Simulating Discharge Behavior of Batteries using PSpice

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Purpose

The purpose of this application note is to explain the charging and discharging behavior of batteries and to discuss battery models and their simulation in PSpice to see the result.

Audience

The document is for electronics or telecommunication engineers and college or university teachers and students.

Prerequisite

Familiarity with battery and the PSpice simulation tool.

Download

References can be found at ‘Attachments’ sections below the PDF. This pdf can be searched with the document title on https://support.cadence.com

Introducing Battery Discharge Basic Concepts

A battery converts chemical energy into electrical energy. The most common batteries in use today are: non-rechargeable alkaline cells, rechargeable nickel-cadmium (NiCad) cells, nickel- metal-hydride (NIMH) cells, lithium-ion battery, and so on.

NiCad and Nickel- Metal-Hydride (NIMH) Battery

A basic unit of the NiCad battery is the cell. A cell contains positive and negative plates, separators, electrolyte, cell vent, and cell container. Positive and negative plates are made from a nickel powder plaque on which nickel-hydroxide and cadmium-hydroxide has been deposited.

- Charging NiCad batteries

  When a charging current is applied to a NiCad battery, the negative plates lose oxygen and begin forming metallic cadmium. The active material of the positive plates, nickel-hydroxide, becomes highly oxidized. This process continues while the charging current is applied or until all the oxygen is removed from the negative plates and only cadmium remains.

  Towards the end of the charging cycle, the cells emit gas — which also occurs if the cells are overcharged. The gas is released by the decomposition of the water in the electrolyte into hydrogen at the negative plates and oxygen at the positive plates. The voltage applied during charging, as well as the temperature, determines when gassing will occur. To completely charge a NiCad battery, some gassing, however slight, must take place; thus, some water will be used.

- Discharge

  The chemical action is reversed during discharge. The positive plates slowly give up oxygen, which is regained by the negative plates. This process results in the conversion of the chemical energy into electrical energy. During discharge, the plates absorb a quantity of the electrolyte. On recharge, the level of the electrolyte rises and, at full charge, the electrolyte will be at its highest level. Therefore, water should be added only when the battery is fully charged.

- Construction.

  The cell is the basic unit of the NiCad battery. It consists of positive and negative plates, separators, electrolyte, cell vent, and cell container. The positive plates are made from a porous plaque on which nickel-hydroxide has been deposited. The negative plates are made from similar plaques on which cadmium-hydroxide is deposited. In both cases, the porous plaque is obtained by sintering nickel powder to a fine-mesh wire screen. Sintering is a process that fuses together extremely small granules of powder at a high temperature. After the active positive and negative materials are deposited on the plaque, it is formed and cut into the proper plate size. A nickel tab is then welded to a corner of each plate and the plates are assembled with the tabs welded to the proper terminals. The plates are separated from each other by a continuous strip of porous plastic.

The electrolyte used in the NiCad battery is a 30 percent solution of potassium hydroxide (KOH) in distilled water. The specific gravity of the electrolyte remains between 1.240 and 1.300 at room temperature. It must be noted that no appreciable changes occur in the electrolyte during charge or discharge. Because of this, the battery charge cannot be determined by a specific gravity check of the electrolyte. The electrolyte level should be maintained just above the tops of the plates.

At the time of charging of NiCad battery, the negative plates lose oxygen and begin forming metallic cadmium. On the other hand, nickel-hydroxide at the positive plates becomes more oxidized. This process continues until all the oxygen is removed from the negative plates and only cadmium remains.

During discharge the process is reversed. The positive plates give up oxygen, which is regained by the negative plates. This chemical process results in the conversion of the chemical energy into electrical energy.

Nickel- Metal-Hydride (NIMH) batteries are similar to NiCad batteries. The only difference is that NIMH battery uses Hydrogen as an active element at the hydrogen absorbing electrode in place of Cadmium which is a toxic heavy metal.

Lithium-ion Battery

Like NiCaD batteries, a basic unit of the rechargeable lithium-ion battery is a cell with major components like positive electrode, a negative electrode, and a chemical called an electrolyte in between the electrodes.

The positive electrode is made of lithium-cobalt oxide ($LiCoO_2$) or lithium iron phosphate ($LiFePO_4$) and the negative electrode is made of carbon (graphite). When the battery is charging up, the lithium-based positive electrode gives up some of its lithium ions that move through the electrolyte to the negative electrode and are stored there.

At the time of discharging, the lithium ions move back across the electrolyte to the positive electrode generating the power. Generally speaking, lithium ion batteries are lighter, do not have "memory effect" issue, and are more environment friendly.

Battery Variables

All of the battery types modeled here share some common characteristics and deviations from ideal during discharge.

- The *capacity* of any group of cells may vary from +/- 20% up to +/- 50% when shelf time, number of recharge cycles, and manufacturing variances are taken into account. For this reason, parameters that change less than 15% are not considered in these models.
- The *capacity* of a cell decays with time after a complete charge. For Alkaline cells, this decay takes years to affect the usable capacity. For NICD and Lead-Acid batteries, the decay is 10 to 30% per month. This effect may be simulated by specifying a reduced state of charge at the start.
- The major deviation from ideal is that the *usable capacity* of a cell varies depending on the discharge rate. At very low discharge rates (< 100 hours), all batteries are very efficient. At very fast discharge rates (< 10 hours), the batteries are not as efficient and usable capacity is lost.
- For *pulsed loads* with cycle times greater than 10 seconds, the cell gives more total capacity than under a constant load. The rest portion of the pulsed load allows the battery chemistry to recover some of the lost capacity. But, as the pulsed load cycle time becomes less than one second, the cell does not have enough time to recover and usable capacity is not increased. In these cases, the RMS value of the pulsed discharge current should be used in the simulation.
- *Cell temperature* affects both the cell resistance and usable capacity. Low cell temperatures reduce the usable capacity; only a slight decrease is noted at high temperatures. For the battery types modeled here, the change in resistance versus temperature falls below the 15% change threshold, so these effects are not modeled. These changes may be accounted for by adjusting the parameters passed to the various cell subcircuits.
- *Cell resistance* is a function of the cell's state of charge and, although there is a negligible effect on Lead-Acid and NICD types, Alkaline cells show a 2:1 to 4:1 increase in cell resistance from full charge to full discharge. Still, cell resistance is fairly flat and constant until 80% discharged, then the resistance increases sharply. The sharp fall in cell voltage during discharge can be looked upon as a large increase in cell resistance.
- *Open circuit cell voltage* varies with discharge temperature. But, this variation, even over a 0 to 60°C range, is much less than the difference in actual cell discharge voltage. Therefore, it is not useful to simulate. NICD batteries are the exception; these are used in high-rate discharge applications where the cells may increase in temperature by 25°C during discharge. Cell discharge voltage versus temperature is modeled in the NICD subcircuit.

Behavioral Modeling

The batteries are modeled using the following abstract:

1. Capacitor representing the A-H capacity of the cell.

2. Discharge rate normalizer to determine the lost capacity at high discharge rates.

3. A circuit to discharge the A-H capacity of the cell.

4. Cell voltage versus state-of-charge lookup table.

5. Cell resistance.

6. For NICD batteries, the thermal effects of the cell under high discharge rates.

To start modeling a cell, several actual discharge curves should be measured on a computerized constant-current load analyzer at a low rate (20 to 200 hours) to get an actual voltage versus capacity curve. A single curve is then made by averaging several curves, or picking a *typical* curve from the data. This data is then converted into a parameterized PSpice lookup table Voltage- Controlled Voltage Source (VCVS). This models the cell's output voltage versus the state-of-charge at low discharge rates.

A simplified VCVS definition is

```
E_Cell+OUT –OUT TABLE {V(x)} = (0,1.5) (0.5,1.3) (1.0,0.0)
```

where:

`E_Cell` signifies the PSpice call to a VCVS named *E_Cell*

`+OUT` and `-OUT` are the output nodes of the VCVS

`TABLE` is the PSpice behavioral modeling *TABLE* directive

`{V(x)}` is the controlling voltage for the table

`(0, 1.5) (0.5, 1.3) (1.0, 0.0)` are the table pairs that are output to *+OUT* and *-OUT* based on the value of V(x). If V(x) is `0`, signifying 0% discharge, then E_Cell will have a value of 1.5 Volts.

If the cell is 50% discharged then the second table pair will be used and so on. For in-between discharge values, PSpice uses linear interpolation between the table pairs.

To model the discharge current sense and the cell resistance, a zero-valued voltage source is added in series with the output voltage. The cell resistance is modeled as a simple resistor for NICD or Lead-Acid cells and as a more complex variable resistance that depends on the cell's state of charge for alkaline cells.

To model the state-of-charge, a simple, appropriately sized capacitor is used as the charge storage element that simulates the available charge of the cell. This capacitor is sized so that it has a value of 1 Volt at 100% cell capacity and 0.5 Volts at 50% cell capacity. This capacitor is given the following value at the start of the simulation by PSpice's "Parameterization" function:

```
C_CellCapacity 50 0 {3600*CAPACITY*FudgeFactor}
```

The capacitor, *C_CellCapacity*, is connected between nodes 50 and 0 and is given a value of the Amp-hour capacity of the cell times a conversion from hours to seconds (3,600 seconds = 1 hour) times a *fudge factor* (FudgeFactor). If a cell has a 10 Amphour capacity, C_CellCapacity equals 10 * 3,600 or 36,000 Farads; this is a big capacitor, but a workable value that is easy to understand.

The actual usable capacity of a cell depends on the rate at which it is being discharged. Most manufacturers list the capacity at the most favorable rate—usually at greater than 20 hours discharge. At any faster rate, the cell is less efficient and results in a nonlinear function of the discharge rate. This must be characterized as a lookup table at many discharge rates. This inefficiency is modeled as a VCVS in series with the output voltage of the battery state-of-charge node (the voltage on C_CellCapacity). This VCVS subtracts a given amount of *capacity* from the cell during discharge. The amount subtracted depends on the rate at which the cell is being discharged. To determine the rate at which the cell is being discharged, it is convenient to normalize the discharge rate in Amps to a more conventional cell rate called the *C rate*. The C rate is defined as the capacity of the cell in Amp-hours when it is discharged completely in one hour. This normalization makes it easy to determine the cell inefficiency at different rates, and between different cell sizes, because it converts discharge in Amps to discharge in "C" units of the battery capacity in one hour. This conversion is done in the model by the VCVS, E_Rate, as follows.

```
E_Rate RATE 0 VALUE = {(V_Sense) / CAPACITY}
```

E_Rate is the sensed discharge current in Amps divided by the Amp-hour capacity of the cell. The node, RATE, is the instantaneous rate at which the cell is being discharged.

Battery Discharge Series and Parallel Combination

In the batteries industry, single use batteries are called primary batteries and rechargeable batteries are known as secondary batteries. The voltage of a battery cell is determined by the manufacturer.

There are four primary parameters of a battery: Current (I), Voltage (V), Resistance (ESR), and Capacity (C_cell).

`I = V / ESR`

`C_cell = V*` (Amp-hours). =`V*I*T` (Where T=Time in hour)

As an example, if the battery has a 5 Ah (Amp hour) rating, it can provide 1.0 Amp for 5 hours or 5.0 Amps for 1.0 hour.

Series Connection (Double voltages, Same-capacity (Ah))

In case of series connection, positive terminals of one battery is connected to the negative of another, and so on

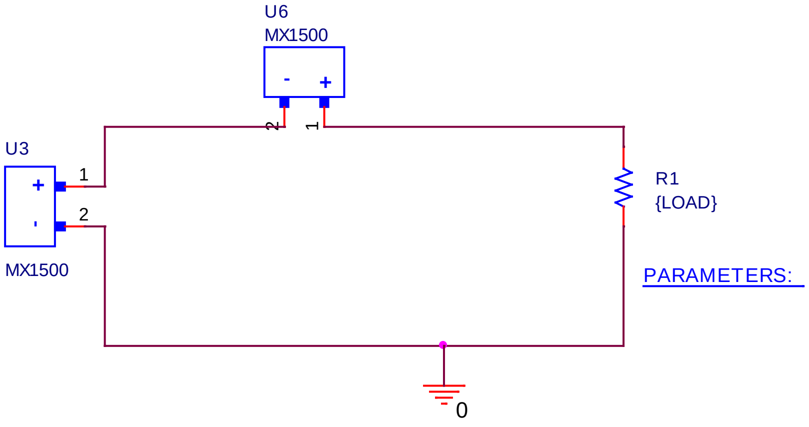


Figure 1: Connection in Series

Two 1.6V-1.0Amp Batteries joined in series produces 3.2V, but the total capacity is still 1.0A.

Parallel Connection (Same voltages, Double capacity (Ah))

In case of parallel connection, positive terminals of all the batteries are connected together, negatives all connected together.

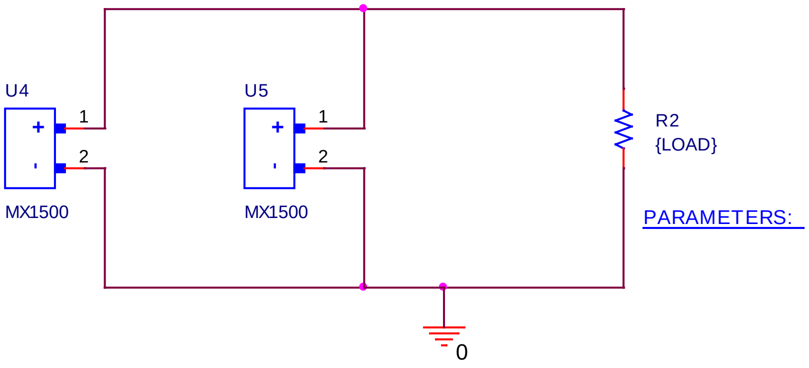
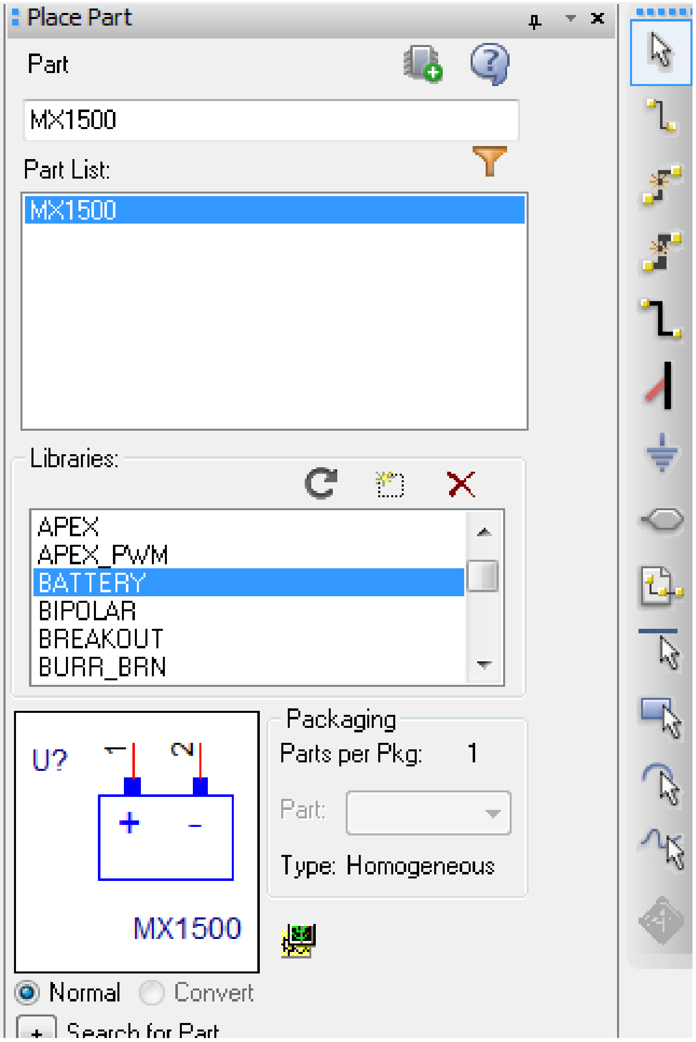


Figure 2: Connecting in Parallel

Two 1.6V-1.0Amp Batteries joined in parallel produces 1.6V, but the total capacity is increase to 2.0A.

Battery Model in PSpice Library

Cadence library (`<CADENCE_INSTALLATION>\TOOLS\CAPTURE\LIBRARY\PSPICE\BATTERY.OLB`) has battery models that can be simulated using PSpice.



Part

MX1500

Part List:

MX1500

Libraries:

APEX
APEX_PWM
BATTERY
BIPOLAR
BREAKOUT
BURR_BRN

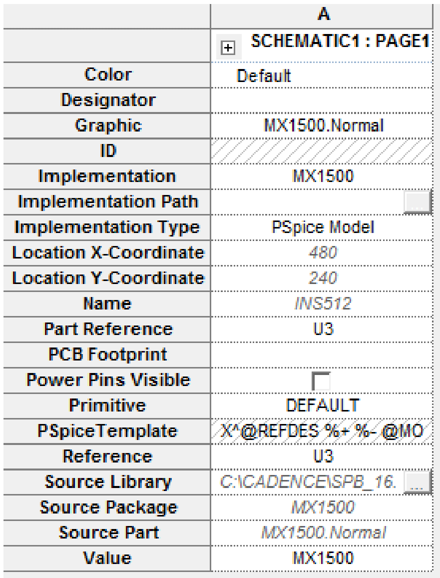
Packaging
Parts per Pkg: 1
Part:
Type: Homogeneous

● Normal ○ Convert

Figure 3: Battery in PSpice Library

You can use the *MX1500* part from the PSpice battery library for simulation.

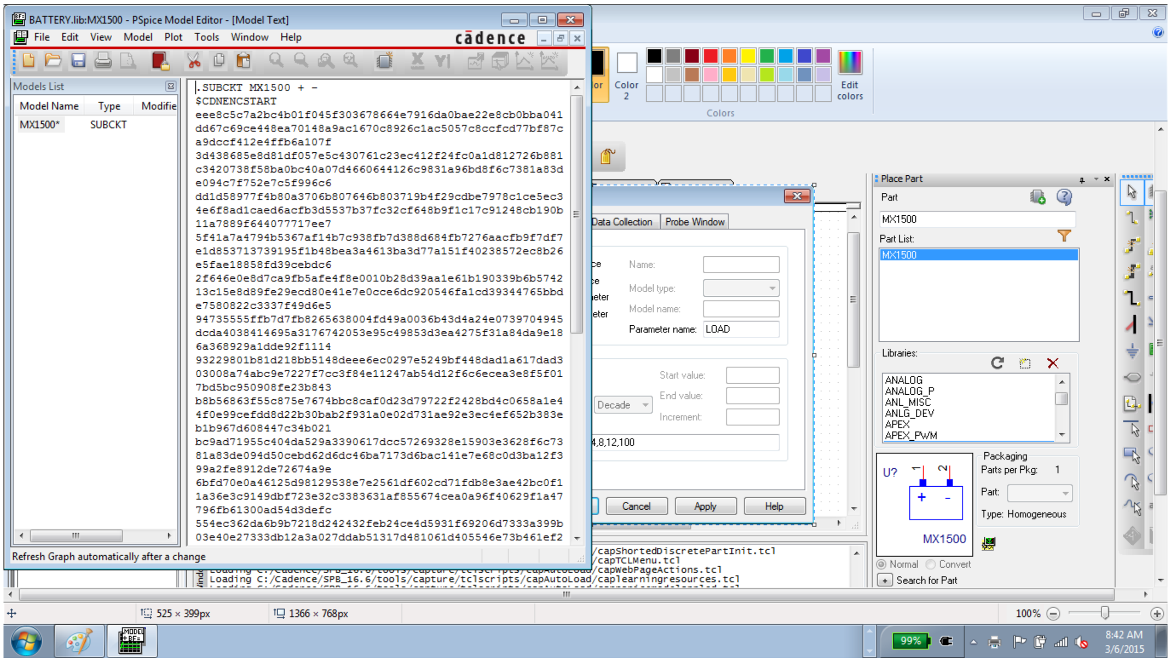
Select the MX1500 part and place it in the Capture schematic, right-click the part on the schematic and choose *Edit properties* to open the property editor window.



	A
	SCHEMATIC1 : PAGE1
Color	Default
Designator	
Graphic	MX1500.Normal
ID	
Implementation	MX1500
Implementation Path	
Implementation Type	PSpice Model
Location X-Coordinate	480
Location Y-Coordinate	240
Name	INS512
Part Reference	U3
PCB Footprint	
Power Pins Visible	☐
Primitive	DEFAULT
PSpiceTemplate	X^@REFDES %+ %- @MO
Reference	U3
Source Library	C:\CADENCE\SPB_16.
Source Package	MX1500
Source Part	MX1500.Normal
Value	MX1500

Figure 4: Edit Properties

If you do right-click and choose *Edit PSpice Model*, the information is encrypted because it is Cadence IP.



```
.SUBCKT MX1500 + -
$CDNENCSTART
eee8c5c7a2bc4b01f045f303678664e7916da0bae22e8cb0bba041
dd67c69ce448ea70148a9ac1670c8926c1ac5057c8ccfcd77bf87c
a9dccf412e4ffb6a107f
3d438685e8d81df057e5c430761c23ec412f24fc0a1d812726b881
c3420738f58ba0bc40a07d4660644126c9831a96bd8f6c7381a83d
e094c7f752e7c5f996c6
dd1d58977f4b80a3706b807646b803719b4f29cdbe7978c1ce5ec3
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11a7889f644077717ee7
5f41a7a4794b5367af14b7c938fb7d388d684fb7276aacfb9f7df7
e1d853713739195f1b48bea3a4613ba3d77a151f40238572ec8b26
e5fae18858fd39cebdc6
2f646e0e8d7ca9fb5afe4f8e0010b28d39aa1e61b190339b6b5742
13c15e8d89fe29ecd80e41e7e0cce6dc920546fa1cd39344765bbd
e7580822c3337f49d6e5
94735555ffb7d7fb8265638004fd49a0036b43d4a24e0739704945
dcda4038414695a3176742053e95c49853d3ea4275f31a84da9e18
6a368929a1dde92f1114
93229801b81d218bb5148deee6ec0297e5249bf448dad1a617dad3
03008a74abc9e7227f7cc3f84e11247ab54d12f6c6ecea3e8f5f01
7bd5bc950908fe23b843
b8b56863f55c875e7674bbc8caf0d23d79722f2428bd4c0658a1e4
4f0e99cefdd8d22b30bab2f931a0e02d731ae92e3ec4ef652b383e
b1b967d608447c34b021
bc9ad71955c404da529a3390617dcc57269328e15903e3628f6c73
81a83de094d50cebd62d6dc46ba7173d6bac141e7e68c0d3ba12f3
99a2fe8912de72674a9e
6bfd70e0a46125d98129538e7e2561df602cd71fdb8e3ae42bc0f1
1a36e3c9149dbf723e32c3383631af855674cea0a96f40629f1a47
796fb61300ad54d3defc
554ec362da6b9b7218d242432feb24ce4d5931f69206d7333a399b
03e40e27333db12a3a027ddab51317d481061d405546e73b461ef2
```

```
/capShortedDiscretePartInit.tcl
/capTCLMenu.tcl
/capWebPageActions.tcl
Loading C:/Cadence/SPB_16.6/tools/capture/tclscripts/capAutoLoad/caplearningresources.tcl
```

Figure 5: Edit PSpice Model Window

A Sample PSpice Circuit Design and Simulation

A sample circuit using batteries can be designed and simulated in OrCAD Capture with PSpice license.

Select MX1500 part from PSpice ANALOG library and place one battery in the Capture schematic. Make three circuits as shown in Figure 6. Connect a load R1, R2 and R3 to the battery.

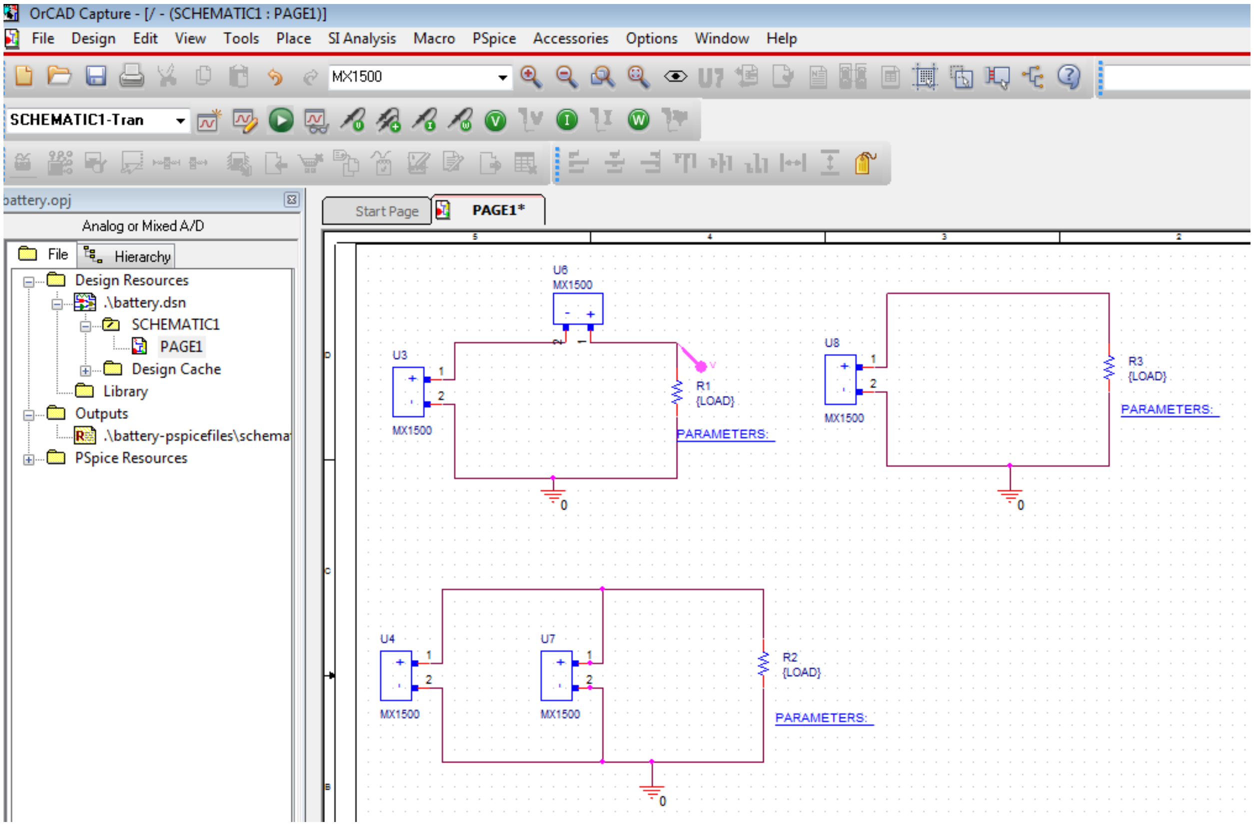
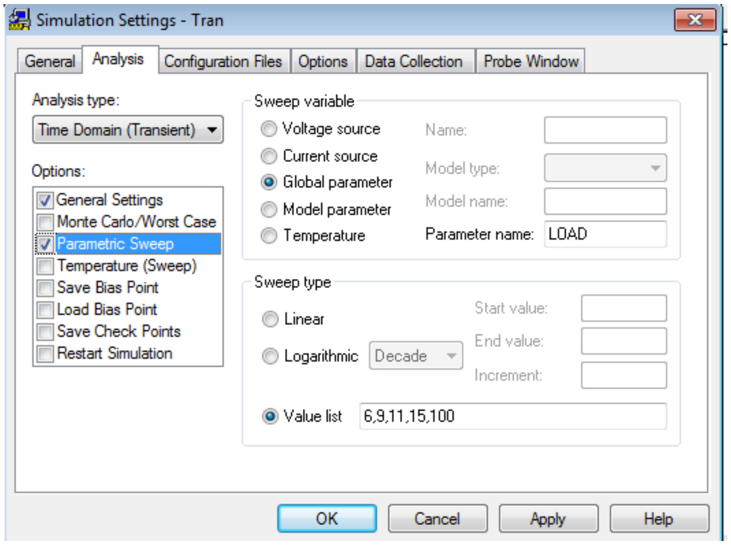


Figure 6: Battery Simulation Circuit

The same circuit can be downloaded from the link provided at page No. 4. You can unzip and open the design in OrCAD Capture/PSpice and simulate directly to get the following results.

If you are designing a new circuit, do a parametric sweep of the load as shown below.



Analysis type: Time Domain (Transient)

Options:

- ☑ General Settings
- ☐ Monte Carlo/Worst Case
- ☑ Parametric Sweep
- ☐ Temperature (Sweep)
- ☐ Save Bias Point
- ☐ Load Bias Point
- ☐ Save Check Points
- ☐ Restart Simulation

Sweep variable

- ○ Voltage source
- ○ Current source
- ● Global parameter
- ○ Model parameter
- ○ Temperature

Name:
Model type:
Model name:
Parameter name: LOAD

Sweep type

- ○ Linear
- ○ Logarithmic Decade
- ● Value list 6,9,11,15,100

Start value:
End value:
Increment:

Figure 7: Simulation Settings

Here you are doing parametric sweep of the load with load resistance value of 6, 9, 11, 15 and 100 ohm.

Choose *PSpice — Run Simulation*. When Simulation is complete, connect a probe at the load.

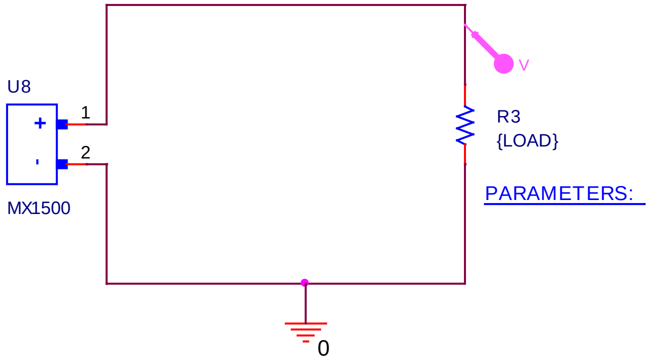


Figure 8: Single Battery with Load Circuit

Now you will see the output Voltage waveform with respect to time and different load conditions.

As the time increases, the output voltage across the battery decreases. You will also see that the lesser the load, the longer is the battery.

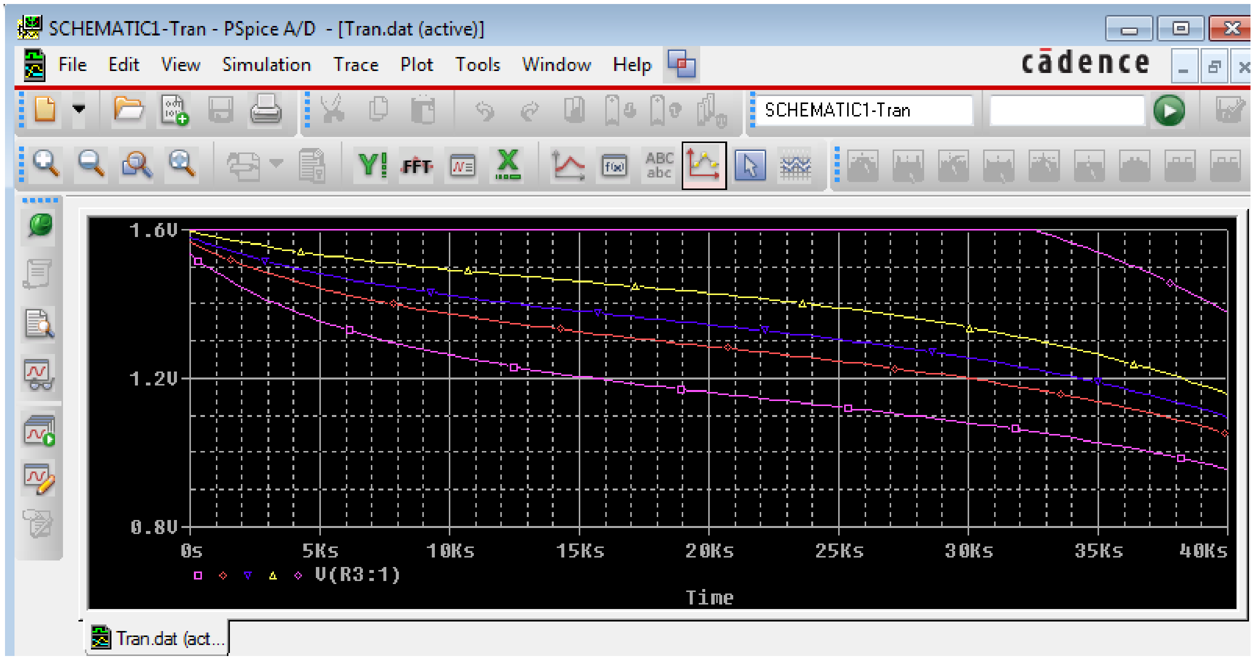


Figure 9: Output Result in PSpice Probe Window

Battery Parallel Simulation

Connect two batteries in parallel as shown in the following figure.

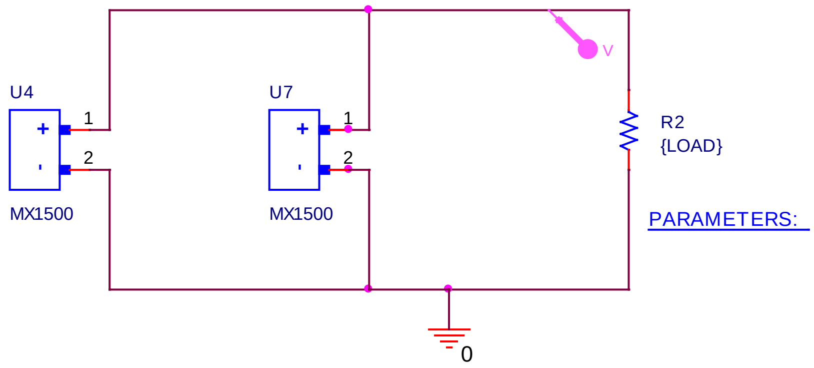


Figure 10: Parallel Battery with Load

You will observe that the output voltage is same while doubling the capacity rating (amp hours).

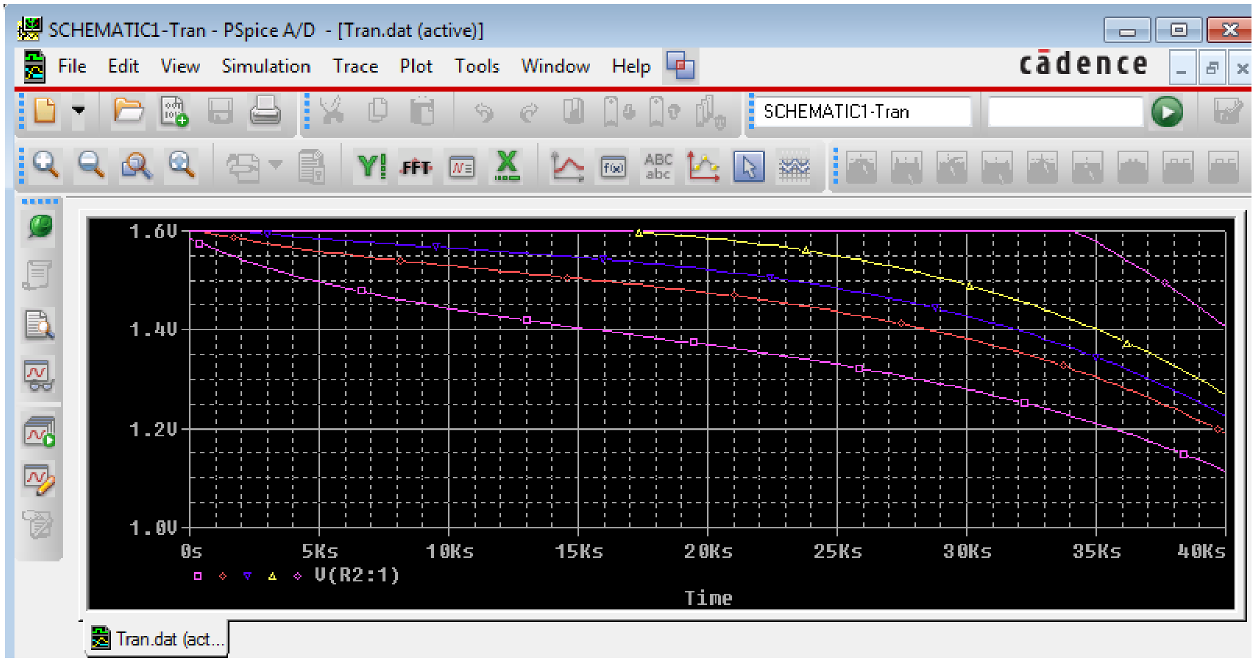


Figure 11: Output Result in PSpice Probe Window

Battery Series Simulation

When connecting in series you are doubling the voltage maintaining the same capacity (amp hours).

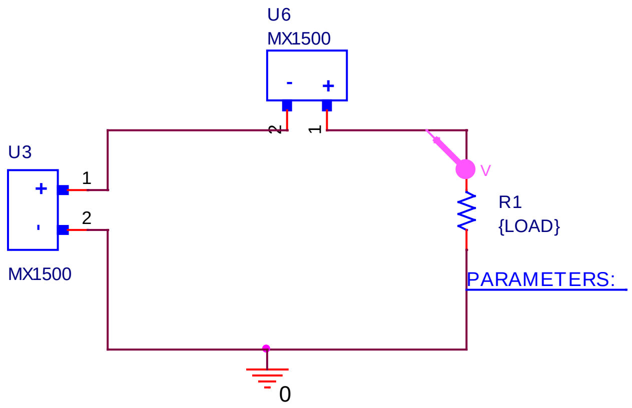


Figure 12: Series Battery with Load

In series simulation, two 1.6V batteries are connected in series that produce 3.2 V output with the same capacity.

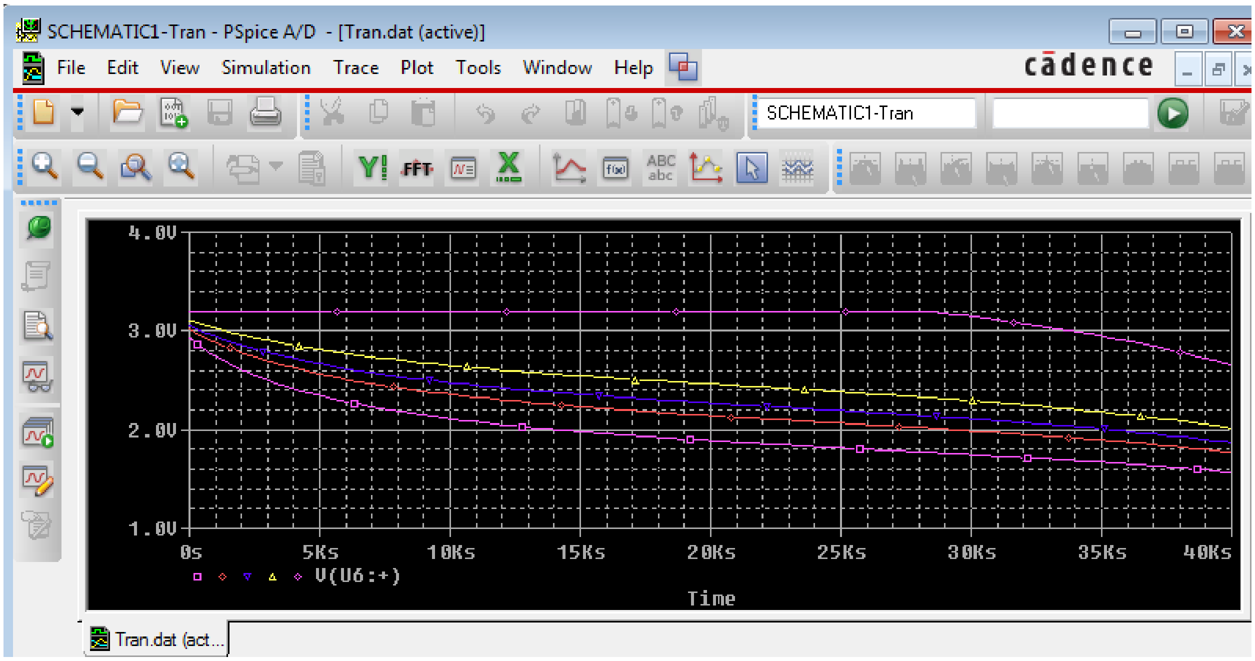


Figure 13: Output Result in PSpice Probe Window

Support

Cadence Online Support provides access to support resources, including an extensive knowledge base, access to software updates for Cadence products, and the ability to interact with Cadence Customer Support. Visit https://support.cadence.com.

Feedback

Email comments, questions, and suggestions to content_feedback@cadence.com.

References

MicroSim Application Notes, MicroSim Corporation.