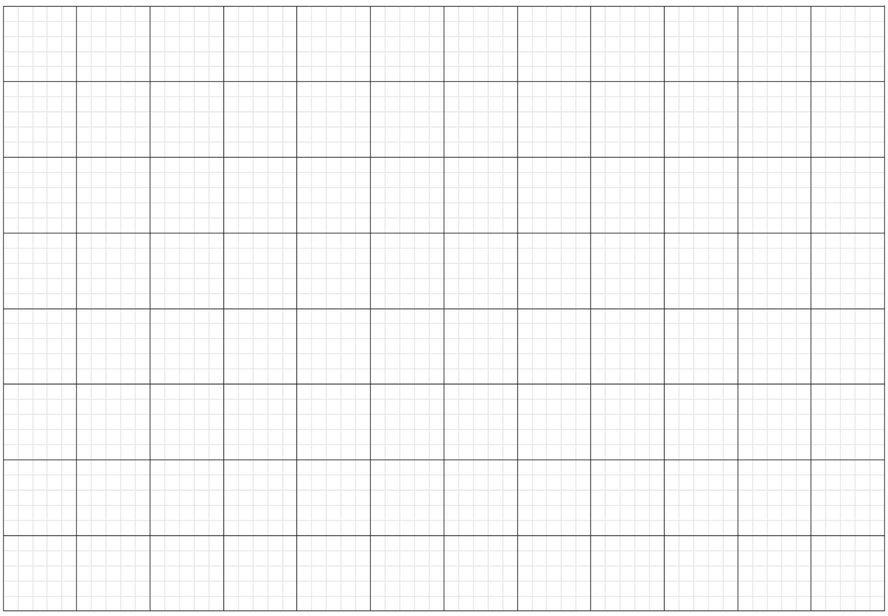
Worksheet 5 - Battery Discharge Curves

Remaining Charge	Pb-acid 6S1P	Li-ion 3S1P	LiFePO4 3S1P
100%			
90%			
80%			
70%			
60%			
50%			
40%			
30%			
20%			
10%			



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Challenge:

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WORKSHEETS

Worksheet 6 - Battery Discharge Behaviour

Charge	Open-Circuit Voltage	Load Voltage	Current	Internal Resistance
100%				
90%				
80%				
70%				
60%				
50%				
40%				
30%				
20%				
10%				

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Worksheet 7 - Battery Charging

Simulation Time	Battery Voltage	Changing Current	State of Charge

Simulation Time	Battery Voltage	Charging Current	State of Charge

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Worksheet 7 - Battery Charging

Simulation Time	Battery Voltage	Charging Current	State of Charge

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Challenge:

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Notes

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BATTERY SIMULATOR

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