Systems On-Chip

MEEC

Lab 2 - Verilog analog modelling

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Group 4

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Contents

1 Power Block Model

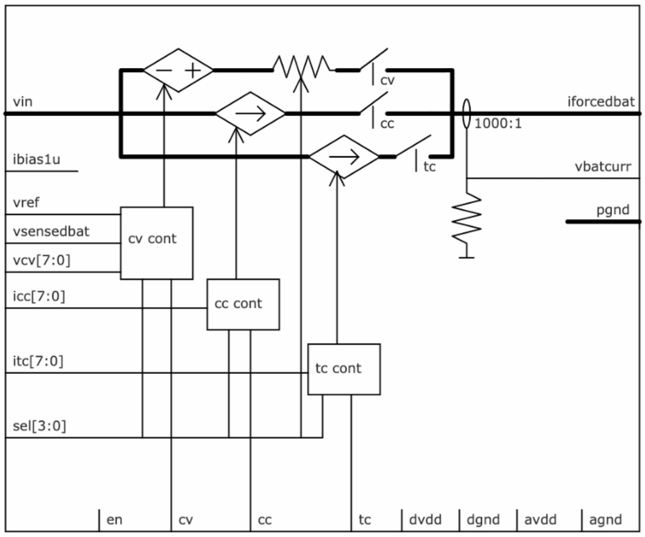

Figure 1: Charger power block diagram

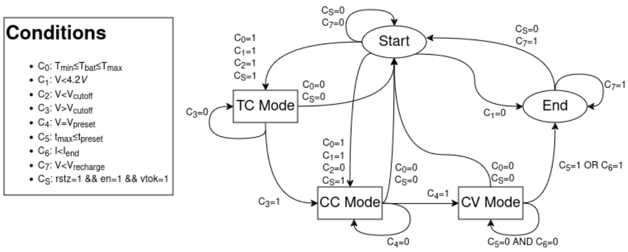

Figure 2: Finite State Machine designed for the controller

The goal of this project is to create and define a verilog model regarding the power block of the charger. The power block accounts with several inputs that define the power block's outputs `iforcebat` (current to be forced on the battery) and `vbatcurr` (scaled mirrored current of `iforcedbat`, used for monitoring and as a ADC input). As mentioned in the previous report, the current imposed on the battery will be defined in terms of the operating mode (found in Figure 2), with the expected outputs of each state represented: $tc, cc, cv, vmonen, imonen, tmonen$ as the outputs of the controller and the currents regarding the power block, resumed in Table 1. Each mode (`CV`, `CC` and `TC`) defines the current as a fraction of the forced current (based on `vcv`, `icc` and `itc`, respectively), as stated on equation 1. While in `TC MODE` and `CC MODE` the current will be constant and directly obtained from itc and icc, while in `CV MODE` the current will be defined by the equation below. For the other modes, the current will always be $0A$.

$$i_{\text{forcedbat}} = \begin{cases} C \cdot (0.502 \cdot b_7 + 0.251 \cdot b_6 + 0.1255 \cdot b_5 + \cdots + 0.0039 \cdot b_0)\,, & \text{if TC mode} \\ C \cdot (0.502 \cdot b_7 + 0.251 \cdot b_6 + 0.1255 \cdot b_5 + \cdots + 0.0039 \cdot b_0)\,, & \text{if CC mode} \\ \frac{V_{\text{target}} - V_{\text{sensed}}}{R_{\text{ch}}}, & \text{if CV mode} \\ 0, & \text{other cases} \end{cases} \tag{1}$$

- C: Battery capacity in Ah.
- $b_7, b_6, \ldots, b_0$: Control bits for current scaling.
- R_{ch}: Resistance, CV mode: $R_{\text{ch}} = \frac{0.4}{0.5 \cdot C}$
- V_{target}: Target voltage for the CV mode: $V_{\text{target}} = 5\,(0.502 \cdot b_7 + 0.251 \cdot b_6 + ... + 0.0039 \cdot b_0)$

State	Code	Outputs						
		TC	CC	CV	imonen	vmonen	tmonen	Current (A)
START	0	0	0	0	0	1	1	0
TC MODE	1	1	0	0	0	1	1	C*icc
CC MODE	2	0	1	0	0	1	1	C*icv
CV MODE	3	0	0	1	1	0	1	(V_{target}-V_{bat})/R
END	4	0	0	0	0	0	0	0

Table 1: Output assignment of the original controller's state machine

The currents depend not only on a forced current, but also on the capacity value defined by `sel` on the following manner, as in Listing 1, with the values presented in Table 2.

```
    //initialize capacity
    initial assign rl_C = (0.05 + sel[0]*0.05 + sel[1]*0.1 + sel[2]*0.2 +
   sel[3]*0.4);
```

Listing 1: Real Capacity Value

sel[3:0]	C [mAh]	sel[3:0]	C [mAh]
0000	50	1000	450
0001	100	1001	500
0010	150	1010	550
0011	200	1011	600
0100	250	1100	650
0101	300	1101	700
0110	350	1110	750
0111	400	1111	800

Table 2: Mapping of `sel[3:0]` to Battery Capacity (`C`)

The logic applied on the power block, could be resumed to a line of code (Listing 3), that states that the current it's either `rl_itc`, `rl_icc`, `rl_vcv`, or zero, if none of the modes is activated or enable is set to zero.

```
    initial assign rl_iforcedbat = en ? (tc ? rl_itc : (cc ? rl_icc : (cv ?
    rl_vcv : 0.0))): 0.0;
```

Listing 2: Power Block Logic for *iforcedbat*

Regarding the voltage monitoring of the forced current this was calculated using the formula indicated on the datasheet, $vbatcurr = \frac{V_{ref}}{C} * I_{forcedbat}$. This value will be important to convert the battery current to the controller input *ibat* in the ADC block, which will be essential to monitor the current and alter the state, since the only current changes will be due to the power block.

```
    initial assign rl_vbatcurr = (rl_vref/rl_C)*rl_iforcedbat;
```

Listing 3: Power Block Logic for *vbatcurr*

Every input and output of this block is binary. However, current, voltage, and resistance take real values, arising the need to convert these variables to real in the beginning of the code (Listing 4) and converting the outputs to bits at the end of the code (Listing 5).

```
    //convert inputs to real
    initial assign rl_vsensbat = $bitstoreal(vsensbat);
    initial assign rl_vin = $bitstoreal(vin);
    initial assign rl_ibias1u = $bitstoreal(ibias1u);
    initial assign rl_vref = $bitstoreal(vref);
```

Listing 4: Bits to real conversion

```
    //convert outputs from real to bits
    assign iforcedbat = $realtobits (rl_iforcedbat);
    assign vbatcurr = $realtobits (rl_vbatcurr);
```

Listing 5: Real to bits conversion

2 Validation of the power block and the charger

2.1 Powerblock test bench and simulation

Building upon the methodology employed in Lab 1 for the battery controller, this section will examine the Verilog design of the power block self-testable testbench.

To check that this block works properly, we use its datasheet. Since the power block manages battery switching in the various `CC`, `CV` and `TC` mods, the idea is to check whether the measured `iforcedbat` output current corresponds to that calculated theoretically via the formulas available in the datasheet. These give the expected value for the current in `CC`, `TC` and `CV` modes, based on the 8 bits of the arbitrary values we have set: `icc`, `itc` and `vcv` respectively. The output current $i_{\text{forcedbat}}$ for the three charging modes is defined by equation 1.

Then, to calculate the expected `iforcedbat` currents in each mode, we use the previous formulas to calculate the values displayed at each test during simulation, and compare them with the output value of the previously designated power block. Each of the theoretical current values calculated above is displayed at the same time in brackets under the name `iforcedXX`, with `XX` the mode, as shown in the **SimVision simulation output log below**. Regarding *vbatcurr*, a condition to check its behavior was also added (also based in the formulas presented), printing a message in the console if the value diverges from the expected.

New Power block Self-testable Testbench Output Log

```
cc=1, tc=0, cv=0 (iforcedcv=0.243250 A iforcedcc=0.199200 A iforcedtc=0.039200 A) output current is: 0.199200 A
===== TESTING CC MODE ====
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE ====
cc=0, tc=1, cv=0 (iforcedcv=0.243250 A iforcedcc=0.199200 A iforcedtc=0.039200 A) output current is: 0.039200 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE ====
cc=0, tc=0, cv=1 (iforcedcv=0.243250 A iforcedcc=0.199200 A iforcedtc=0.039200 A) output current is: 0.243250 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE ====
SUCCESS: iforcedbat if correctly 0 A when en = 0.
===== ALL TESTS COMPLETED ====
Simulation complete via $finish(1) at time 850 NS + 0
```

In summary, the process is as follows: each mode is activated independently of the others, the theoretical current value associated with that mode is compared with the power block output value `iforcedbat`, and a message is displayed to indicate whether the measured current corresponds to what was expected.

Furthermore, as the measured value will inevitably differ from the calculated one, we have incorporated a tolerance of 1 mA to ensure a fair and accurate comparison between the theoretical current value of a given mode and the output measured value `iforcedbat`. As this absolute value function is not a standard feature of Verilog, it has been implemented directly via its mathematical definition.

Once we have quantitatively verified that the powerblock is working properly with the console test showing with the messages that all the tests have been carried out correctly, we turn to the waveform associated with this simulation, as shown in the **Figure 3 below**.

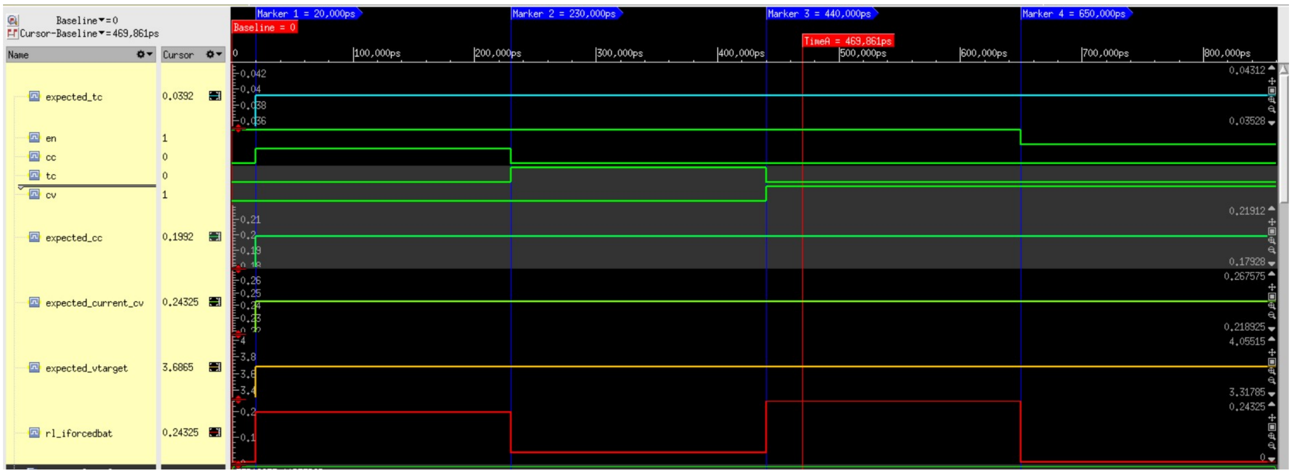

Figure 3: Waveform of the self-testable testbench of the powerblock

This way, we can verify the procedure we described earlier. First, all activation signals for `CC`, `CV` and `TC` modes are set to 0, and the module is activated by setting the `en` variable to 1. The current actually measured at output (in red) is therefore zero.

Then, starting from marker 1, we activate `CC` mode. At the same time, we calculate the theoretical values of the forced current in each mode, using the equations in 1 defined above. We then observe that the measured output current increases to reach the expected value in `CC` mode.

Similarly, at marker 2, we deactivate `CC` mode and activate only `TC` mode, and see that the measured current drops to the small value theoretically calculated in `TC` mode of 0.0392 A. Finally, starting from marker 3, we deactivate `TC` mode to activate only `CV` mode, and then compare the current value measured in red with that calculated in yellow.

Lastly, we check that the module has been activated correctly. We deactivate the module by setting the `en` variable to 0 at marker 4, and immediately see that the measured current is zero. This process was repeated to test all 16 values of *sel*. The output log can be consulted in the annex, but the behavior is as expected, with a increase in the current, as *sel* also increases.

2.2 Full charger testbench and simulation

The approach for the test of the full charger was similar to the one in the previous lab. Instead of forcing a certain value in the direct input of power block, the whole charger is working, so it isn't possible to describe *a priori* the input. Instead, the current is checked periodically, verifying if the value is correct according to the equations provided in the documentation. As such, if, from the controller outputs, the detected mode is `TC MODE` (from evaluating *tc=1*), the current should be equal to *itc* (after conversion from 8 bits to a real value), if the mode is `CC MODE`, the current should be *icc*, and if the mode is `CV MODE`, the expected current should be $i_{forcedbat} = \frac{V_{target} - V_{sensbat}}{R}$, where $R = 0.4/(0.5 * C)$, with V_{target} being the conversion of *icv* to a real value. This approach was added to the state check of the previous laboratory, now checking both the state, has well as the correct output, from the power block and from the controller.

To indicate the changes, the state is being checked each 30000 time units ($1ns$ in this case), and if the state changes, a message appears in the console, indicating the change in state. Regarding the current, the checks are also performed, but only printed each 20*30000 time units for `TC MODE`, `CC MODE`, and `CV MODE`. For `END`, the current check is printed each 1000*30000 time units. This was added to the previous testbench, where the state was already being verified. Now, with both information is possible to track the correct functioning of the whole charger. Like in the previous project, a message will be displayed each time the state changes, with the state, outputs (*tc*, *cc*, *cv*,*vmonen*, *tmonen*, and *imonen*) and current forced on the battery.

Regarding the normal functioning of the full charger, and combining the information of the monitoring of both blocks, the following waveform and log was obtained. The first six lines indicate the controller inputs, the following two, the battery voltage and current (which is the current forced upon the battery). The three predicted currents (from each mode), can be found in the last three lines. The yellow marker indicates the beginning of `TC MODE`, which is confirmed by the outputs $tc = 1, cc = cv = 0, imonen = 0, vmonen = tmonen = 1$, with a current *ibat* correspondent to the expected *itc*, plotted below. This is followed by `CC MODE`, with outputs $tc = 0, cc = 1, cv = 0, imonen = 0, vmonen = tmonen = 1$, and a green marker, and a current behavior that is the same as the expected with a constant current *icc*. As $vbat = V_{preset}$, the charger enters `CV MODE`, with a blue marker, and outputs $tc = 0, cc = 0, cv = 1, imonen = 1, vmonen = 0, tmonen = 1$. The current here will be dependent on the target voltage V_{target}, obtained through *vcv*, and on the detected voltage *vbat*, leading to a decrease of the current, as *vbat* increases to V_{target}, as seen in the voltage plot. Finally, marked in purple, the charger enters in `END`, due to the timeout condition, where the current will constantly $0A$.

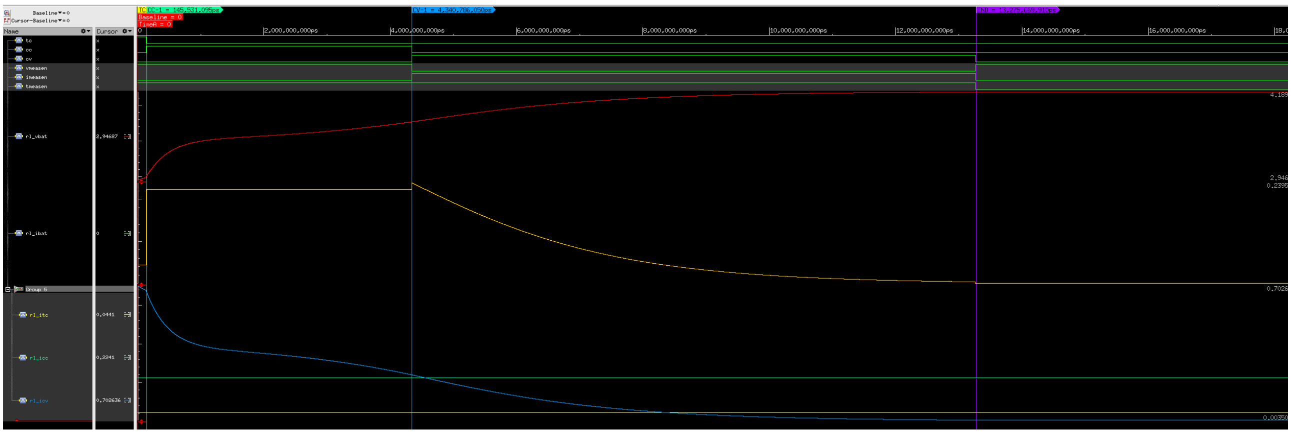

Figure 4: Waveform of the self-testable testbench of the full charger

Further behaviors were tested, namely regarding the correct functioning of the enable, the recharge process and temperature control. Regarding the testing of the enable signal (working as a switch for the whole charger), represented in Figure 5, the test was performed in a similar fashion to the previous test, by going to `TC MODE` (with the dark blue marker in the beginning of the waveform) and `CC MODE` (light blue marker), both with constant current. Then, when the circuit is in `CV MODE` (orange marker) with the expected current drop as $vbat < V_{target}$, en goes to 0 the charging process is interrupted, and the current drops automatically to $0A$ too, since the state is `IDLE` (green marker). As en is turned back on, the charging is resumed, the state goes first to `CC MODE` (as $vbat > V_{cutoff}$) and then to $CV\ MODE$ again, since $vbat > V_{preset}$. Finally the process ends (`END` state with purple marker), due to the decrease in the forced current ($ibat$). The log of the test can be found in the annex.

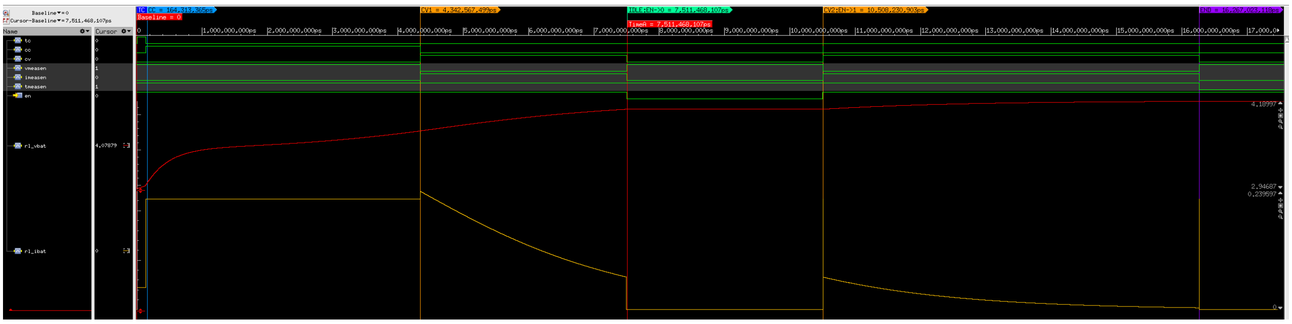

Figure 5: Waveform of the self-testable testbench of the full charger - Enable switch testing

New Power block Self-testable Testbench Output Log

```
===== Starting the testbench and charging the battery =====
Correct state - TC MODE at time 30300000
In TC MODE, current within boundaries: 0.044100
Correct state - TC MODE at time 60300000
In TC MODE, current within boundaries: 0.044100
Correct state - CC MODE at time 180300000
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
Correct state - CV MODE at time 4380300000
In CV MODE, current within boundaries: 0.236999
In CV MODE, current within boundaries: 0.206388
In CV MODE, current within boundaries: 0.165487
In CV MODE, current within boundaries: 0.129740
In CV MODE, current within boundaries: 0.099935
In CV MODE, current within boundaries: 0.075936
In CV MODE, current within boundaries: 0.057107
In CV MODE, current within boundaries: 0.042613
In CV MODE, current within boundaries: 0.031613
In CV MODE, current within boundaries: 0.023352
In CV MODE, current within boundaries: 0.017195
In CV MODE, current within boundaries: 0.012631
In CV MODE, current within boundaries: 0.009263
In CV MODE, current within boundaries: 0.006784
In CV MODE, current within boundaries: 0.004964
In CV MODE, current within boundaries: 0.003630
Correct state - END MODE at time 13320300000
END, current is 0A
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
Verification completed or timed out after 5000 time units
Test 1 : battery fully charged, Vbat=4.189762
==== Test concluded with success ====
Simulation complete via $finish(1) at time 150000300 NS + 0
```

Regarding the recharge process, since the original battery file does not consider the discharge process, a virtual load, represented by a constant leakage current was added, draining the battery. To demonstrate the process, the leakage current is purposefully put to a high value, $0.1mA$, if the current forced on the battery ($iforcedbat$) is $0A$. The waveform used to check can be seen below, in Figure 6. As previously, the process is the same, with `TC MODE`, and then `CC MODE` (green marker), both with constant currents, and then entering `CV MODE` (orange marker), where the current decreases. After arriving at *END* (exiting due to the current condition), the current goes to $0A$, resulting in a visible, but slow, voltage drop. Another change was a different $V_{recharge}$, whose value was decreased to allow for a more visible behavior of the voltage drop, in this case, $V_{recharge} = 3.4V$. So, as $vbat \leq V_{recharge}$, the charging process begins again, entering `CC MODE` (pink marker)[1], as $vbat > V_{cutoff}$, with constant current icc, and then `CV MODE` (yellow marker), as the current starts decreasing according to the expected equation, and

[1] Although not visible, there is a passage in `IDLE` as supposed according to the finite state machine designed in the previous project.

reaching `END` once again. The log of the test can be found in the annex.

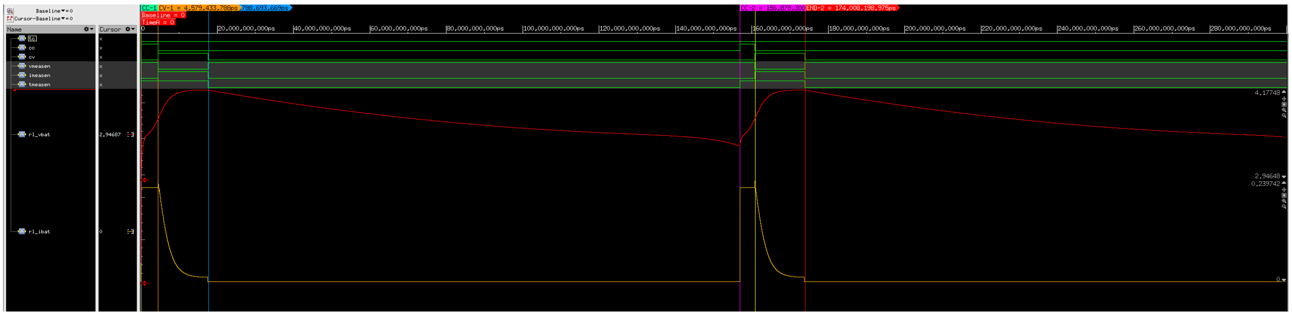

Figure 6: Waveform of the self-testable testbench of the full charger - Recharge testing

Finally, the temperature behavior was also tested. To allow for this test, changes were performed again on the battery file ($LiPo$), altering the ambient temperature to 42° and the equivalent series resistance (ESR) to 2Ω, to allow for faster warm up. As seen in Figure 7 (once again with `TC MODE` and `CC MODE`), the rise of *tbat*, until it is equal to $vtempmax$, corresponds to a constant current. As soon as $tbat = tempmax$, there is a transition to `IDLE`, where $ibat = 0A$, leading to a small cool down. This leads to $tbat < tempmax$, going to `CC MODE` again, where the constant current *icc*, is enough to warm up the battery to the point where $tbat \geq tempmax$, going to *IDLE* again. Since here there is no leakage current, there will be no voltage drop, so this cycle will continue until $vbat = V_{preset}$, where the state is `CV MODE`. A similar cycle also occurs here, but since the current is decreasing, so is the warm up, leading to a cool down (which happens at the same time as the current drop), until `END`. The resulting log can be found in the annex.

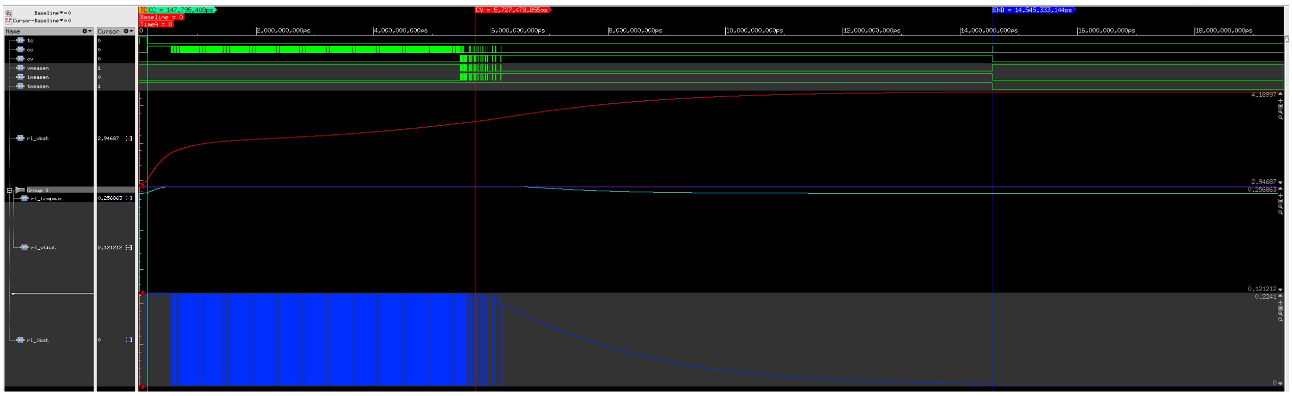

Figure 7: Waveform of the self-testable testbench of the full charger - Temperature testing

A Testbench Output Log for the 16 values of capacity

```
***** TEST for C=0.050000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.030406 A iforcedcc=0.024900 A iforcedtc=0.004900 A) output
    current is: 0.024900 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.030406 A iforcedcc=0.024900 A iforcedtc=0.004900 A) output
    current is: 0.004900 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.030406 A iforcedcc=0.024900 A iforcedtc=0.004900 A) output
    current is: 0.030406 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.050000 Ah =====
 ==================================================
***** TEST for C=0.100000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.060812 A iforcedcc=0.049800 A iforcedtc=0.009800 A) output
    current is: 0.049800 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.060812 A iforcedcc=0.049800 A iforcedtc=0.009800 A) output
    current is: 0.009800 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.060812 A iforcedcc=0.049800 A iforcedtc=0.009800 A) output
    current is: 0.060812 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.100000 Ah =====
 ==================================================
***** TEST for C=0.150000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.091219 A iforcedcc=0.074700 A iforcedtc=0.014700 A) output
    current is: 0.074700 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.091219 A iforcedcc=0.074700 A iforcedtc=0.014700 A) output
    current is: 0.014700 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.091219 A iforcedcc=0.074700 A iforcedtc=0.014700 A) output
    current is: 0.091219 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.150000 Ah =====
 ==================================================
***** TEST for C=0.200000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.121625 A iforcedcc=0.099600 A iforcedtc=0.019600 A) output
    current is: 0.099600 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.121625 A iforcedcc=0.099600 A iforcedtc=0.019600 A) output
    current is: 0.019600 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.121625 A iforcedcc=0.099600 A iforcedtc=0.019600 A) output
    current is: 0.121625 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
```

```
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.200000 Ah =====
 ==================================================
***** TEST for C=0.250000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.152031 A iforcedcc=0.124500 A iforcedtc=0.024500 A) output
    current is: 0.124500 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.152031 A iforcedcc=0.124500 A iforcedtc=0.024500 A) output
    current is: 0.024500 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.152031 A iforcedcc=0.124500 A iforcedtc=0.024500 A) output
    current is: 0.152031 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.250000 Ah =====
 ==================================================
***** TEST for C=0.300000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.182437 A iforcedcc=0.149400 A iforcedtc=0.029400 A) output
    current is: 0.149400 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.182437 A iforcedcc=0.149400 A iforcedtc=0.029400 A) output
    current is: 0.029400 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.182437 A iforcedcc=0.149400 A iforcedtc=0.029400 A) output
    current is: 0.182437 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.300000 Ah =====
 ==================================================
***** TEST for C=0.350000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.212844 A iforcedcc=0.174300 A iforcedtc=0.034300 A) output
    current is: 0.174300 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.212844 A iforcedcc=0.174300 A iforcedtc=0.034300 A) output
    current is: 0.034300 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.212844 A iforcedcc=0.174300 A iforcedtc=0.034300 A) output
    current is: 0.212844 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.350000 Ah =====
 ==================================================
***** TEST for C=0.400000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.243250 A iforcedcc=0.199200 A iforcedtc=0.039200 A) output
    current is: 0.199200 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.243250 A iforcedcc=0.199200 A iforcedtc=0.039200 A) output
    current is: 0.039200 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.243250 A iforcedcc=0.199200 A iforcedtc=0.039200 A) output
    current is: 0.243250 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
```

```
===== ALL TESTS COMPLETED FOR C=0.400000 Ah =====
 ==================================================
***** TEST for C=0.450000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.273656 A iforcedcc=0.224100 A iforcedtc=0.044100 A) output
    current is: 0.224100 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.273656 A iforcedcc=0.224100 A iforcedtc=0.044100 A) output
    current is: 0.044100 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.273656 A iforcedcc=0.224100 A iforcedtc=0.044100 A) output
    current is: 0.273656 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.450000 Ah =====
 ==================================================
***** TEST for C=0.500000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.304062 A iforcedcc=0.249000 A iforcedtc=0.049000 A) output
    current is: 0.249000 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.304062 A iforcedcc=0.249000 A iforcedtc=0.049000 A) output
    current is: 0.049000 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.304062 A iforcedcc=0.249000 A iforcedtc=0.049000 A) output
    current is: 0.304062 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.500000 Ah =====
 ==================================================
***** TEST for C=0.550000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.334469 A iforcedcc=0.273900 A iforcedtc=0.053900 A) output
    current is: 0.273900 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.334469 A iforcedcc=0.273900 A iforcedtc=0.053900 A) output
    current is: 0.053900 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.334469 A iforcedcc=0.273900 A iforcedtc=0.053900 A) output
    current is: 0.334469 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.550000 Ah =====
 ==================================================
***** TEST for C=0.600000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.364875 A iforcedcc=0.298800 A iforcedtc=0.058800 A) output
    current is: 0.298800 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.364875 A iforcedcc=0.298800 A iforcedtc=0.058800 A) output
    current is: 0.058800 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.364875 A iforcedcc=0.298800 A iforcedtc=0.058800 A) output
    current is: 0.364875 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.600000 Ah =====
```

```
 ==================================================
***** TEST for C=0.650000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.395281 A iforcedcc=0.323700 A iforcedtc=0.063700 A) output
    current is: 0.323700 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.395281 A iforcedcc=0.323700 A iforcedtc=0.063700 A) output
    current is: 0.063700 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.395281 A iforcedcc=0.323700 A iforcedtc=0.063700 A) output
    current is: 0.395281 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.650000 Ah =====
 ==================================================
***** TEST for C=0.700000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.425687 A iforcedcc=0.348600 A iforcedtc=0.068600 A) output
    current is: 0.348600 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.425687 A iforcedcc=0.348600 A iforcedtc=0.068600 A) output
    current is: 0.068600 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.425687 A iforcedcc=0.348600 A iforcedtc=0.068600 A) output
    current is: 0.425687 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.700000 Ah =====
 ==================================================
***** TEST for C=0.750000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.456094 A iforcedcc=0.373500 A iforcedtc=0.073500 A) output
    current is: 0.373500 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.456094 A iforcedcc=0.373500 A iforcedtc=0.073500 A) output
    current is: 0.073500 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.456094 A iforcedcc=0.373500 A iforcedtc=0.073500 A) output
    current is: 0.456094 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.750000 Ah =====
 ==================================================
***** TEST for C=0.800000 Ah *****
===== TESTING CC MODE =====
cc=1, tc=0, cv=0, (iforcedcv=0.486500 A iforcedcc=0.398400 A iforcedtc=0.078400 A) output
    current is: 0.398400 A
SUCCESS: CC mode with expected value of the current
===== TESTING TC MODE =====
cc=0, tc=1, cv=0, (iforcedcv =0.486500 A iforcedcc=0.398400 A iforcedtc=0.078400 A) output
    current is: 0.078400 A
SUCCESS: TC mode with expected value of the current
===== TESTING CV MODE =====
cc=0, tc=0, cv=1, (iforcedcv=0.486500 A iforcedcc=0.398400 A iforcedtc=0.078400 A) output
    current is: 0.486500 A
SUCCESS: CV mode with expected value of the current
===== TESTING DESACTIVATION OF THE MODULE =====
SUCCESS: iforcedbat is correctly 0 A when en = 0.
===== ALL TESTS COMPLETED FOR C=0.800000 Ah =====
```

B Testbench Output Log for enable switch ON-OFF process of the whole charger

```
===== Starting the testbench and charging the battery =====
Correct state - TC MODE at time 30300000
In TC MODE, current within boundaries: 0.044100
Correct state - TC MODE at time 60300000
In TC MODE, current within boundaries: 0.044100
Correct state - CC MODE at time 180300000
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
Correct state - CV MODE at time 4380300000
In CV MODE, current within boundaries: 0.236999
In CV MODE, current within boundaries: 0.206388
In CV MODE, current within boundaries: 0.165487
In CV MODE, current within boundaries: 0.129740
In CV MODE, current within boundaries: 0.099935
In CV MODE, current within boundaries: 0.075936
EN to 0, at time 7500300000
Correct state - IDLE at time 7530300000
IDLE, current is 0A
EN to 1, at time 10500300000
Correct state - CV MODE at time 10560400000
In CV MODE, current within boundaries: 0.064208
In CV MODE, current within boundaries: 0.057231
In CV MODE, current within boundaries: 0.042708
In CV MODE, current within boundaries: 0.031685
In CV MODE, current within boundaries: 0.023406
In CV MODE, current within boundaries: 0.017235
In CV MODE, current within boundaries: 0.012661
In CV MODE, current within boundaries: 0.009285
In CV MODE, current within boundaries: 0.006800
In CV MODE, current within boundaries: 0.004976
In CV MODE, current within boundaries: 0.003638
Correct state - END MODE at time 16320400000
END, current is 0A
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
Verification completed or timed out after 750 time units
Test 1 : completed with success, Vbat=4.189845
==== Test concluded with success ====
Simulation complete via $finish(1) at time 22500400 NS + 0
```

C Testbench Output Log for recharge process of the whole charger

```
===== Starting the testbench and charging the battery =====
Correct state - TC MODE at time 30300000
In TC MODE, current within boundaries: 0.044100
Correct state - TC MODE at time 60300000
In TC MODE, current within boundaries: 0.044100
Correct state - CC MODE at time 210300000
In CC MODE, current within boundaries: 0.224100
```

```
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
Correct state - CV MODE at time 4620300000
In CV MODE, current within boundaries: 0.236863
In CV MODE, current within boundaries: 0.224201
In CV MODE, current within boundaries: 0.183723
In CV MODE, current within boundaries: 0.147608
In CV MODE, current within boundaries: 0.116981
In CV MODE, current within boundaries: 0.091967
In CV MODE, current within boundaries: 0.072105
In CV MODE, current within boundaries: 0.056659
In CV MODE, current within boundaries: 0.044832
In CV MODE, current within boundaries: 0.035879
In CV MODE, current within boundaries: 0.029160
In CV MODE, current within boundaries: 0.024148
In CV MODE, current within boundaries: 0.020427
In CV MODE, current within boundaries: 0.017674
In CV MODE, current within boundaries: 0.015642
In CV MODE, current within boundaries: 0.014145
In CV MODE, current within boundaries: 0.013043
In CV MODE, current within boundaries: 0.012233
In CV MODE, current within boundaries: 0.011638
In CV MODE, current within boundaries: 0.011202
In CV MODE, current within boundaries: 0.010881
In CV MODE, current within boundaries: 0.010646
In CV MODE, current within boundaries: 0.010474
Correct state - END MODE at time 17670300000
END, current is 0A
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
Correct state - CC MODE at time 156930300000
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
In CV MODE, current within boundaries: 0.238809
Correct state - CV MODE at time 160830300000
In CV MODE, current within boundaries: 0.236688
In CV MODE, current within boundaries: 0.197324
In CV MODE, current within boundaries: 0.159510
In CV MODE, current within boundaries: 0.126929
In CV MODE, current within boundaries: 0.100004
In CV MODE, current within boundaries: 0.078435
In CV MODE, current within boundaries: 0.061551
In CV MODE, current within boundaries: 0.048561
In CV MODE, current within boundaries: 0.038693
In CV MODE, current within boundaries: 0.031267
In CV MODE, current within boundaries: 0.025717
In CV MODE, current within boundaries: 0.021590
In CV MODE, current within boundaries: 0.018534
In CV MODE, current within boundaries: 0.016276
In CV MODE, current within boundaries: 0.014611
In CV MODE, current within boundaries: 0.013386
In CV MODE, current within boundaries: 0.012486
In CV MODE, current within boundaries: 0.011824
In CV MODE, current within boundaries: 0.011338
In CV MODE, current within boundaries: 0.010981
In CV MODE, current within boundaries: 0.010720
```

```
In CV MODE, current within boundaries: 0.010528
Correct state - END MODE at time 173880300000
END, current is 0A
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
Verification completed or timed out after 10000 time units
Test 1 : battery fully charged, Vbat=3.521773
==== Test concluded with success ====
Simulation complete via $finish(1) at time 300000300 NS + 0
```

D Testbench Output Log for recharge process of the whole charger

```
===== Starting the testbench and charging the battery =====
Correct state - TC MODE at time 30300000
In TC MODE, current within boundaries: 0.044100
Correct state - TC MODE at time 60300000
In TC MODE, current within boundaries: 0.044100
Correct state - CC MODE at time 180300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 600300000
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 630300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 930300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 960300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 1050300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 1080300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 1140300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 1170300000
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 1260300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 1290300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 1470300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 1500300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 1590300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 1620300000
In CC MODE, current within boundaries: 0.224100
Correct state - IDLE at time 1680300000
IDLE, current is 0A
Correct state - CC MODE at time 1740300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 1800300000
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 1830300000
In CC MODE, current within boundaries: 0.224100
```

```
Correct state - CC MODE at time 2130300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 2160300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 2250300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 2280300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 2340300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 2370300000
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 2460300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 2490300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 2790300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 2820300000
In CC MODE, current within boundaries: 0.224100
Correct state - IDLE at time 2880300000
IDLE, current is 0A
Correct state - CC MODE at time 2940300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 3000300000
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 3030300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 3120300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 3150300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 3330300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 3360300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 3450300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 3480300000
In CC MODE, current within boundaries: 0.224100
Correct state - IDLE at time 3540300000
IDLE, current is 0A
Correct state - CC MODE at time 3600300000
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 3660300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 3690300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 3990300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 4020300000
In CC MODE, current within boundaries: 0.224100
Correct state - IDLE at time 4080300000
IDLE, current is 0A
Correct state - CC MODE at time 4140300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 4200300000
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 4230300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 4320300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 4350300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 4530300000
```

```
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 4560300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 4650300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 4680300000
In CC MODE, current within boundaries: 0.224100
Correct state - IDLE at time 4740300000
IDLE, current is 0A
Correct state - CC MODE at time 4800300000
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 4860300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 4890300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 5190300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 5220300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 5310300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 5340300000
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 5400300000
In CC MODE, current within boundaries: 0.224100
In CC MODE, current within boundaries: 0.224100
Correct state - CC MODE at time 5430300000
In CC MODE, current within boundaries: 0.224100
Correct state - CV MODE at time 5520300000
In CV MODE, current within boundaries: 0.237606
Correct state - IDLE at time 5550300000
IDLE, current is 0A
Correct state - CV MODE at time 5580300000
In CV MODE, current within boundaries: 0.234510
Correct state - CV MODE at time 5610300000
In CV MODE, current within boundaries: 0.233185
Correct state - CV MODE at time 5700300000
In CV MODE, current within boundaries: 0.228331
Correct state - CV MODE at time 5730300000
In CV MODE, current within boundaries: 0.226570
Correct state - CV MODE at time 5820300000
In CV MODE, current within boundaries: 0.221739
Correct state - CV MODE at time 5850300000
In CV MODE, current within boundaries: 0.219988
In CV MODE, current within boundaries: 0.210856
In CV MODE, current within boundaries: 0.170687
In CV MODE, current within boundaries: 0.134180
In CV MODE, current within boundaries: 0.103573
In CV MODE, current within boundaries: 0.078828
In CV MODE, current within boundaries: 0.059354
In CV MODE, current within boundaries: 0.044330
In CV MODE, current within boundaries: 0.032910
In CV MODE, current within boundaries: 0.024322
In CV MODE, current within boundaries: 0.017916
In CV MODE, current within boundaries: 0.013164
In CV MODE, current within boundaries: 0.009656
In CV MODE, current within boundaries: 0.007073
In CV MODE, current within boundaries: 0.005176
In CV MODE, current within boundaries: 0.003785
Correct state - END MODE at time 14580300000
END, current is 0A
In END, current within boundaries: 0.000000
In END, current within boundaries: 0.000000
Verification completed or timed out after 650 time units
Test 1 : completed with success, Vbat=4.189973
==== Test concluded with success ====
Simulation complete via $finish(1) at time 19500300 NS + 0
```