Chapter 7

Results and Analysis

Finally the results and analysis are presented. This chapter presents the outcome and data obtained as plots and also draws inferences on this data.

The data is grouped according to subsystems defined in section 5.2, chapter 5. Before that some of the important things about the setup are to be mentioned. The main simulation for design was performed in MATLAB 2017 and Simulink. The data was logged in the 'simulink-data-inspector' or sdi for short. The UREF data was manually generated to accommodate most of the driving behaviours to be presented like slow-acceleration, fast-acceleration, cruising, slow braking, hard-braking similar to events that might be observed by a rider in an urban environment. However, it should be noted that the data is in accelerated time with a ratio of about 1:20 where 1 second of simulation is 20 seconds of real world data. This scaling is because the data generated during simulation is very large in size > 6.4 GB for the 20 second simulated run. The author has designed the pseudo-user input UREF in similarity to standard EV tests like MATLAB inbuilt-standard-input "drive cycle source" (NYCC (598 seconds)). To keep the simulation time and scope realistic the decision for custom data was considered.

The results are now presented as per subsystems;

7.0.1 Temperature and Cooling-results

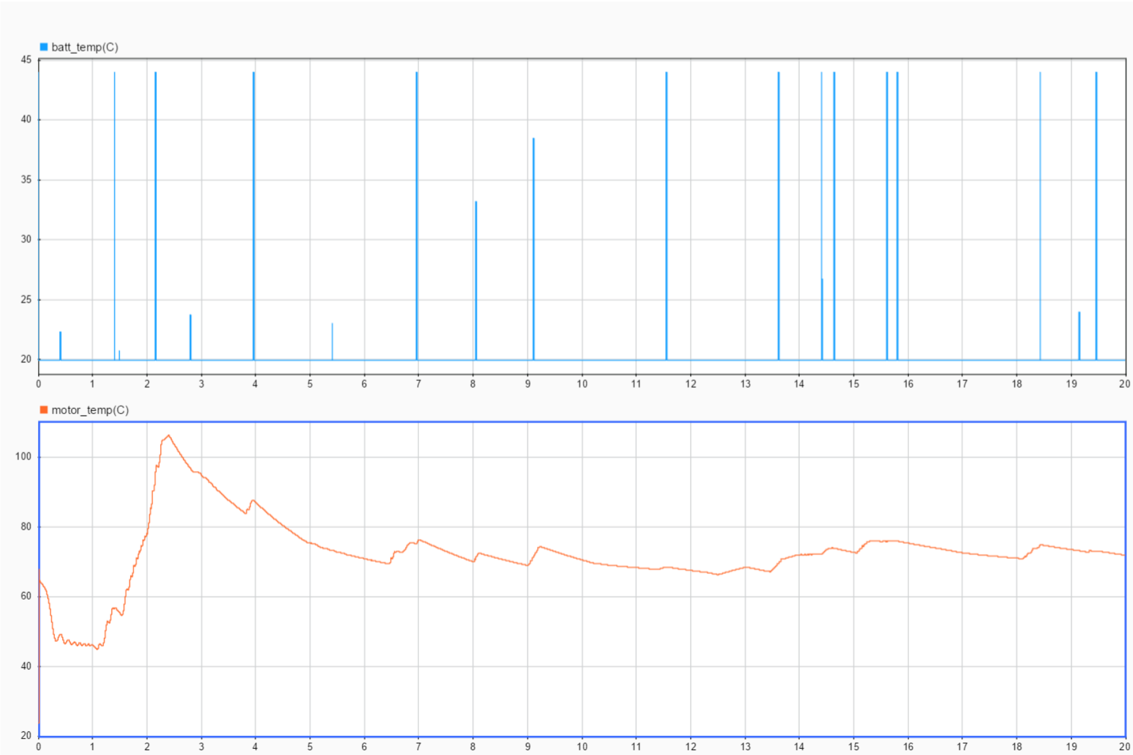

Figure 7.1: Temperature characteristics obtained for battery and motor. Note the spikes in battery-temperature (Top) whenever a sudden current demand is seen, however being cooled very fast by active cooling. For the motor (Bottom), initial heating is high since it is air cooled and vehicle is moving relatively slow. However as vehicle accelerates and is operating in a high speed zone the outcome is that motor is better cooled

The base ambient temperature for both battery and motor is initially set to environmental 25^{o}C. After which the active cooling and passive cooling for battery is engaged, which consistently maintain the battery at a constant temperature of 20^{o}C. The current surges from battery are transients due to switching in MCC and are thus very short lived. The temperature spikes are a result of that. They are also restricted within 50 degrees, whereas the cell pack can withstand operating ranges of around 50 degrees celsius, however that degrades battery life. Note here that the battery temperature is the surface temperature of the pack near output terminals and not the deep-pack cell temperature. That is shown in next

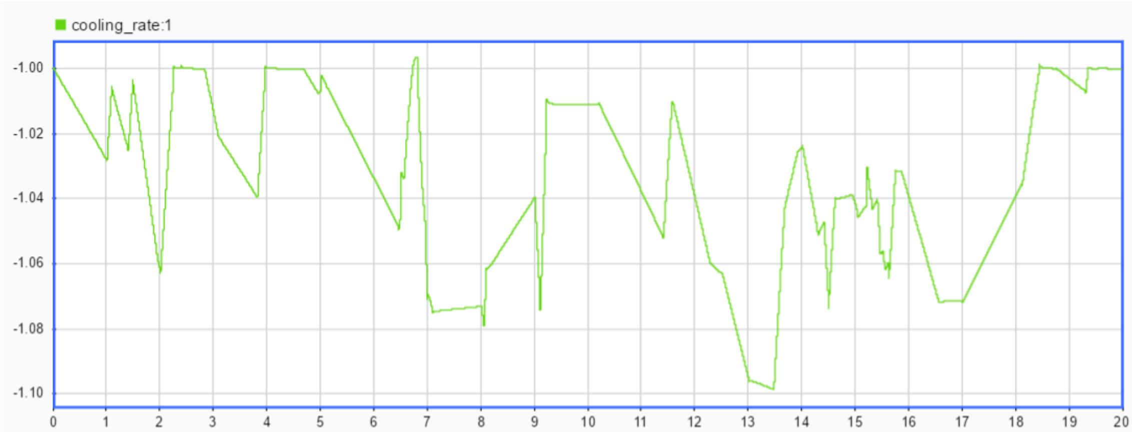

Figure 7.2: Cooling Rate - Factor. This plot shows the cooling rate factor which is then used to generate the actual cooling level based on local parameters in the temperature subsystem.

section. This temperature-data is considered ambient for the cells.

Similarly for the motor their is no active cooling. Almost all the cooling comes from the passive heat-sink casing of the motor and airflow due to motion, the cooling factor computed from the rotor speed is shown in fig. 7.2 . It is noticeable in the second plot, in the early low speed time limits the motor heats up a lot even though the current is not high as compared to later stages, however even in later time intervals the temperature falls to a stable range. This is due to the increased airflow taking hold in the heat-sink casing fins. This is modelled by the exponential term in the block-diagram.
Cooling rate itself is the exponentially saturating value which can at maximum decrease the temperature by 50 degrees given appropriate conditions.

7.0.2 Battery-results

The above plot is the current going in and out of the battery as per sign convention. The current draw from battery during normal operation is pulsed and is thus shown in a pulsed band. The positive current spikes are during the MCC transition and

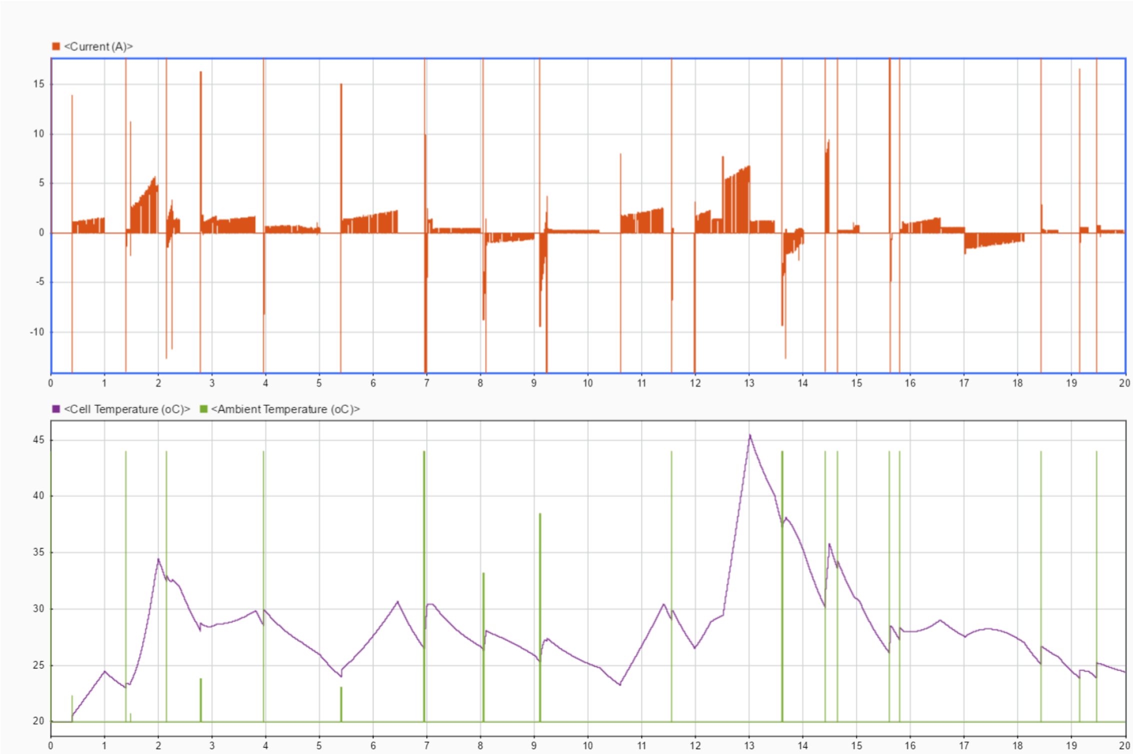

Figure 7.3: Battery Current (Top) and Battery Cell temperature, ambient temperature (Bottom)

regenerative braking when the UC is off and battery takes then energy. In the bottom plot can be seen the **cell temperature** and ambient temperature of the battery pack. It can be noted that the cell temperature rises every time the battery is supplying current or storing energy from RB. It coincides with the battery current demand. It also floats around 50^{o}C as mentioned in the temperature section above, during high load. Note that the current spikes which touch the boundary sometime reach up-to 60A which is drawn by the UC and drive during transition in MCC.

The voltage decrease is due to load and increase due to one of 2 factors, increased current draw which when MCC is switched generates a high positive swing rate-slowed by impedances or due to energy recovered due to RB.

The decrease in SOC is not apparent having only changed by 0.4V in the end in comparison to beginning 128V. This is because of the recovered energy, which directly corresponds to

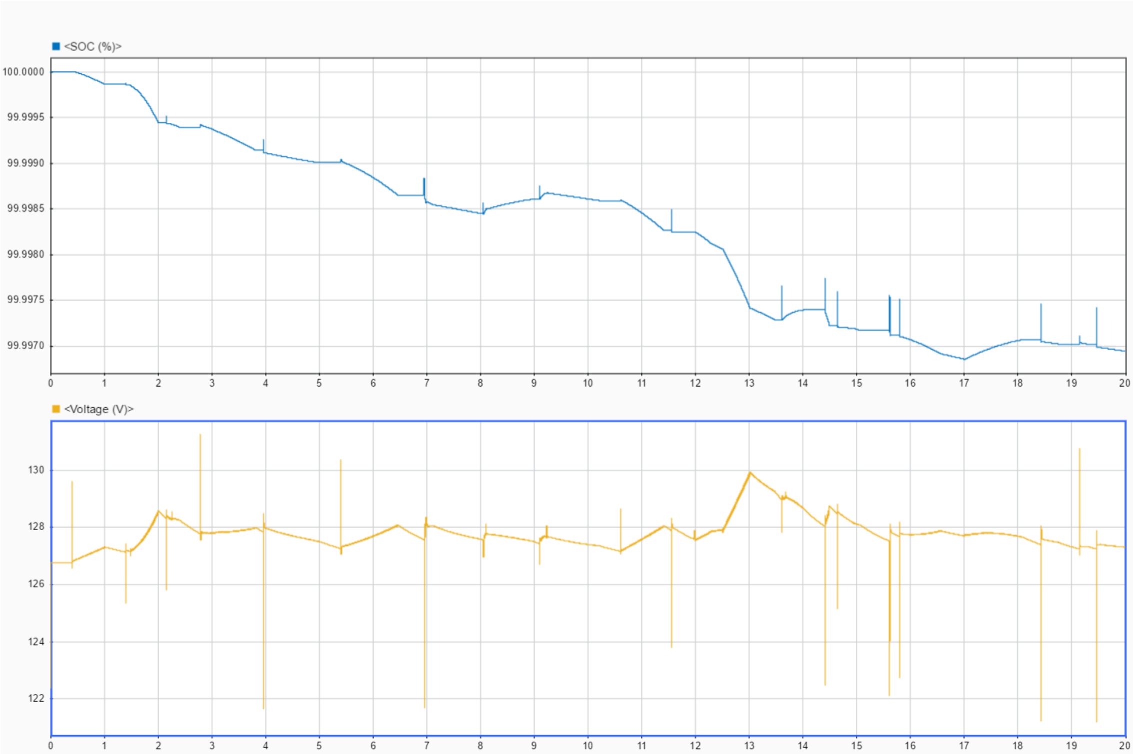

Figure 7.4: Battery pack SOC (Top) and terminal voltage (Bottom). Initial state of charge is 100% @ 130V.

increased range of vehicle. The SOC rate of change can be used to draw extrapolations at various rates in the plot. Which can give us effective operating time and can be used to determine average operating-range to a fixed SOC value of say 10%.
Two intervals of interest are [5.5,6.5] and [12.5, 13]. In these ranges considering the nearest average velocities as 8.8m/s (31.6kmph) and 20m/s (72.3kmph). Then using simple regression for these two scenarios and their averages, the data in tables 7.1 is obtained.

The equation for the linear line is then given by;
$SOC_{10\%} = -3.5000e - 04 * t_{hours} + SOC1_{max}$
for case 1 and
$SOC_{10\%} = -0.0012 * t_{hours} + SOC2_{max}$
for case 2. Knowing $SOC_{10\%} = 10$, the equations can be solved for time. The plots for the same are also shown in fig. 7.5.

From this data a basic range analysis can be performed and assessed.

Time Analysis for SOC $\frac{d}{dt}$ 2-scenarios				
Parameter	**Value** $< avg. >$	**min. value**	**max. value**	**units**
Time range 1 - [5.5, 6.5], slope = -3.5000e-04				
SOC	99.99885 @ 6s	99.99866 @ 6.5s	99.99901 @ 5.5s	%age SOC
$v_{vehicle}$	8.8	4.5	12.4	m/s
Output Time	71.42	-	-	hours
Time range 2 - [12.5, 13], slope = -0.0012				
SOC	99.99777	99.99744 @ 13s	99.99806 @ 12.5s	%age SOC
$v_{vehicle}$	20	16.2	24	m/s
Output Time	20.16	-	-	hours

Table 7.1: Battery load analysis: Time to discharge under 2 cases, v_{avg} = 8.8m/s and v_{avg} = 20m/s

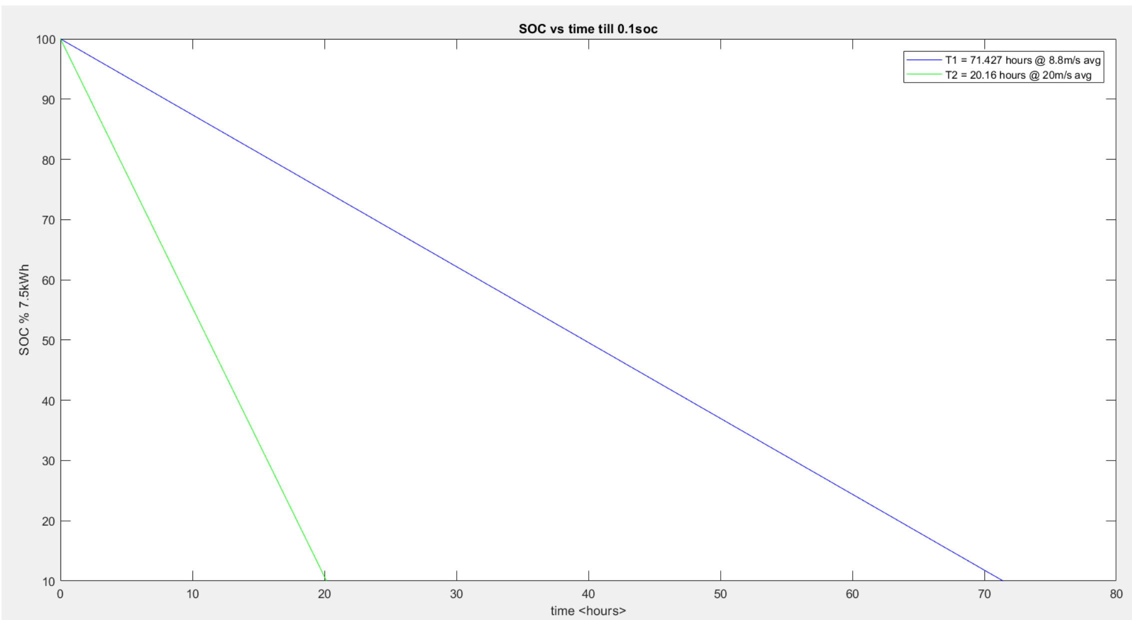

Figure 7.5: SOC vs Time till 0.1*SOC @ 2 different average velocities

Range Analysis for SOC $\frac{d}{dt}$ 2-scenarios				
Parameter	**Value** $< avg. >$	**min. value**	**max. value**	**units**
Time range 1 - [5.5, 6.5], slope = -3.5000e-04				
SOC	99.99885 @ 6s	99.99866 @ 6.5s	99.99901 @ 5.5s	%age SOC
$v_{vehicle}$	8.8	4.5	12.4	m/s
Output Range	301.7	154.2	425.13	km
Time range 2 - [12.5, 13], slope = -0.0012				
SOC	99.99777	99.99744 @ 13s	99.99806 @ 12.5s	%age SOC
$v_{vehicle}$	20	16.2	24	m/s
Output Range	193.54	156.77	232.25	km

Table 7.2: Vehicle range analysis: 2 cases, v_{avg} = 8.8m/s and v_{avg} = 20m/s and driving times of 72 and 20 hours respectively.

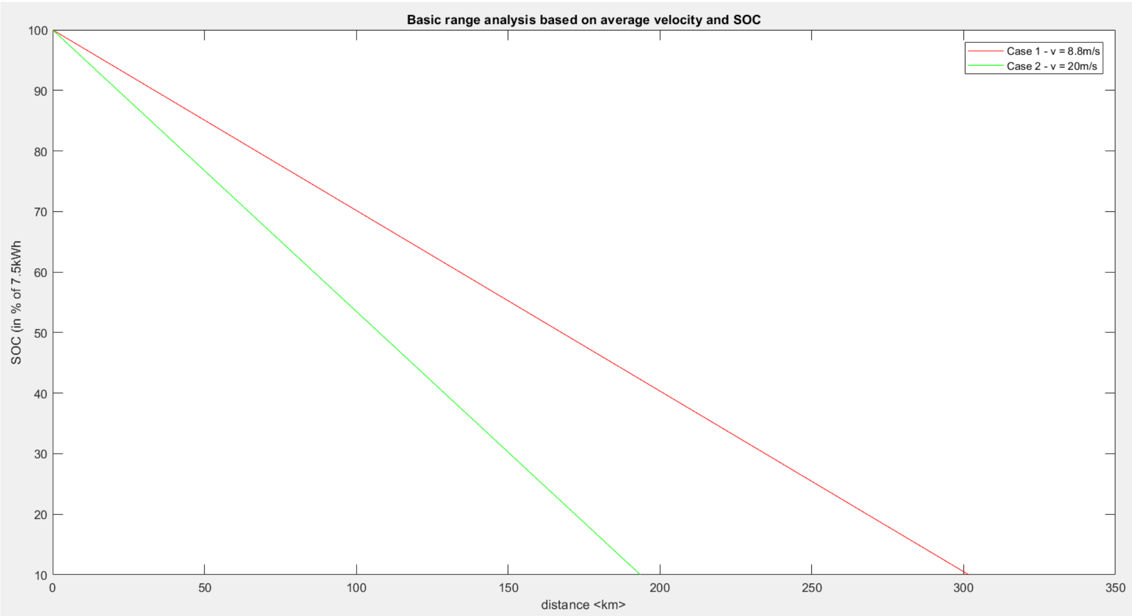

Figure 7.6: Range Analysis. SOC vs distance plot (discharge from 1*SOC to 0.1*SOC). For average velocity case

The range values are simply obtained by kinematic equation $velocity = \frac{distance}{time}$. Using the 3 velocity data points and using an adjusting factor of 0.133, the range can be analysed. The data for the same is shown in table 7.2 and corresponding plots are shown in fig. 7.6

From fig. 7.7, we can draw a realistic conclusion that the range of vehicle will be around 155km per charge while full weight limit is used. And in best case scenarios the range can show a peak of around 232km, which is a substantial increase in comparison to the current market available designs.

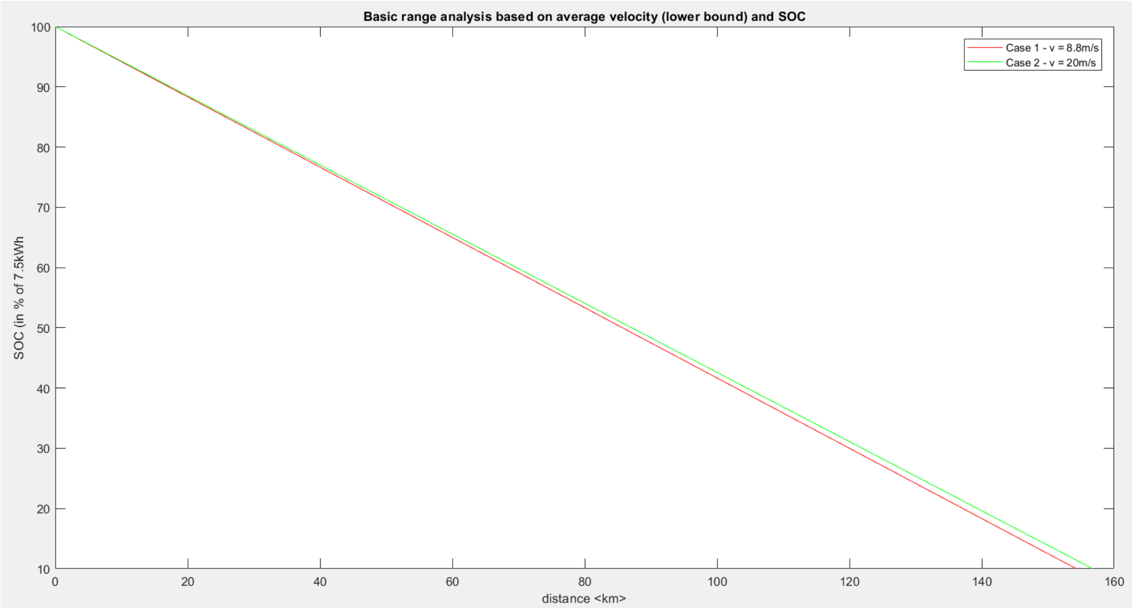

Figure 7.7: Range Analysis. SOC vs distance plot (discharge from 1*SOC to 0.1*SOC). For coinciding cases.

7.0.3 Ultracapacitor-200F

Fig. 7.8 shows the current and voltage and power curves for the ultracapacitor. Positive current-spikes can go as high as 300A while supplying power to the drive through th BDBBC. Voltages corresponding to these positive-current spikes shows sharp loading dips. For the inverse case where the UC is charged through BDBBC after appropriate MCC setting the current values show sharp negative spikes also extending up-to -100A. Corresponding voltage-spikes in positive direction can be seen as well. It can be noted that in certain regions the voltage increase in the UC is significant and can be seen in the plot. Note that these small bumps correspond to kilowatts of RB power harvested. These are immediately used to provide acceleration energy for the immediate next input corresponding to accelerating the vehicle as per UREF. The power recovered during RB by UC and also delivered as per demand, can be seen in plot in fig. 7.8, third plot.

It should be noted here that the current spikes shown here are transition restricted due to BMS. However, these spikes can easily reach ranges extending upto 10kW.

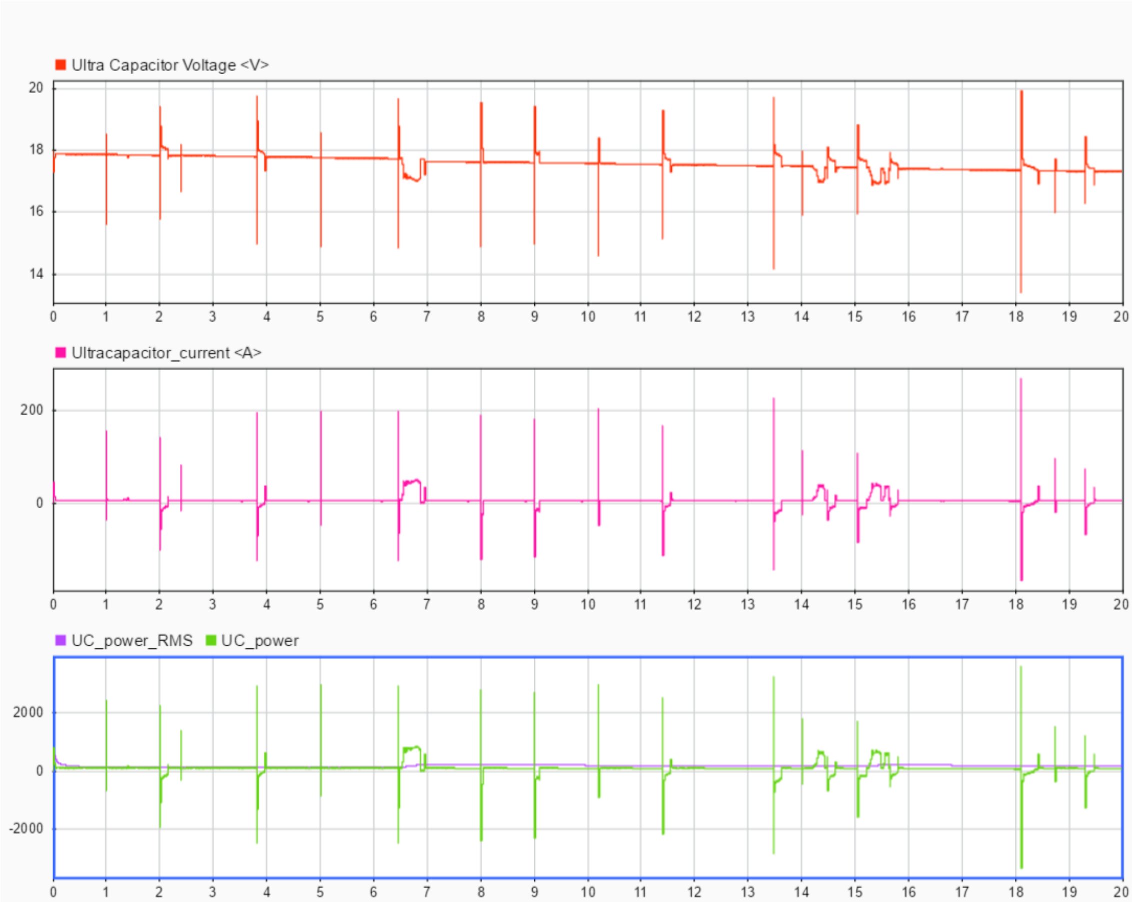

Figure 7.8: Ultracapacitor Voltage(Top), Current (Middle) and Power (Bottom). The third plot shows the power delivered or received by the UC, it also shows the base line RMS power, which is around 200W. The positive spikes can reach upto 2.5kW and negative spikes can reach upto -2.5kW. At t = 14.5, it can be seen that delivered energy is immediately recovered upto 80%. This would have been too lossy with the battery

7.0.4 Ultracapacitor and MCC control

This subsystem generates the control pulses for BDBBC and MCC. Fig. 7.9 shows the plots associated with this subsystem. The MCC switch activation time and duration and the reverse torque threshold detection are shown.

7.0.5 Main Charge Controller (MCC)

This is the main power source selector or switch and consists of relays and several model based losses, filters and DC-link decoupling. Fig. 7.11 shows the DC link voltage on the battery

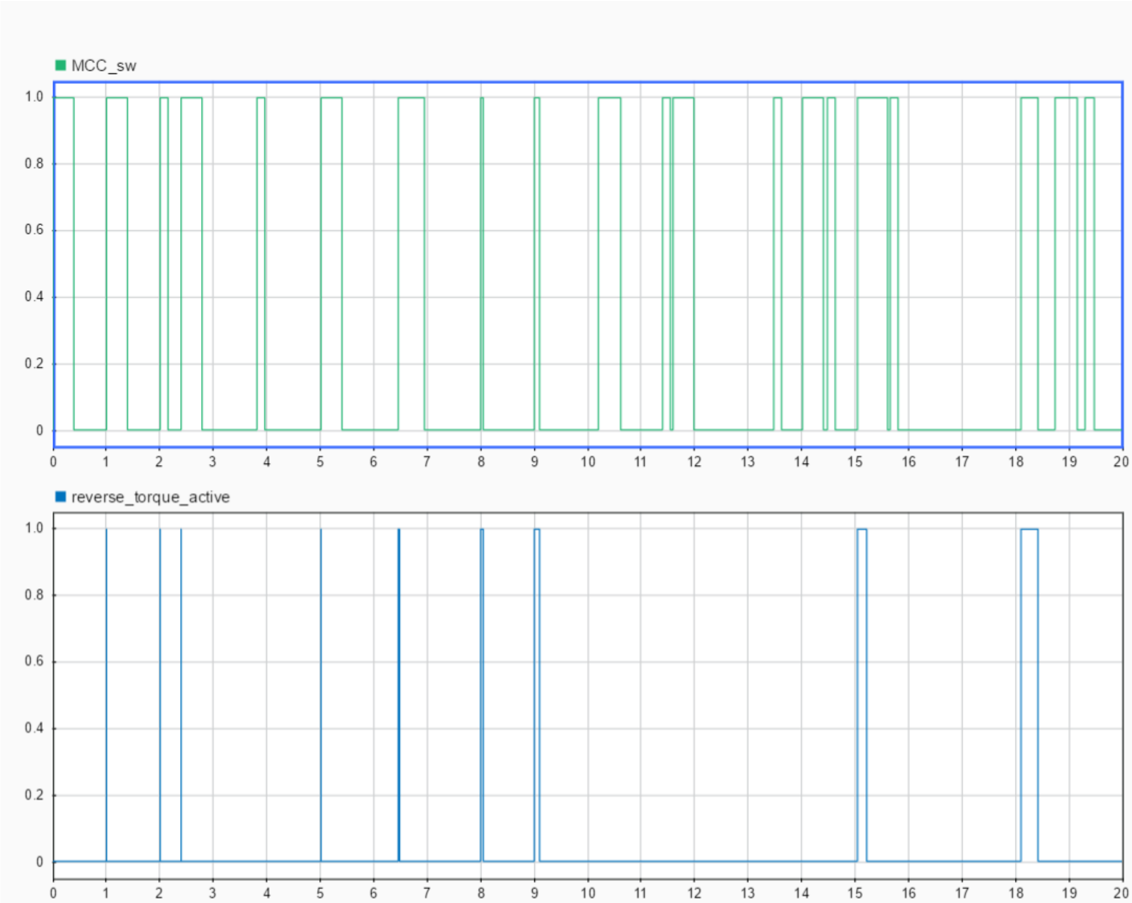

Figure 7.9: UC and MCC control. MCC control signal (0: Battery, 1: UC) [Top] and Reverse Torque detection used for slow deceleration detection events [Bottom].

side. Note that the mean-voltage here is 128V. Spikes above it are due to RB after UC has disconnected. The drops in voltage are when UC is connected for energy recovery using RB, the battery side sees a drop in voltage therefore due to line parasitics.

7.0.6 PMSM drive

There are several drive sensors which are recorded. The most important ones are the stator currents, torque and voltage at inverter-link. The motor drive rotation speed is obtained in radians per second and is related to the speed of vehicle using equations discussed in chapter 5. The rotor speed is used to compute the vehicle velocity, tire rpm and many other control factors critical to the model in mechanical-modelling-

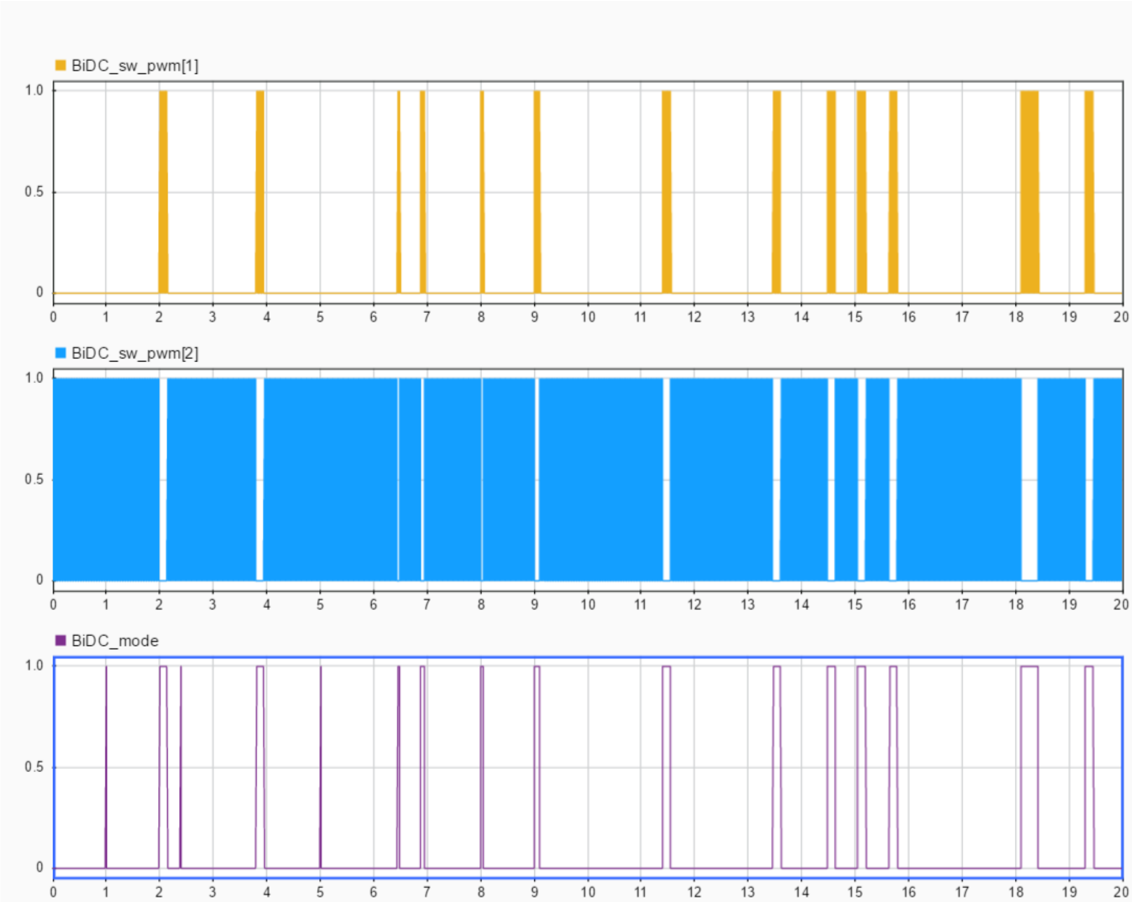

Figure 7.10: BDBBC, plots for 2 switch signals (Top and Middle) and mode selector. The first 2 plots are the PWM switching waveforms being used to control the 2 switches in BDBBC in complimentary mode. The third plot is the mode select between 'Buck' (1) or charging and ''Boost' (0) or power-delivery (standby/default) operation.

subsystem. The electromagnetic torque that is used to drive the system after being calculated in the mechanical-subsystem is also used here to determine error-in-the-loop. Fig.

7.0.7 Mechanical Model and Environmental-Model

The data in this section is recorded for the mechanical model of the vehicle and environment model. Fig. 7.14 shows the velocity model output. The speed calculations for the drive reference and then using the resulting drive output rotational speed to compute the vehicle linear speed and use it as a feed-back. The model computes speeds in 2 variants meters/second and kilometres/hour, there is also the speed-ref computed by subtracting the braking factor from UREF.

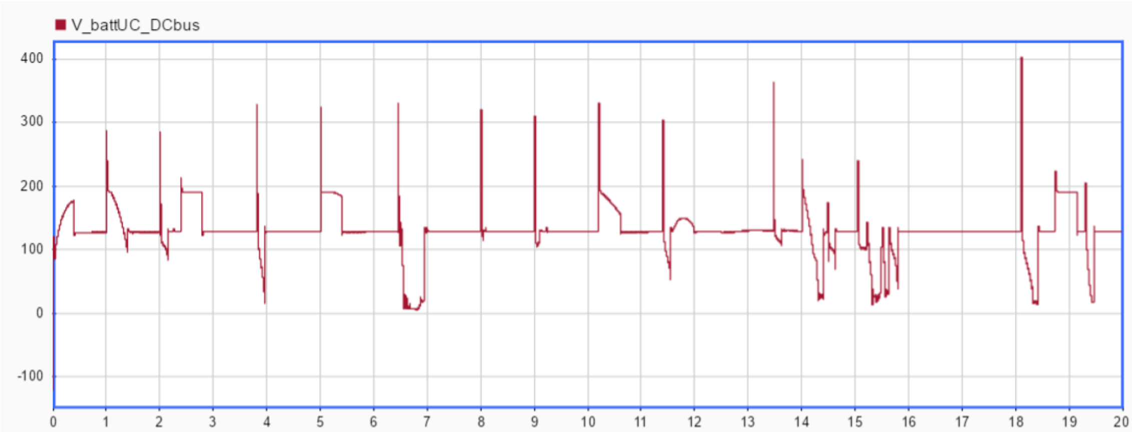

Figure 7.11: DC-link-voltage in MCC on battery side. Here nominal battery-voltage is 128V. The maximum reverse spikes can go upto 320V which can be caused due to MCC switching or reverse transient pulses from drive.

The braking and trigger block which generates the braking factor and activation signal for UC-MCC control is shown in fig. 7.15. The top plot shows the braking factor which is generated with a slight delay in the model. Second plot shows the PMSM-drive speed reference in rad/s and resulting tire rotation in RPM. Third plot is the activation signal for acceleration detection and last plot is the activation-signal for braking/deceleration events. The trigger signals can have an overlap, however acceleration is given preference.

In the loss-model blocks.The drag force is computed for a frontal area of $1.66m^2$ and a drag coefficient of 0.8. The drag is restricted at 200N or 2kg in simulation, however it can extend beyond this. The saturation is done to avoid non-linear region complexity in air drag due to higher velocity and turbulence resulting from it. The drag equation also accounts for wind speed which is set to $2m/s$ in the direction of motion. Alongside this in real life scenarios. The gradient effect is also taken into effect and the resulting torque reference after all the calculation can be seen in fig. 7.12. For the rest of the output see fig. 7.16.

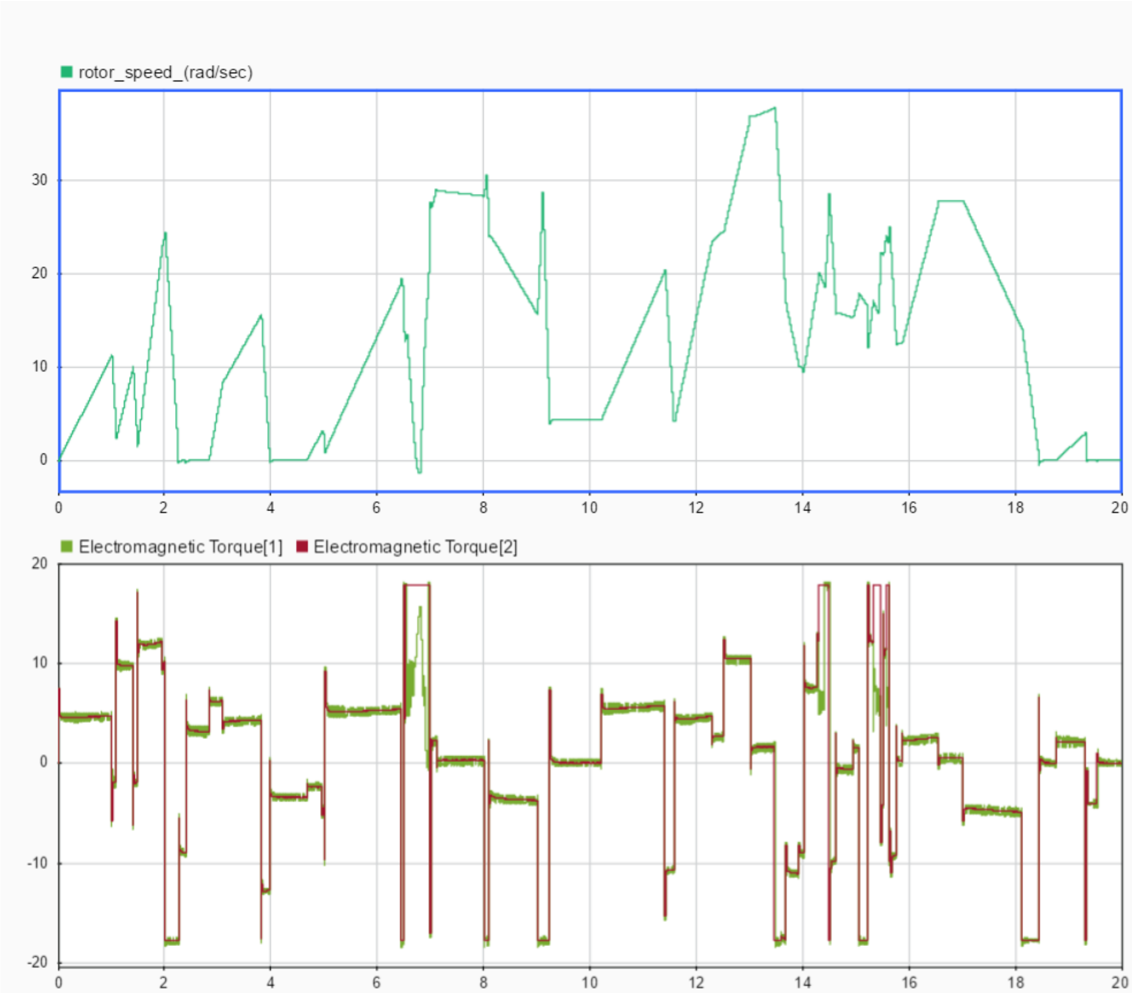

Figure 7.12: PMSM drive - rotor speed (scaled x0.1) and Electromagnetic torque (Bottom) with reference. The first plot is the rotor speed scaled by a factor of 10 for internal references. The second plot shows the reference (Red [2]) and obtained electromagnetic (Green [1]) torque

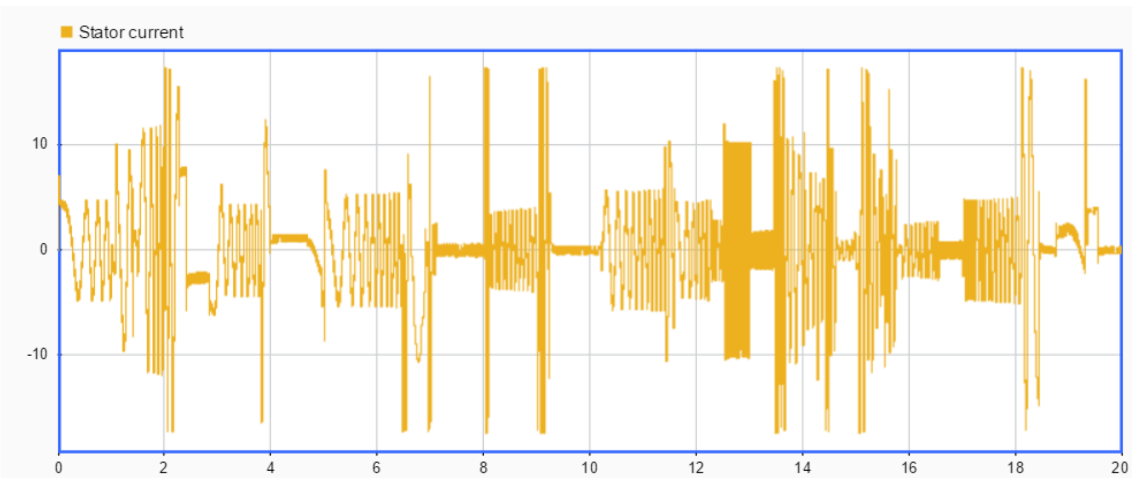

Figure 7.13: Stator ‘a’ phase current, reaching a maximum of $19A_p$ or $38A_{p-p}$.

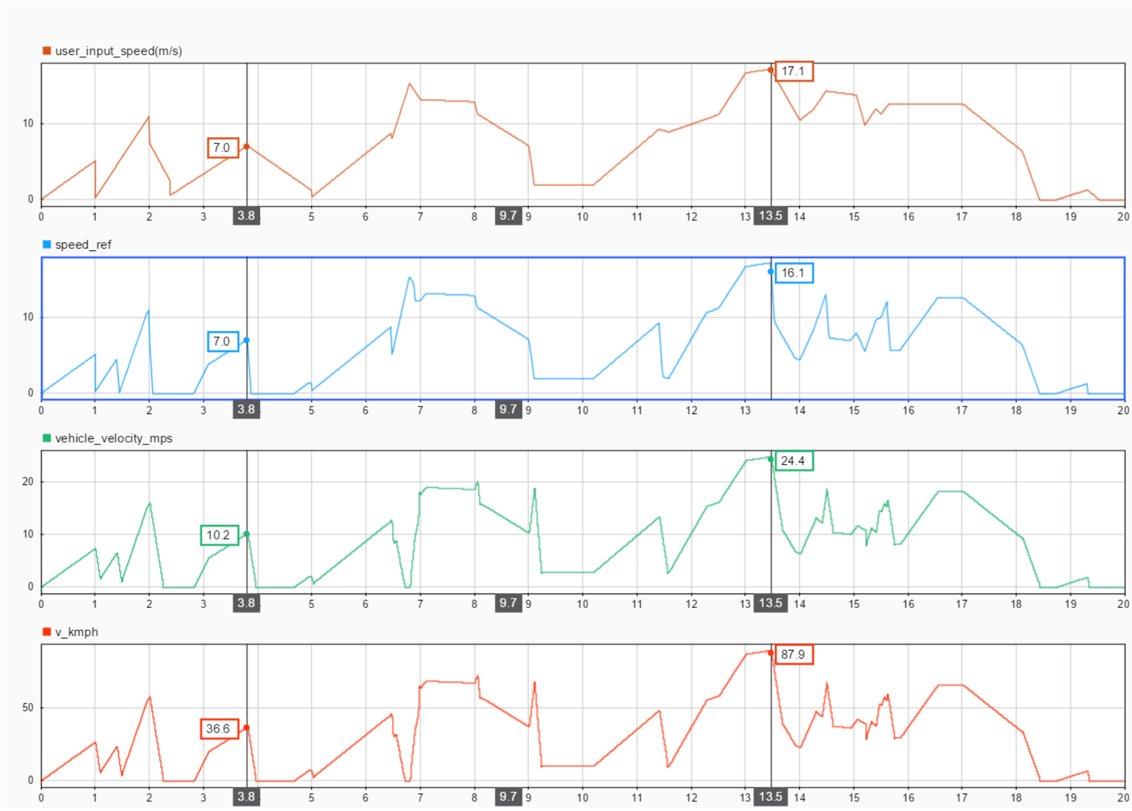

Figure 7.14: Top - UREF, 2nd - Internal Reference, 3rd - velocity in m/s, Bottom - velocity in km/h. Note the cursors showing values @ t = 3.8s and t = 13.5s. At the later the maximum speed is achieved in a holding speed

7.0.8 Power Source: Capacitor-Bank Stand-alone simulation

In order to simulate a capacitor only scenario where, the battery is not providing any energy, the system was run on capacitor only with initial charged condition of 18V. Apart from this, the charge was obtained from the same drive-train battery as is used earlier, which reduced its SoC from 100% to 96%. This capacitor bank is then used to simulate two scenarios, one with regenerative braking enabled and one with RB-disabled. The simulation is again run for 20s and the trends are extended over time, in this case to evaluate the range which our vehicle-model can cover with only UC.

The results are presented below, along with the calculations.

Note that in fig. 7.17, the range of UC-only case is highest however, that is only due to the fact that it is draining energy constantly and the cut-off voltage is 10V, thus it will not

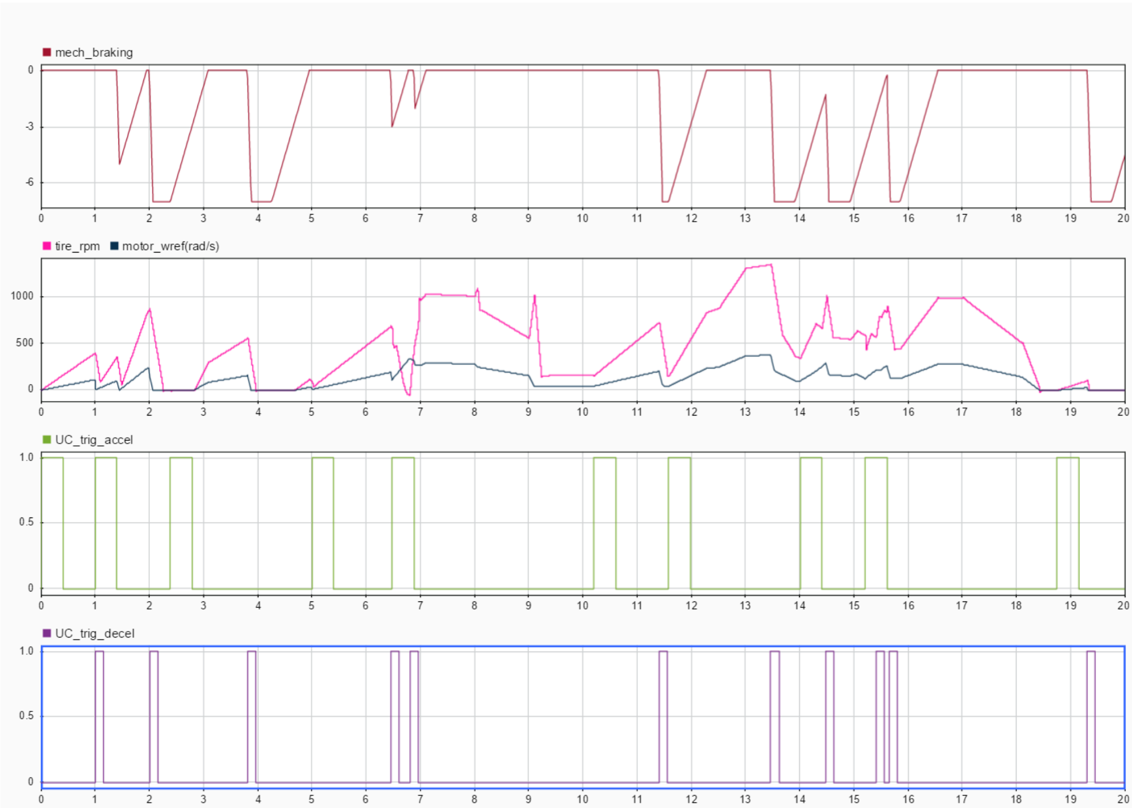

Figure 7.15: Top plot shows the braking values generated with a delay and rate limiting in processing. The second plot shows the tire rotation per minute and also the reference to PMSM in radians per second, generated after error calculation. Third and fourth plots are the UC-MCC trigger events.

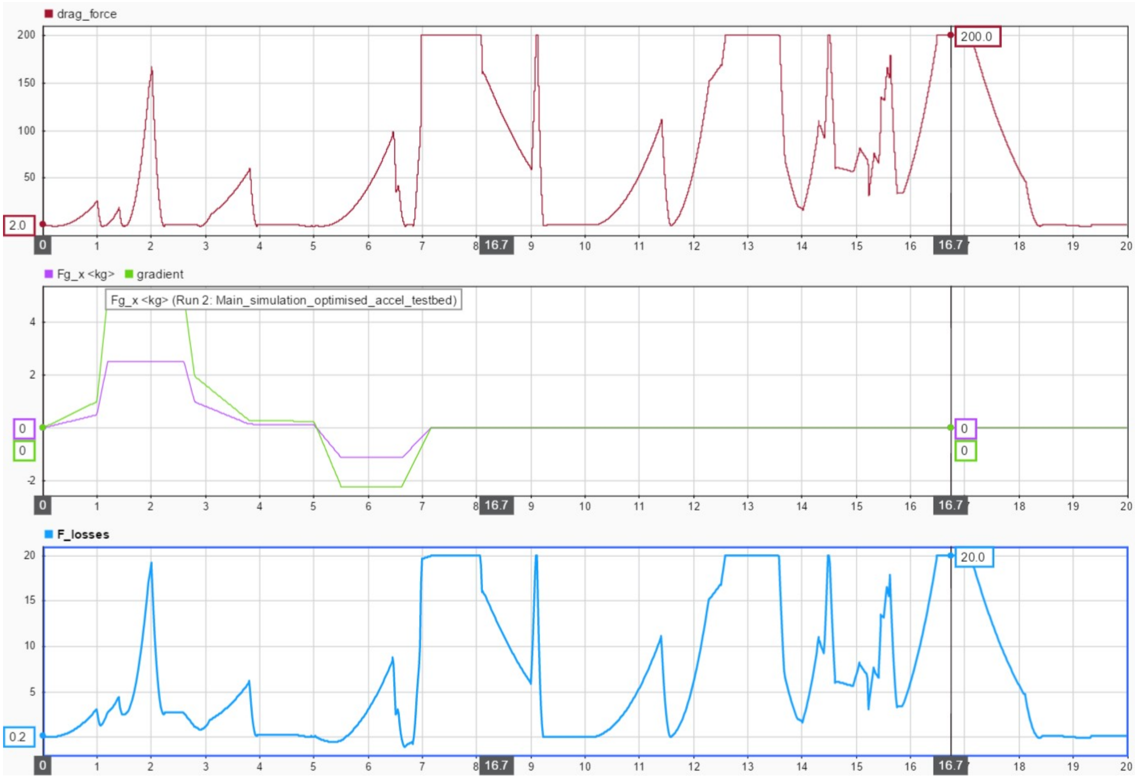

Figure 7.16: The top plot shows the air drag. The middle plot shows the gradient input and resulting vector force component Fg_x in kilograms. the direction of force is given by the sign of the resulting values. The last plot shows the resulting vector sum of these forces.

work for long duration, which can be observed from the time analysis, given below.

Using the linear regression formula $y = mx + c$ for predicting final values;

$$t = \frac{10 - 18}{-0.05} = 158.24s = 2.63minutes \tag{7.1}$$

Now from equation 7.1, we can calculate the range. Cut-off voltage is 10V for UC since the BDBBC operates stably between 10 and 20 volts. Also the slope for voltage curve is -0.05

$$x_{meters} = 9.18 * 158.24 + 0 = 1453.17meters \tag{7.2}$$

where, 9.18 is the slope of displacement curve for UC-only case (green in plot 2 of fig 7.17).

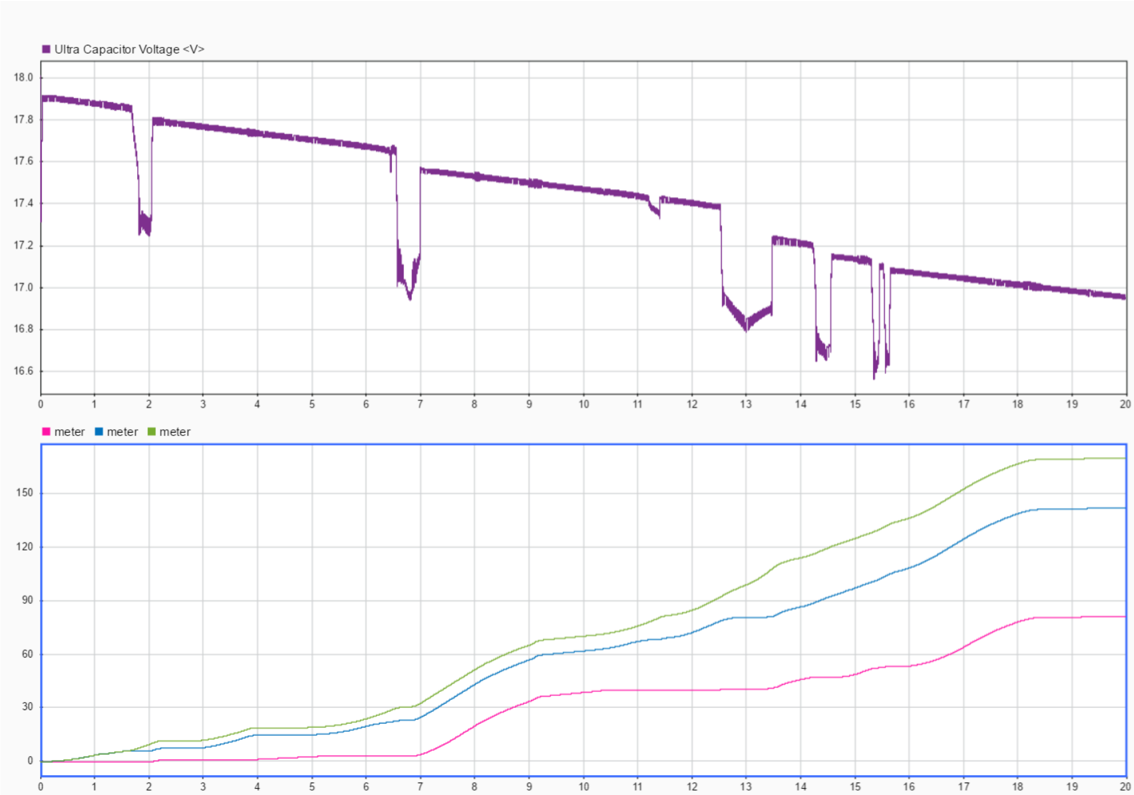

Figure 7.17: UC-only case, top; UC voltage with initial condition of $V_{UC} = 18$V. Bottom; three scenarios, (top graph-line: green) UC only range, (middle graph-line: blue) UC-battery hybrid range, (bottom graph-line: magenta) battery only range.

From this we see that even though the UC can provide range extension by itself, it is not significant when compared to battery only case or even the proposed design where battery-UC hybrid outpaces both stand-alone scenarios. Even if we consider that the UC-only case was extended to 0V instead of 10V, the time in that case would be $360 seconds$ and the range will be $3304.8 meters$, which falls short of the extended range obtained in hybrid-case of more than $30km$ or $30000m$.

The above case was discussed for UC-only with no RB, however even with RB enabled the performance does not show much change in this case, although the voltage magnitude does improve a bit which can increase the range slightly, but in no case going beyond 10km.

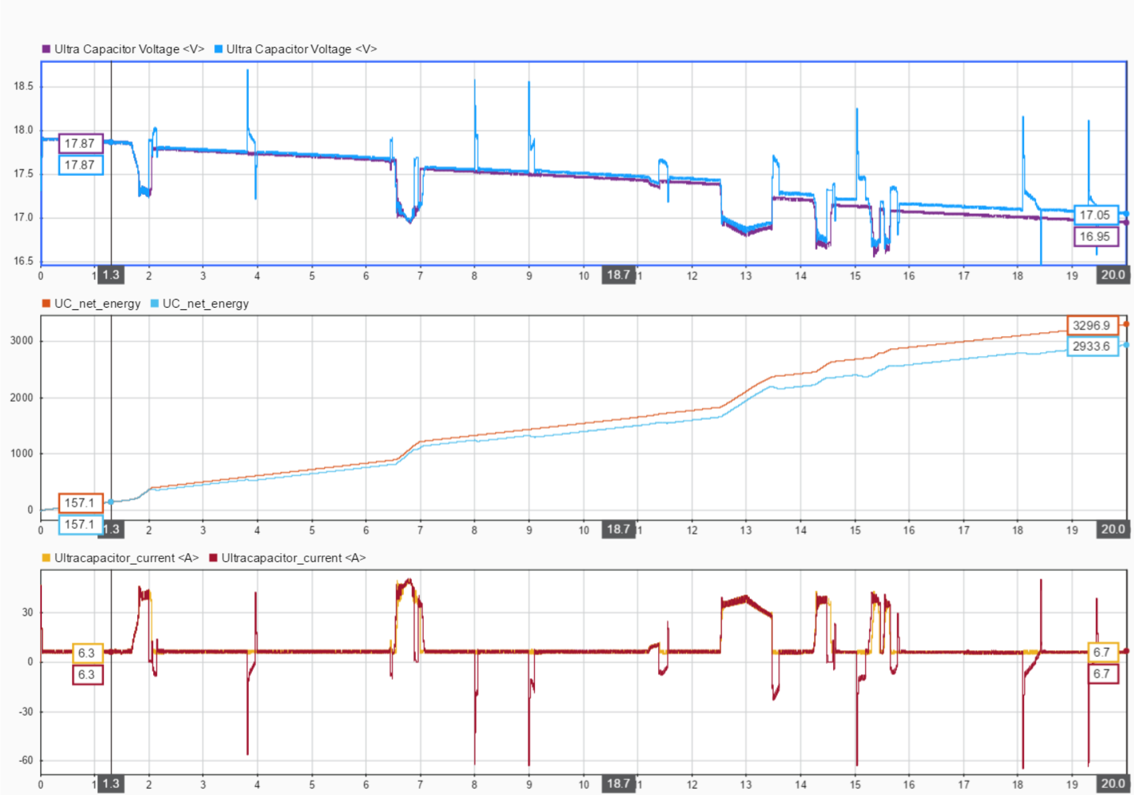

Figure 7.18: UC-only case with RB enabled disabled. Light blue in first graph, red in second graph and red in last graph show the case with RB-enabled. The rest, waveforms are RB-disabled.

7.0.9 An important note on time analysis

Note that the work uses simulation time and generally computes distance. This takes into consideration the driving style and for any extrapolated analysis, this pattern of driving is expected to repeat over and over again. The adjustment for variations in driving cycle which will inevitably effect the output range is done by calculating a scale factor from the data itself.