AUTOMOTIVE ENGINEERING-II

MEEN 689 - Project:2

Design and Simulation of Controller for Prius Hybrid Drive-Train

---

Submitted by

432001794 : **Sasi Preetham Devarasetty**
231003001 : **Subrat Kumar Behera**
530006039 : **Pinjala Sai Sudhir**

Mechanical Engineering

Texas A&M University
College Station, USA

Contents

Nomenclature

PT-split	Power Torque Split
T-split	Torque Split
mpg	Miles per gallon
SoC	State of charge
Vref	Velocity reference in RPM
Tref	Torque Reference in Nm
MG1	Motor-Generator 1
MG2	Motor-Generator 2
eCVT	electronically controlled Continuously Variable Transmission
EPA	Environmental Protection Agency
PID	Proportional, Integrator and Derivative controller
EMF	Electromagnetic Force
bsfc	Brake Specific Fuel consumption

List of Figures

1 Abstract

The Toyota Prius Drive-train was a technical marvel in the field of automobile engineering during the turn of the century. It would set a precedent for hybrid vehicles for years to come. The involvement of both engine and the motor in a hybrid vehicle poses a control and optimization challenge. The controller in a hybrid powertrain tends to bring the best out of both mechanical and electrical systems through various modes of operation, optimising the engine and motor operation. The current project aims to design and demonstrate a control strategy that minimizes the fuel consumption while ensuring considerable discharge of the battery in the Prius Drive-train using Dymola. The EPA Urban driving cycle will be used as a reference for the simulation [6]. The overall system consists of a PID controller, a mode selection and input module, an eCVT, a battery, a final drive and the vehicle model as well as a feedback loop. The PID controller ensures the vehicle traces the EPA Urban driving cycle as close as possible. The mode selection and input modules following the controller maximize the fuel economy by partitioning the powertrain operation into 4 modes - Starting, Sustain, Deplete and Regeneration [1]. Two different control strategies, namely T-split and PT-split were implemented and compared to test for fuel economy and battery SoC. The PT-split algorithm shows the fuel consumed to be 0.097 gallons as compared to 0.16 gallons in the case of T-split. The battery SoC at the end of the cycle was 0.85 and 0.4 for PT-split and T-split algorithms respectively. Finally, the city mode mileage was found to be 76.8 mpg for PT-split as compared to T-split, which produced a mileage of 46.5 mpg.

2 Introduction

Prius has hybrid type drive train, which drives the vehicle by combined effect of engine and electric generator-motors. The drive train consists of two motor generators, one engine and one epicyclic gear-train that works as power split device. The engine is connected to the carrier, one of the motor generator (MG1) to the sun and the other (MG2) to the ring of the planetary gear set. The ring gear is connected to the wheels through a final drive [3].

MG2 works as a motor as the vehicle accelerates, while it works as a generator during braking. MG1 acts as the starter motor for the engine and takes on the role of an alternator to charge the battery. The generator consists of very strong magnets. These Motor-Generator units are connected to a planetary gear system consisting of ring, sun, and planet gears on a carrier. Controlling the engine and motors suitably, continuous variation of gear ratio can be achieved, which is why this transmission is appropriately called an eCVT (Electronically Controlled Continuously Variable Transmission).

When the vehicle is stopped/stationary, MG2 does not turn and in order to charge the battery in such circumstances, the engine rotates MG1 and charges the battery by making it an alternator, and converting AC supply by MG1 to DC by means of an inverter. During starting, MG2 sets the vehicle in motion, rotating MG1 as a consequence. At higher speeds, the engine runs MG1 which in turn runs ring gear and MG2 supplies additional power to the vehicle to fill the torque deficit, thereby making it capable of achieving higher speeds. When the vehicle needs to be reversed, the engine is off and MG1 rotates MG2 in the reverse direction.

In this project, we simulate a Prius drivetrain model using Dymola that runs in 4 modes - Starting, Deplete, Sustain and Regeneration. The model consists of a PID controller that gives the torque required by comparing to the USA EPA urban driving cycle, a mode selection module, a mode input module which governs the control inputs to MG2 and engine, and is then connected to the vehicle model via a final drive. Based upon the torque and power needed, the vehicle always runs at maximum efficiency at that torque by adjusting the mode and the rotation of MG1 and MG2. Two algorithms are implemented in the mode selection-mode input blocks, with one of them running engine and MG2 based on assigned torque split, while the other controls the engine based on power required and MG2 based on torque required.

3 Modeling

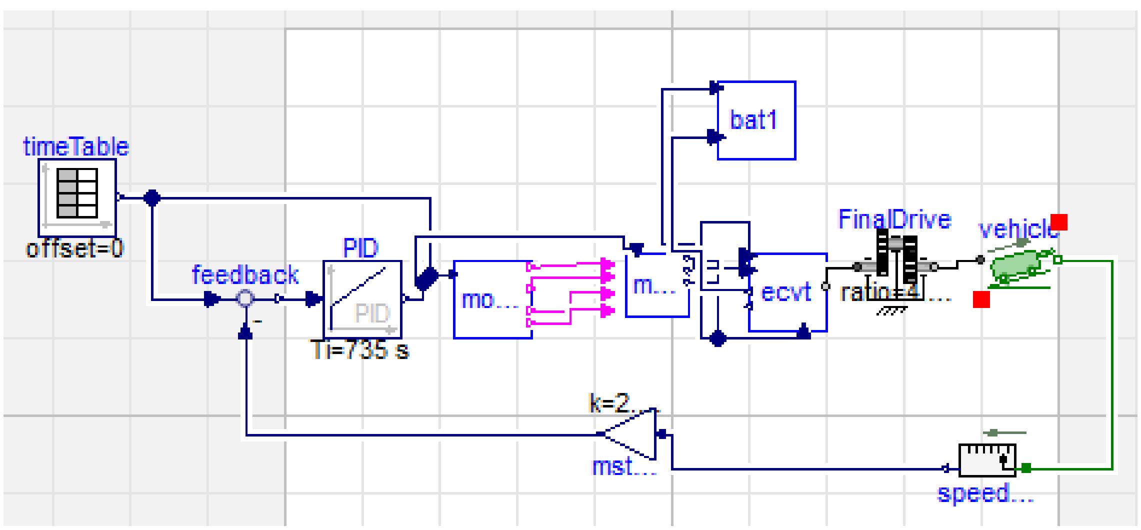

Figure 1: Block diagram for T-split implementation

3.1 PID

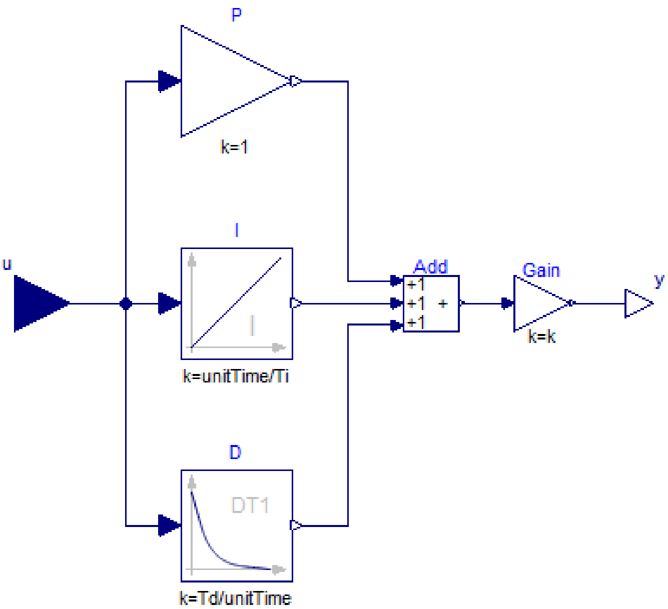

Figure 2: PID model taken from Dymola library

Firstly, we have a PID controller Fig.2 that takes the feedback speed from the vehicle, compares it to the required speed in the next time step as per the drive cycle, and gives the required torque to be supplied to the mode selection module. A PID controller gives a corrective output by passing the error through a proportional gain, an integrator and a differentiator. The proportional gain deals with the rise time of the system, whereas the integral and derivative parts correct the steady state error and overshoot respectively. A PID block from the standard Modelica library is used for this system. For the T-split algorithm, the PID was tuned without the need of a filter as the error was devoid of spikes. For PT-split, a filter is used to block undesirable spikes which might result in unreasonably high control outputs from the PID.

3.2 Mode Selection

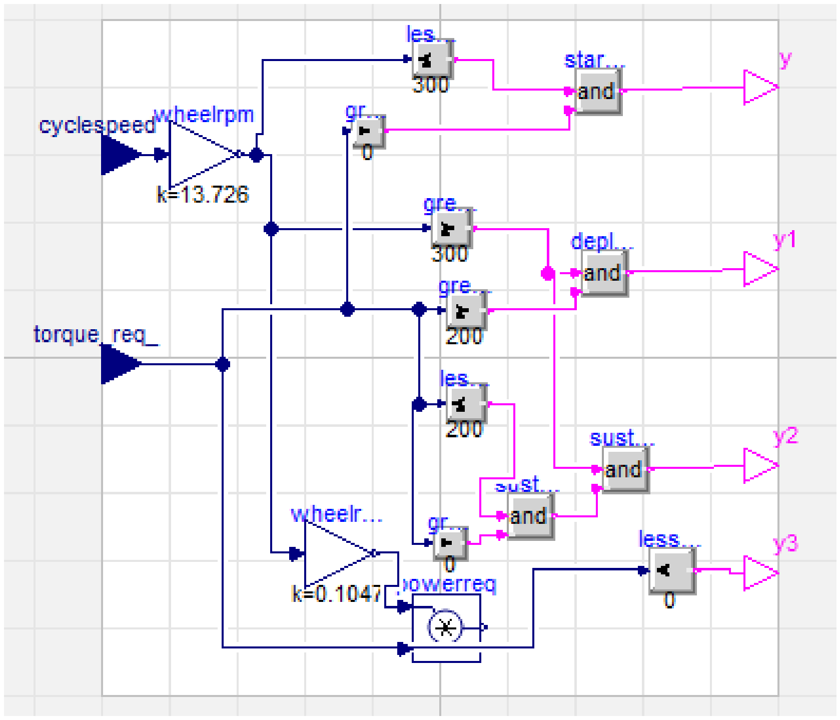

Figure 3: Mode selection block model for T-split: Based on the desired velocity and torque requirement it chooses suitable mode, that is fed into mode input block for controlling engine and MG2.

The mode selection strategy was approximated based on operational modes used in [1]. This block was modeled in-house using gains and logic gates. It takes the torque required from the PID controller as well as the speed input from the urban driving cycle to select the mode by comparing them with the set values. The vehicle speed is converted into the wheel rpm. The vehicle runs in the EV mode until a set speed limit V_{ref}, which is the starting mode. As the vehicle speed goes above V_{ref}, it behaves as a hybrid vehicle with an option to choose between deplete and sustain modes based on a set torque value T_{ref}. When the vehicle is decelerating, the vehicle enters regeneration mode, where MG2 charges in the battery. Different set values of torque and speed were used for both the algorithms to optimize fuel economy and battery SoC. The 4 modes are shown below and shown in flow chart in Fig: 4-

1. T>0 and v$\leq V_{ref}$ - Starting mode
2. T$\geq T_{ref}$ and v$\geq V_{ref}$ - Deplete mode (discharge battery)
3. 0<T$\leq T_{ref}$ and v$\geq V_{ref}$ - Sustain mode (SoC sustain)
4. T_{ref} <0 - Regeneration mode (Battery charge mode)

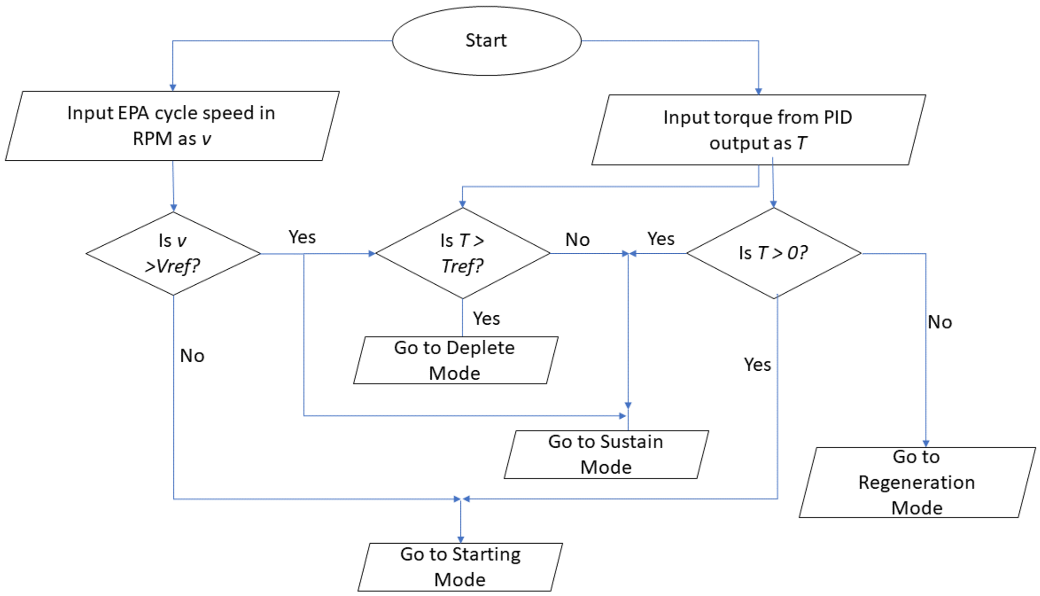

Figure 4: Mode selection Flow chart: Flow chart explaining the parameters to get into different modes of operation. The parameters V_{ref} & T_{ref} are different for two different algorithms.

The output of this block are 4 Boolean values symbolising to the 4 modes. 1 corresponds to the specific mode being ON and 0 represents OFF. At any given instant, only one of the Boolean outputs would be 1 and the other outputs are 0. For the PT-split, the mode selection block gives power required as the output to the mode input block by multiplying the torque with the cycle speed. The corresponding reference values used in this block for the T-split and PT-split algorithms can be found in A.2 section of this report.

3.3 Mode Input

3.3.1 T-split algorithm

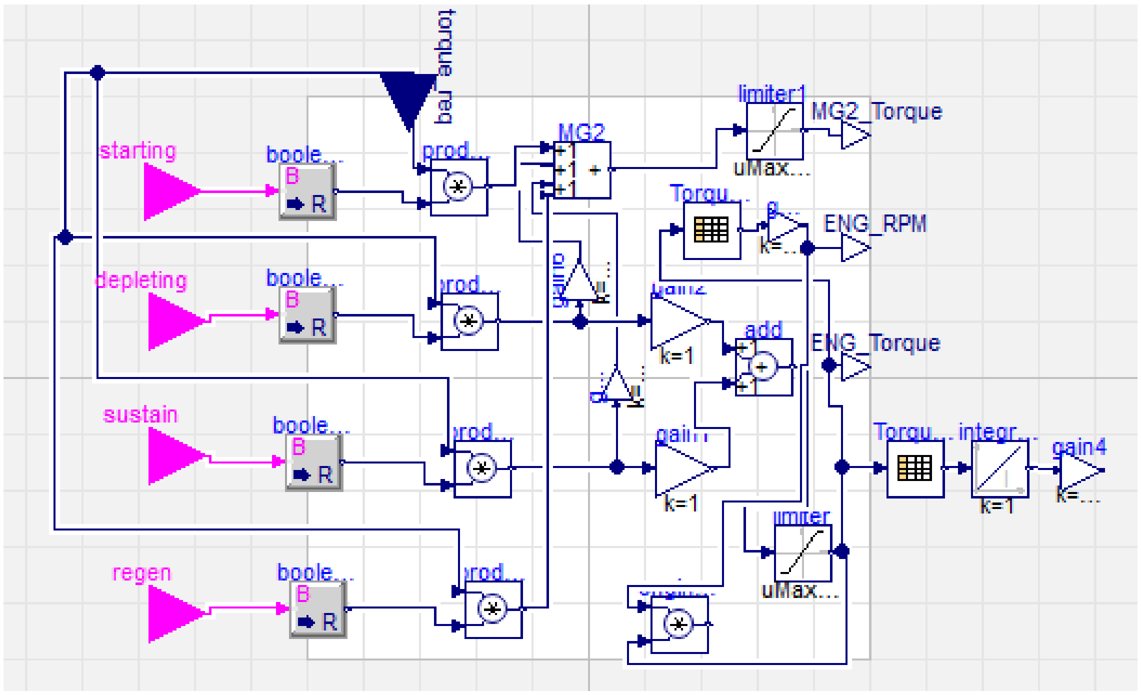

Figure 5: Mode Input Block for T-split: After getting the input from mode selection block, this algorithm provides control inputs to Engine and MG2. It also calculates fuel consumption based on the engine torque and optimal bsfc.

This module converts the Boolean output of the mode selection module (Fig.3) to real 1 or 0 and multiplies it to the required torque that is asked by the PID. During starting, there is no input to the engine and the required torque is supplied by MG2. A limiter is used to restrict the maximum torque that can be supplied by MG2. While in regeneration, the requested negative torque is supplied through MG2 while the engine input is 0. For the other two modes, the torque is split between the engine and MG2 differently. Based on the torque requirement on the engine, the engine is operated at the optimal bsfc (brake specific fuel consumption) point which fixes the engine RPM. MG1 rotates as a consequence of MG2 and engine thereby charging the battery. The outputs of this block are the MG2 torque, engine torque and the engine RPM which are passed to the eCVT model.(Fig.7)

3.3.2 PT-split algorithm

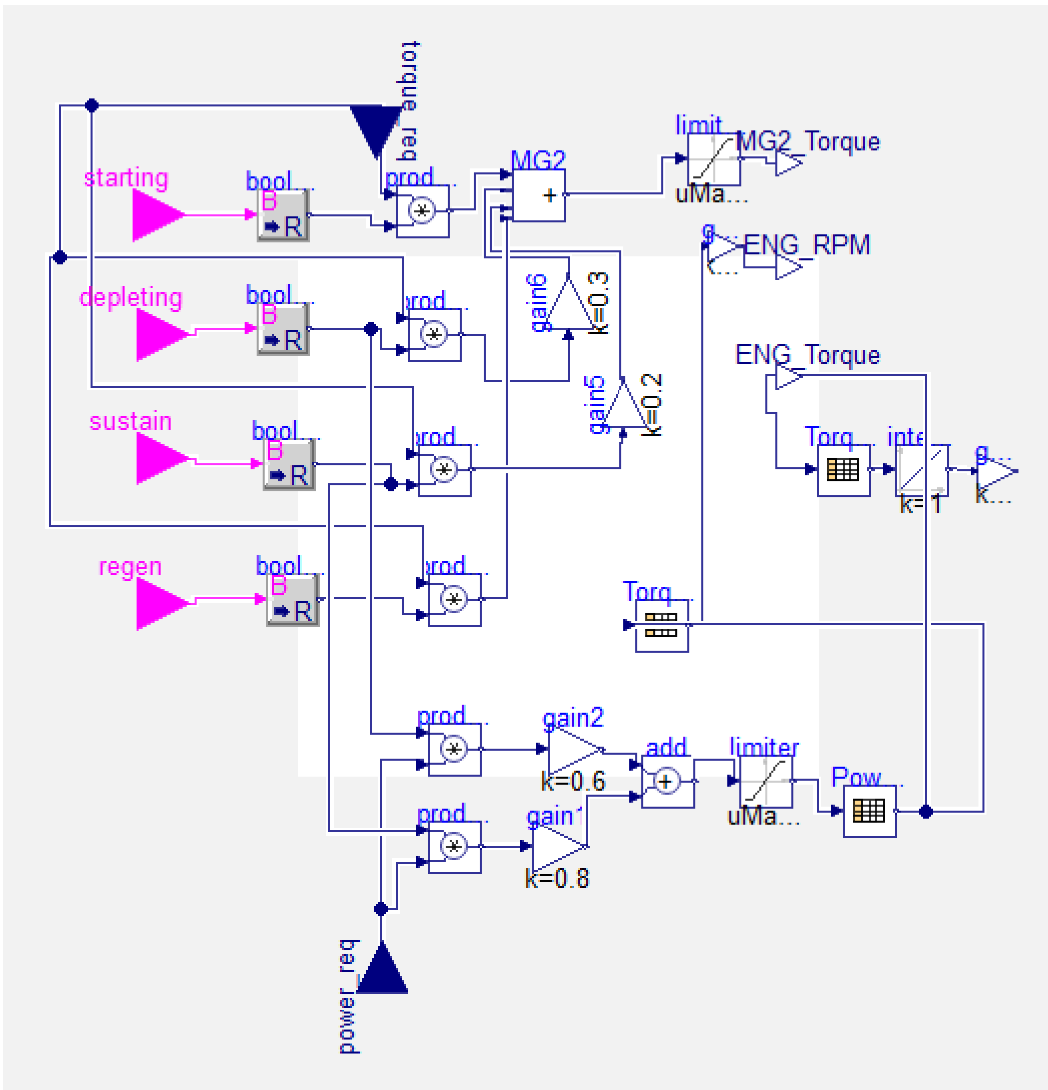

Figure 6: Mode Input Block for PT-split

This algorithm is based such that engine is controlled by the power required and the MG2 is controlled by the torque required at the wheel. Starting and regeneration modes work in the same way as the previous algorithm. In deplete and sustain modes, different fractions of power required is supplied as the engine output to the eCVT whereas different fractions of torque required are supplied for MG2. The limiter used for the engine in this module limits the power to the maximum power it can generate, unlike in the previous algorithm which limits the torque. Based on the requested engine power, engine torque and speed are chosen at the optimal bsfc [5].

3.4 electronically controlled Continuously Variable Transmission

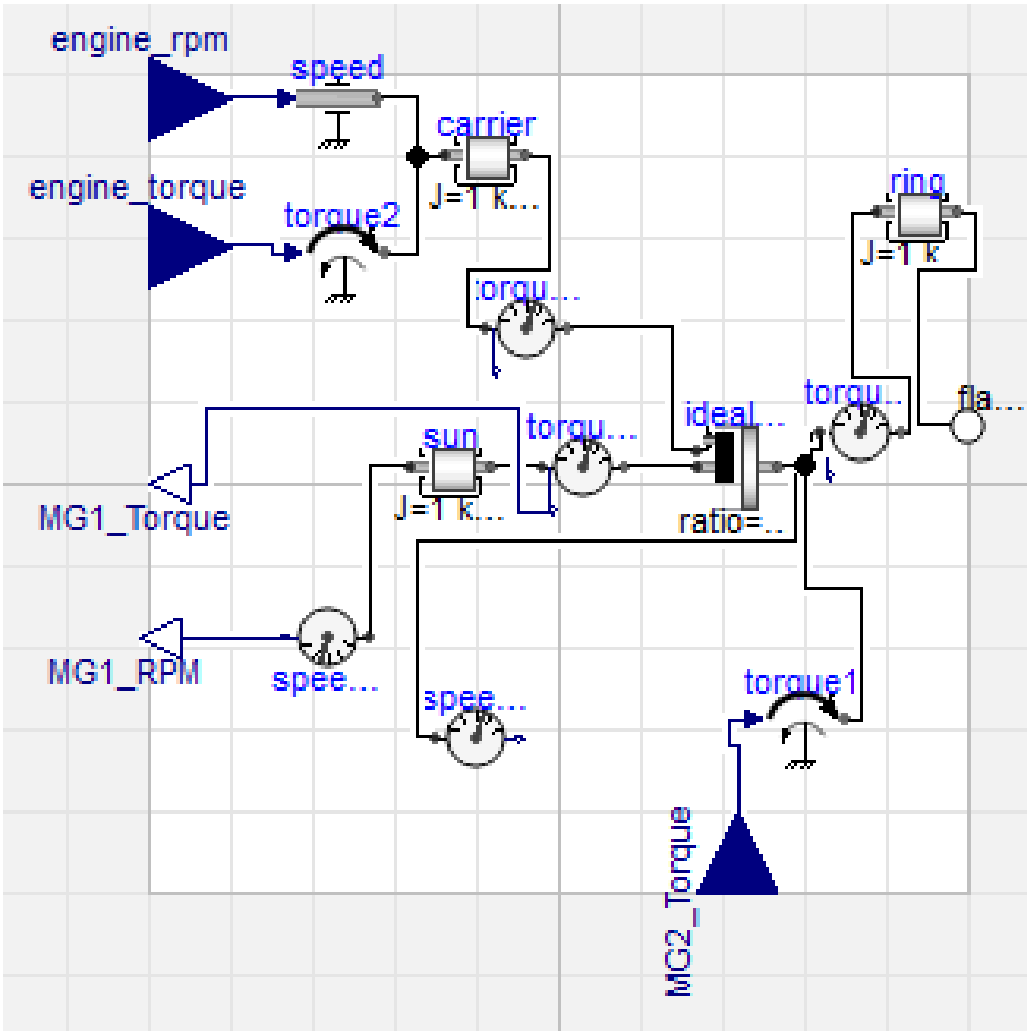

Figure 7: eCVT Block

The eCVT consists of a planetary gear system of sun, ring and planet gears in a carrier, and the torque is then given to the final drive with a gear ratio of 4.113. MG1 is connected to the sun gear, while the MG2 input is connected to the ring gear, and the planet carrier is connected to the engine speed and torque inputs. The final drive then gives the required torque and speed to the vehicle. Inertias are attached to the respective gear-train components. The number of gear teeth in the planetary system are taken from the 2004 Prius power split device.The output of this block is a flange attached to the ring gear which is connected to the final drive. A torque sensor positioned at the sun measures the MG1 torque which is fed into the battery. (Fig.8)

3.5 Battery

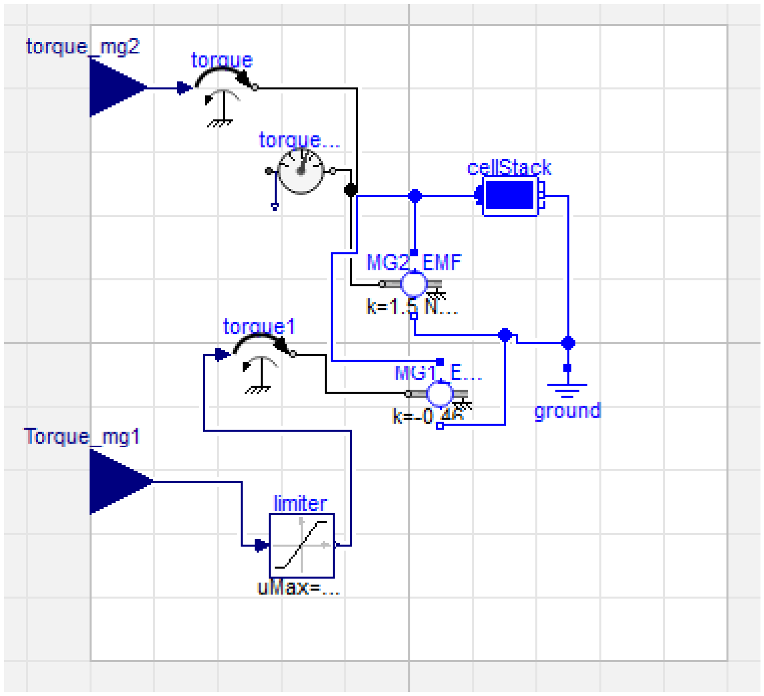

Figure 8: Battery Block: In this model the battery getting charged and discharged based on MG1 and MG2 output. During regeneration MG2 charges the battery, all other time MG1 charges the battery .

A cell stack is used to model the 2004 Prius battery. This takes the MG1 and MG2 torque input from the eCVT (Fig.7) and converts these to an output in the form of current (in amperes). This is achieved with the help of a rotational EMF model which uses a transformation coefficient k (in N-m/A), assumed as a torque constant. There are 2 rotational EMFs, one for Motor-Generator Unit, connected in parallel to the cellstack, thereby helping to charge/discharge the battery. The value of k is taken to be 1.5 N-m/A for MG2 and -0.46 N-m/A for the same from MG1 [2]. For the PT-split, a filter is used to avoid undesirable torque fluctuations.

3.6 Vehicle Model

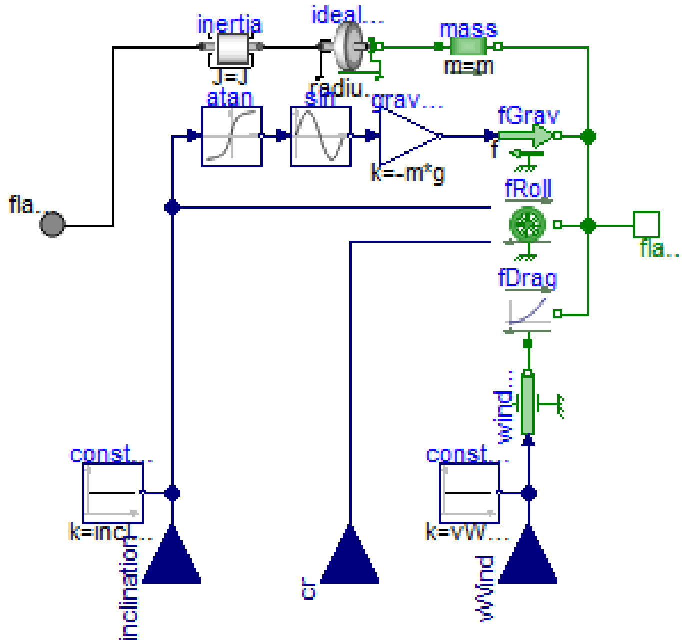

Figure 9: Vehicle Block: This block represents the resistive forces acting on vehicle modelled as a translational mass connected to an ideal rolling wheel.

The final drive output is connected to the vehicle model, taken from the Modelica standard library, which simulates ideal aerodynamic drag and rolling resistance. The vehicle model corresponds to that of a of Prius 2004 model, which is a 1700 kg mass (considering passenger load) and a tire radius of 0.311 m. These values were taken from [2] and [7]. The speed output from the vehicle model is fed to the feedback block, after undergoing a unit conversion through a gain, which gives the error in speed as an input to the PID.

4 Results and Discussion

In this section, we shall be comparing both algorithms based on the concerned parameters such as error in speed, engine speed, engine torque, battery SoC over the entire EPA drive cycle. These models were created for comparing the algorithms. The final SoC and fuel consumed were compared to evaluate the effectiveness of each algorithm. Accurate modeling of losses (electrical and transmission) can be further incorporated to mimic real life situations. The mode selection and PID are tuned to the best of our capability so as to bring out the most logical result out of the mode input module.

4.1 PID Tuning and Drive Cycle Trace

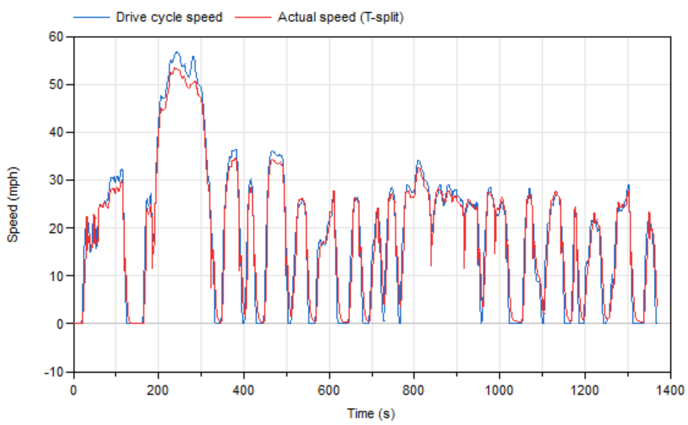

Figure 10: Drive cycle tracing for T-split

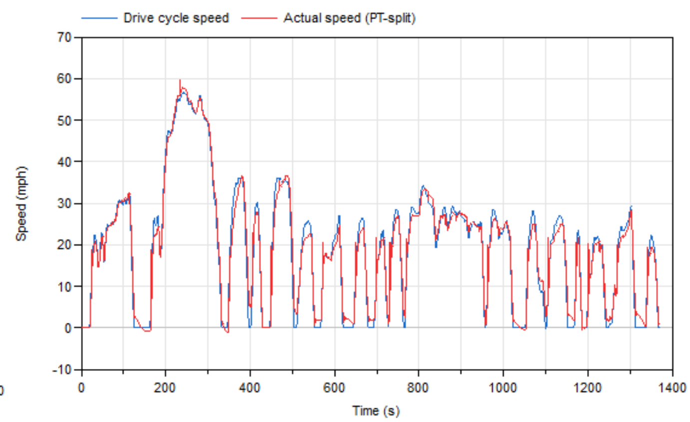

Figure 11: Drive cycle tracing for PT-split

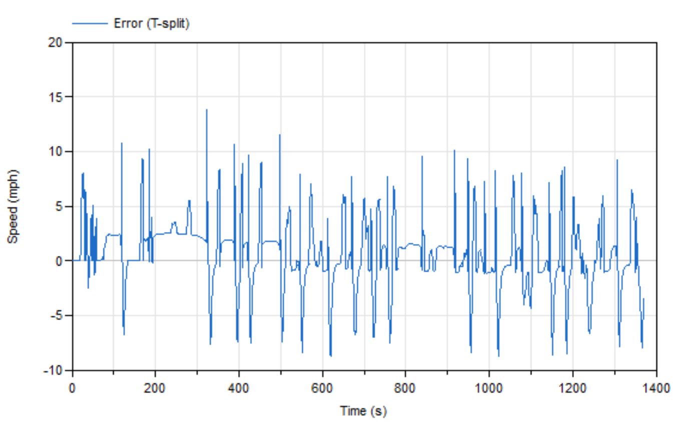

Figure 12: Error in vehicle speed for T-split

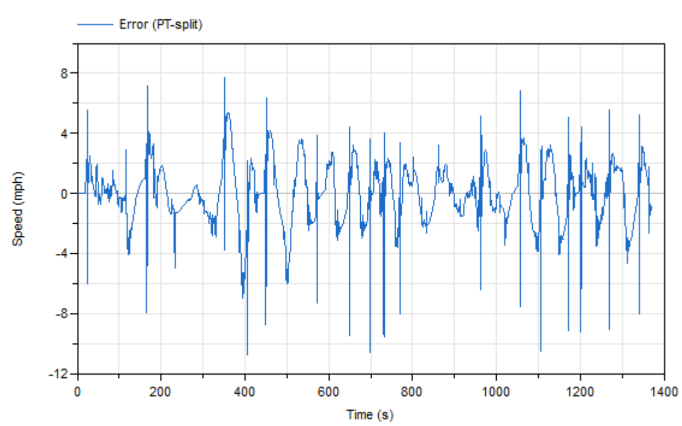

Figure 13: Error in vehicle speed for PT-split

Fig.10 and Fig.11 show the comparison between the drive cycle speed and actual speed for T-split and PT-split respectively. It is apparent that the PID controller was able to trace the drive cycle speed to an agreeable extent and the same is shown in the error graphs, with Fig.12 showing the error for T-split and Fig.13 for PT-split. The error plotted is calculated as the difference between the drive cycle speed in the next time step and the actual speed in the current time step. The error does not go beyond 14 mph for T-split while it does not deviate more than 11 mph for PT-split, owing to a filter which removes the error spikes. A better fine tuned PID using better filter will help in further reducing the errors.

4.2 Mode selection

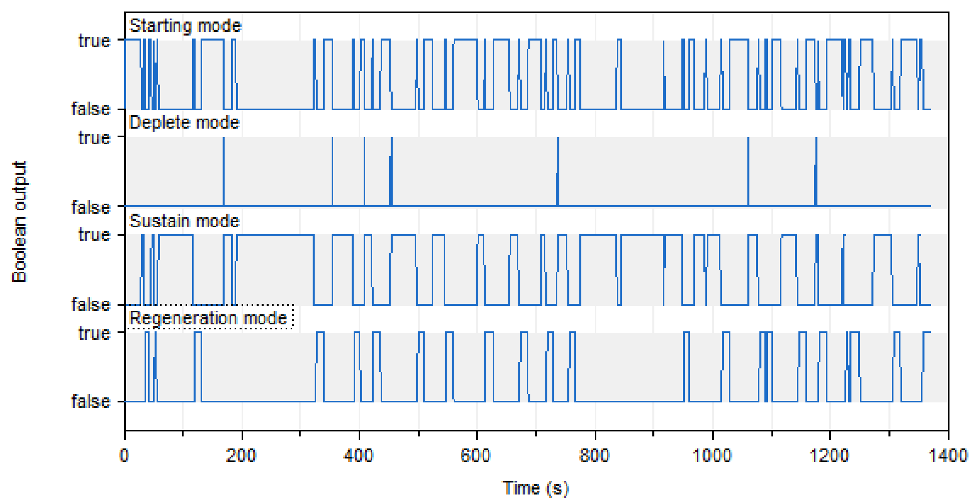

Figure 14: Mode selection for T split over the drive cycle.

Fig.14 and Fig.15 show the mode selection variation over the entire drive cycle for T-split and PT-split algorithms respectively. In the T-split, the mode selection is such that it seldom goes into to deplete region to optimise the Battery SoC.

Conversely, the mode selection implemented in PT-split balances the Battery SoC and fuel efficiency to an extremely good extent, thereby resulting in higher frequency of operation in deplete region, yet maintaining the battery SoC remarkably well. The comparison between the battery SoCs will be explained in detail in Section 4.5. Better filtering can avoid high frequency mode switching, while better tuning of the PID controller can ensure that the drive cycle curve is traced with less overshoot.

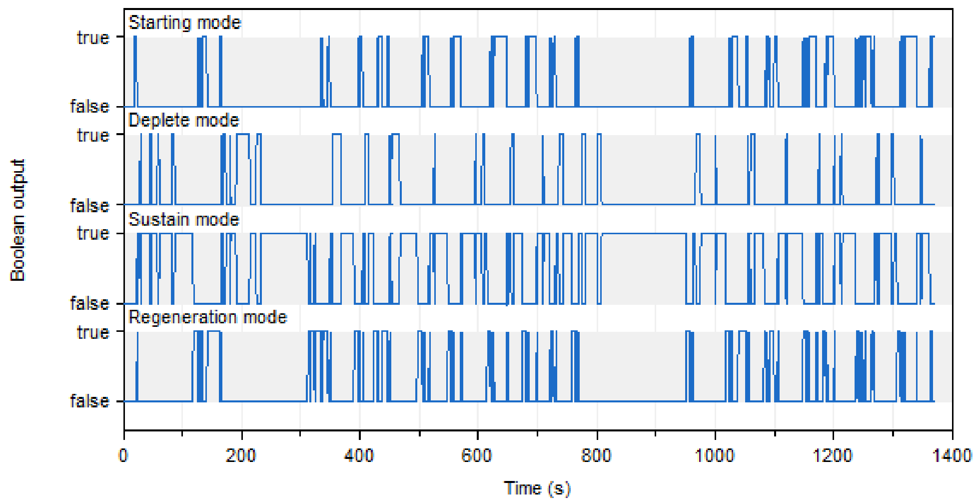

Figure 15: Mode selection for PT split over the drive cycle.

4.3 Mode Input

In the T-split algorithm, maximum torque is invoked much more frequently, thereby putting a harsh load on the engine, whereas in the PT-split algorithm, the engine never reaches maximum torque even though it is allowed to do so, which means that the PT-split has a better split between MG2 and engine, resulting in less fuel consumed in PT-split over T-split. The above explanation is in reference to the plots in Fig: 16 and Fig :17. Similar inferences can be made from the Engine speed comparison graphs in Fig: 18 and Fig: 19, where the engine stays in a much lower speed in PT-split as compared to T-split, which showcases the power saving characteristic of the former.

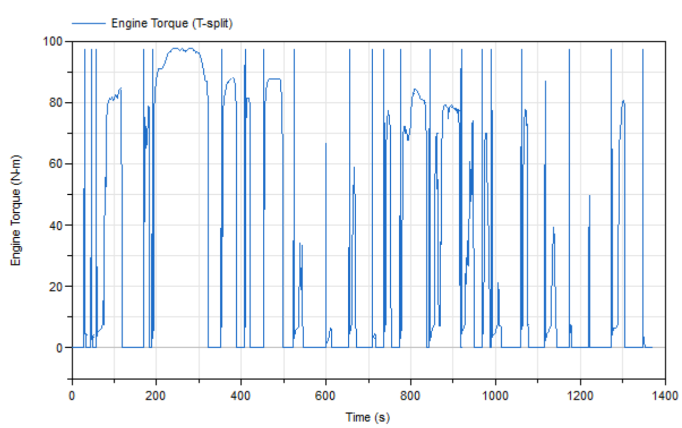

Figure 16: Engine torque vs Time for T-split

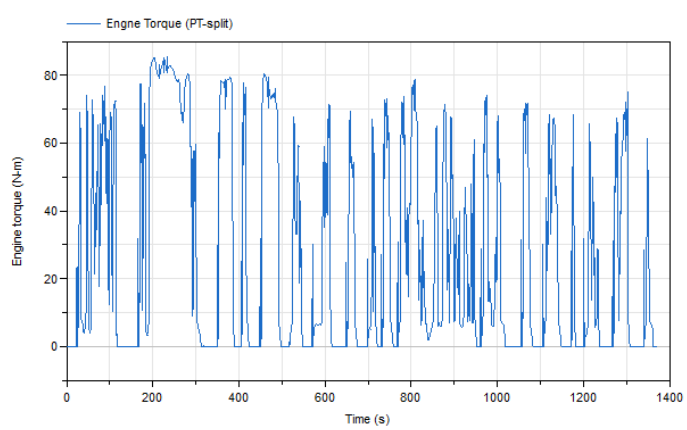

Figure 17: Engine torque vs Time for PT-split

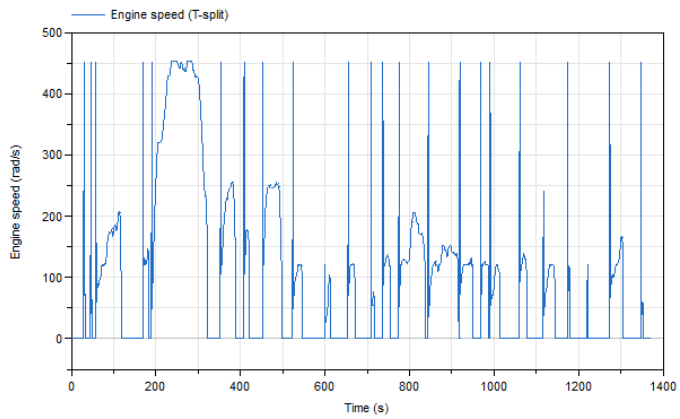

Figure 18: Engine speed vs Time for T-split

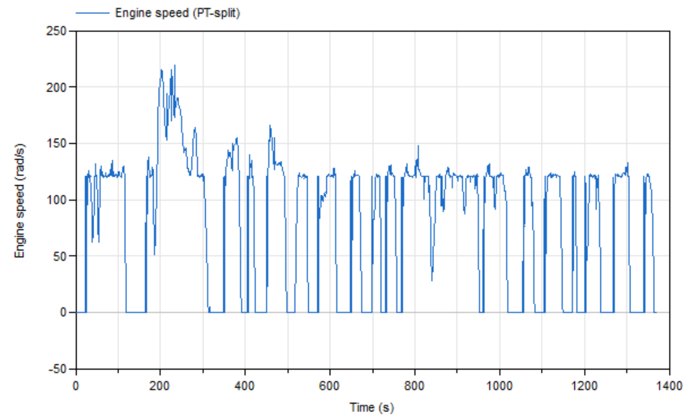

Figure 19: Engine speed vs Time for PT-split

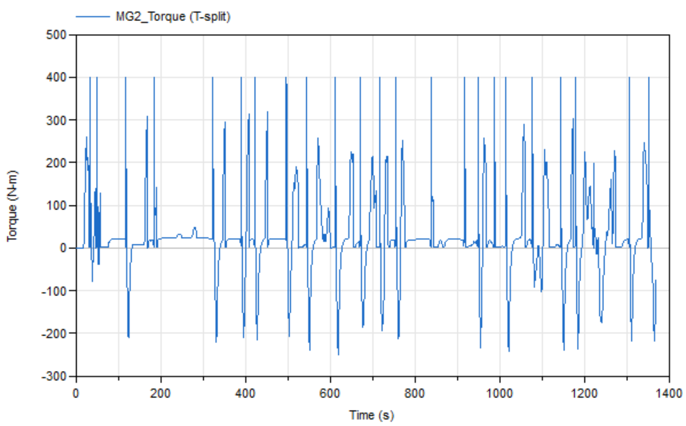

Figure 20: MG2 Torque vs Time for T-split

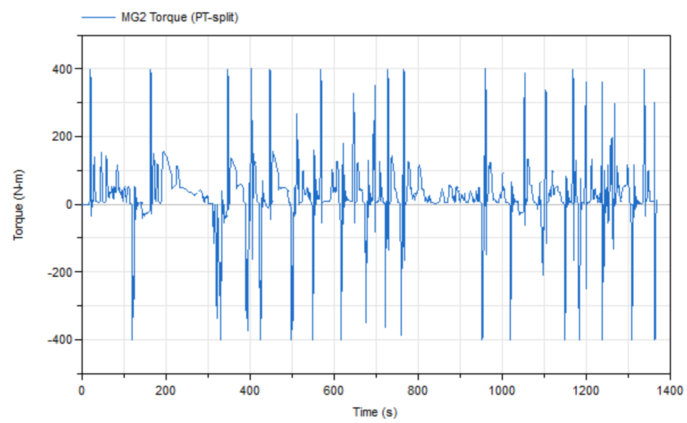

Figure 21: MG2 Torque vs Time for PT-split

Fig: 20 and Fig: 21 show the torque variation in MG2 over the drive cycle. From the graph, it can be observed that, in the PT-split algorithm, the regeneration mode occurs at higher negative torque values (-400 N-m in PT-split as compared to ∼-220 N-m in T-split). As a consequence, the battery SoC is expected to be at a higher level at the end of the drive cycle. Additionally, the average positive torque demanded from MG2 in T-split is much higher than that in PT-split, due to which it is expected that the battery is drained by MG2 to a greater extent in the former algorithm. The same can be observed in the Fig: 20 and Fig: 21 where MG2 is made to deliver its maximum torque more often in T-split than in PT-split.

4.4 eCVT

Fig: 22 and Fig: 23 show the variation of ring and carrier and speeds for T-split and PT-split algorithms respectively. In the T-split algorithm, for a given mode, the torque ratio between engine and MG2 is fixed, which essentially fixes the gear ratio for the eCVT for that mode. This is not an effective way of controlling the eCVT. To have variable gear ratios within a given mode, the engine needs to be controlled based on the power requirement and MG2 needs to be controlled by the torque requirement, which is the case in PT-split. This allows variable speeds at the carrier and the ring, thereby achieving variable speed ratio.

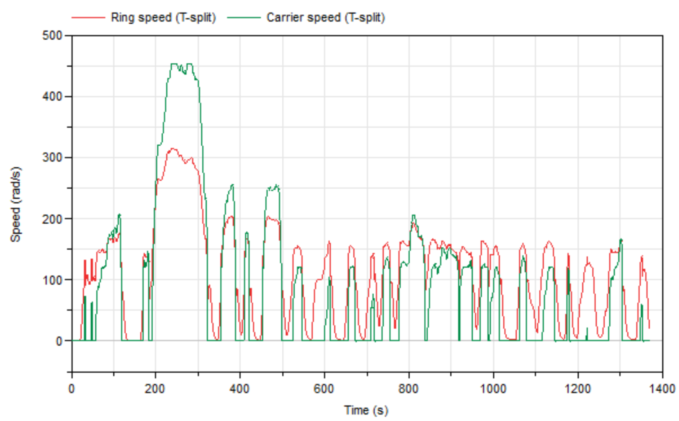

Figure 22: Ring and carrier speeds for T-split

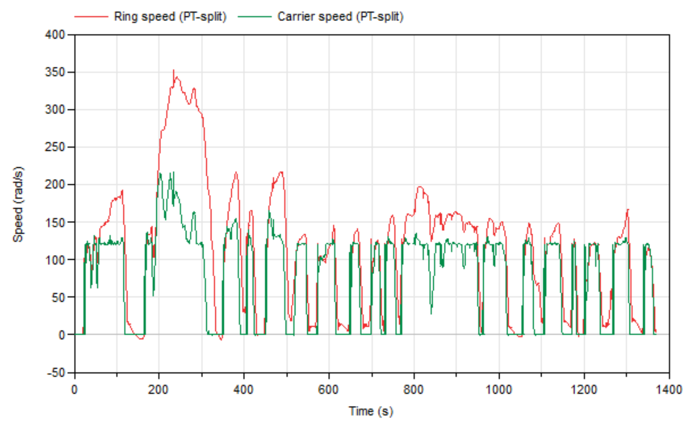

Figure 23: Ring and carrier speeds for PT-split

4.5 Battery SoC

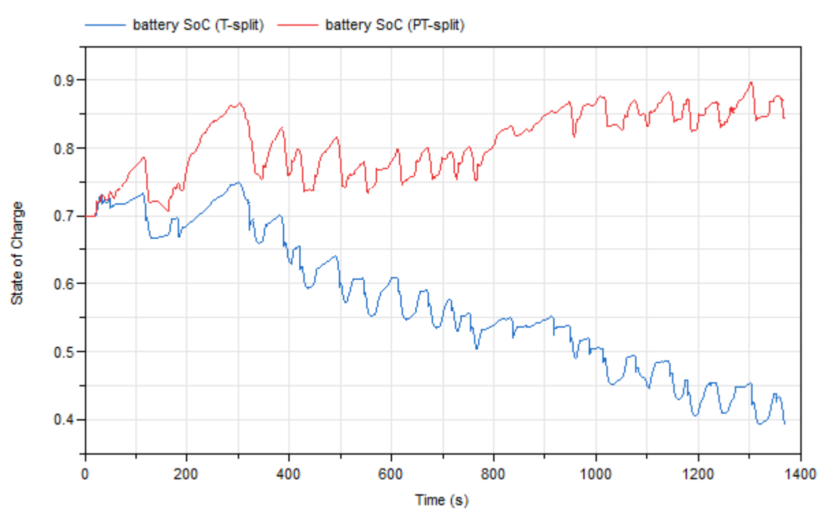

Figure 24: Comparison between Battery SoC for the two algorithms

Fig: 24 shows the variation of battery SoC for the two algorithms. Both batteries start at 0.7 SoC, and the T-split SoC undergoes rapid discharge and depletes to a value of 0.4 whereas PT-split SoC charges to 0.85. The change in SoC for both algorithms are given for the current mode selection and mode input models. SoC and fuel economy can be changed by optimizing split fractions between torque and MG2 for both the algorithms.

4.6 Fuel consumption and mileage calculations

The total fuel consumed is calculated by integrating the fuel consumed at each time step over the entire drive cycle. The city mode mileage is calculated by taking the ratio of total distance travelled to the total fuel consumed over that time period. The T-split algorithm resulted in 0.16 gallons of fuel consumed which gives a city mode mileage of 46.5 mpg. The fuel consumed in the PT-split algorithm was calculated to be 0.097, giving a mileage of 76.8 mpg. The SoC at the end of cycle for the two algorithms was 0.4 and 0.85 respectively. This shows that the PT-split is more efficient from both the perspective of the battery and fuel in the given configuration. These values do not give the full picture of the real scenario and are used purely for relative comparisons. Given proper modeling of losses, the system can be used to achieve results that are closer to those in real life.

5 Conclusion

In this model, a Prius drivetrain model running on 4 modes - Starting, Deplete, Sustain, Regeneration, was simulated by implementing 2 algorithms, namely T-split and PT-split. The results between the two were compared with different parameters such as engine speed, engine torque, MG2 Torque, Battery SoC, as well ring and carrier speeds. The results showed that the PT-split gave a more efficient model overall, showing the fuel consumed to be 0.097 gallons as compared to 0.16 gallons in the case of T-split. The battery SoC at the end of the cycle was 0.85 and 0.4 for PT-split and T-split algorithms respectively. Finally, the city mode mileage was found to be 76.8 mpg for PT-split as compared to T-split, which produced a mileage of 46.5 mpg.

References

[1] Mathworks,*"Explore the Hybrid Electric Vehicle Input Power-Split Reference Application,* *Link*

[2] Staunton, R. H.; Ayers, C. W.; Marlino, L. D.; Chiasson, J. N.; Burress, B. A. *"Evaluation of 2004 Toyota Prius Hybrid Electric Drive System",Link*

[3] ConsuLabOfficial, *Learning and Teaching - "Exploring the Power Split Function of a Hybrid Planetary Gear Set",Link*

[4] Toyota UK Magazine, *"Efficiency by design: the aerodynamics of Toyota Prius",Link*

[5] SAE, *"SAE bsfc graph",Link*

[6] EPA, *"EPA Urban Driving Cycle ", Link*

[7] Wheelsize.com, *"Toyota Prius 2004 Alloy wheel fitment guide",Link*

A Model Parameters

A.1 PID

The gain parameters were obtained by tuning the PID (as shown in Fig: 25) in order to align with EPA drive cycle performance. The gain parameters for the two algorithms are taken as below:

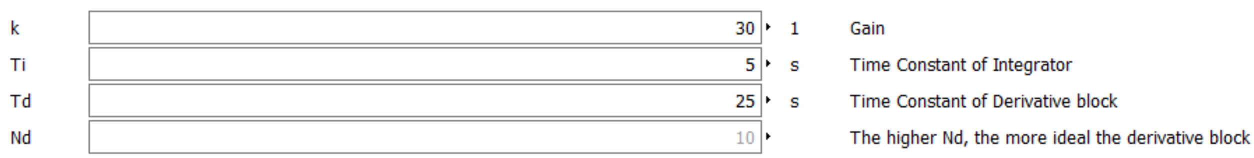

Figure 25: Parameters taken for tuning of PID based on feedback for T-split

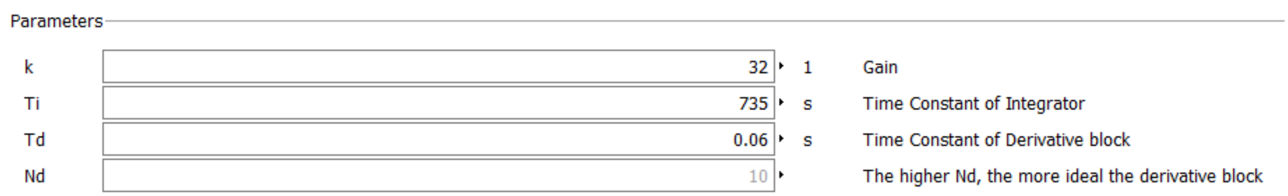

Figure 26: Parameters taken for tuning of PID based on feedback for PT-split

A.2 Mode Selection

For selecting the different modes of operation, the filtering torque (T_{ref}) and velocity (V_{ref}) are different for both algorithms. These values are taken as shown in the graphs below:

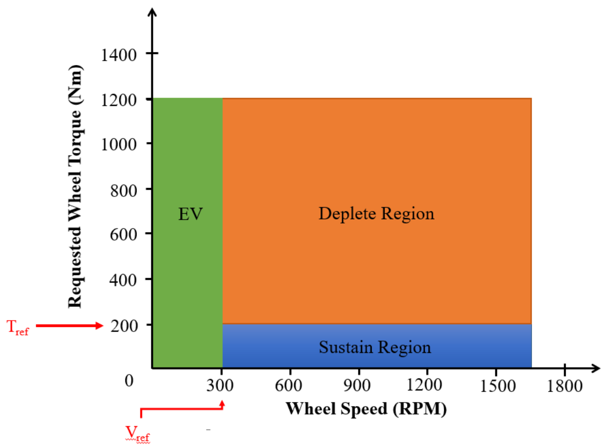

Figure 27: V_{ref} & T_{ref} values for T-split

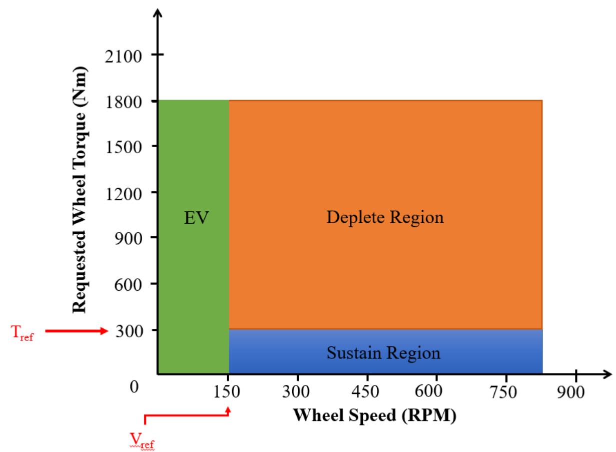

Figure 28: V_{ref} & T_{ref} values for PT-split

A.3 Mode Input

A.3.1 T-split

In the first method of splitting the power and torque between engine and MG2,the gain values and limiting factors are shown below:

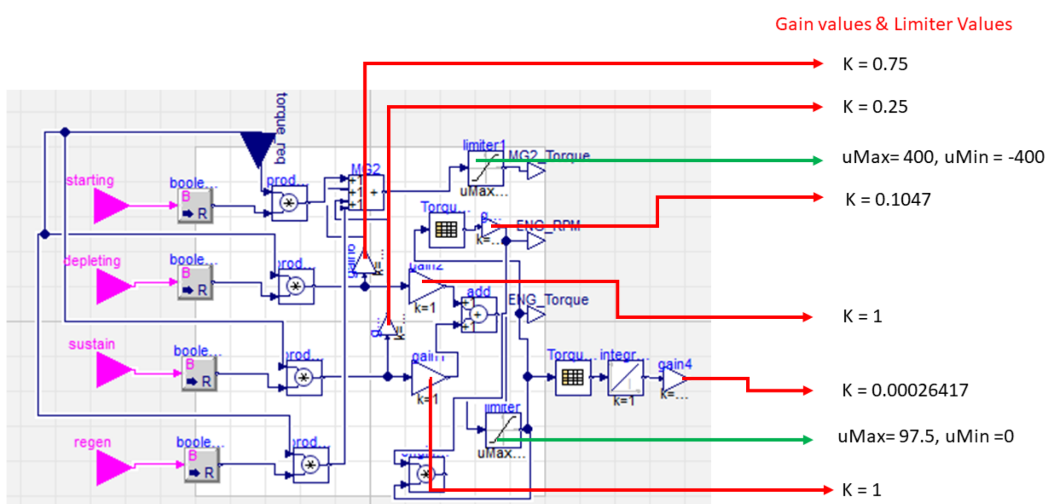

Figure 29: Parameters taken for gain values and limiting values in Mode input block for T-split

A.3.2 PT-split

In the second method of splitting the power and torque ,the gain values and limiting factors are shown below:

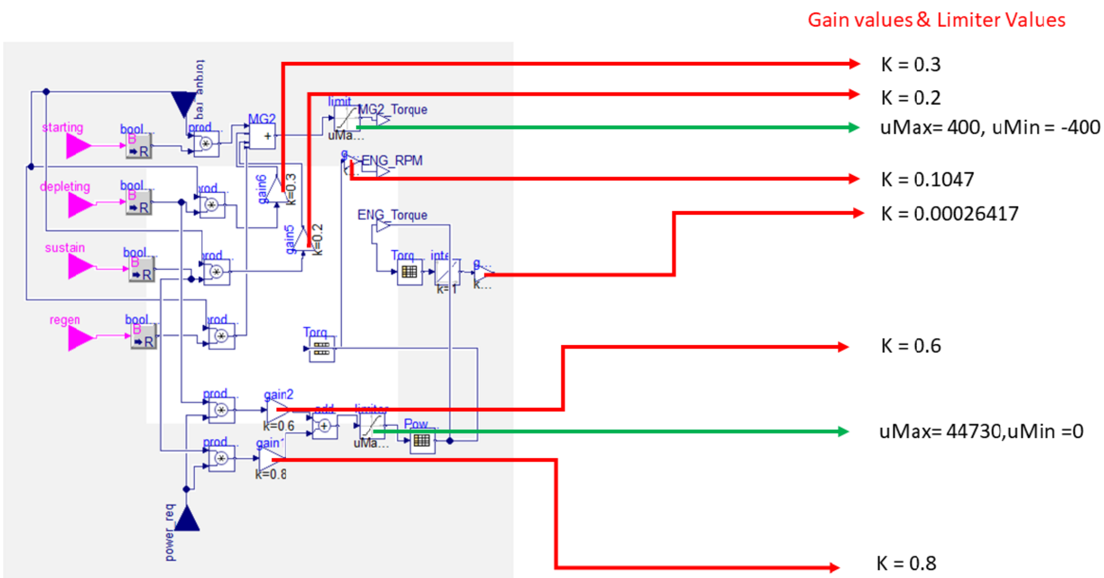

Figure 30: Parameters taken for gain values and limiting values in Mode input block for PT-split

The Torque-Power table based on maximum efficiency used in both algorithms is shown below in a graphical format:

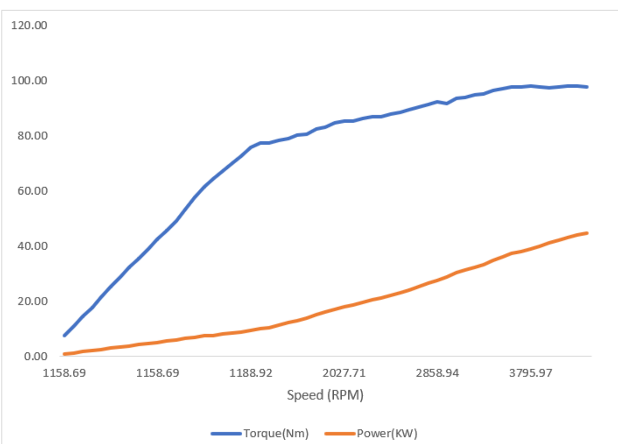

Figure 31: Torque, Power vs Speed used in both algorithms

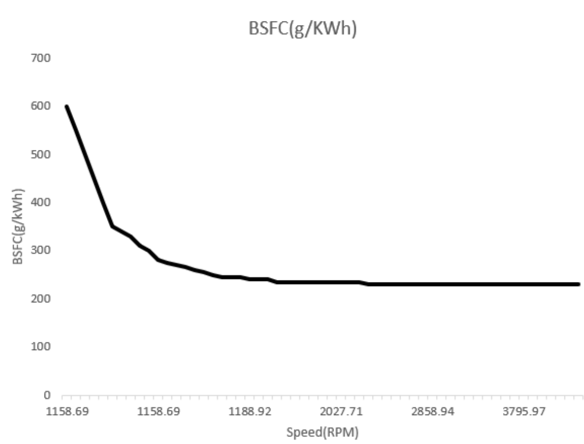

Figure 32: BSFC values in g/kWh vs Speed(RPM)

A.4 e-CVT Final Drive

The values for inertia, gear ratios used in e-CVT model are shown below:

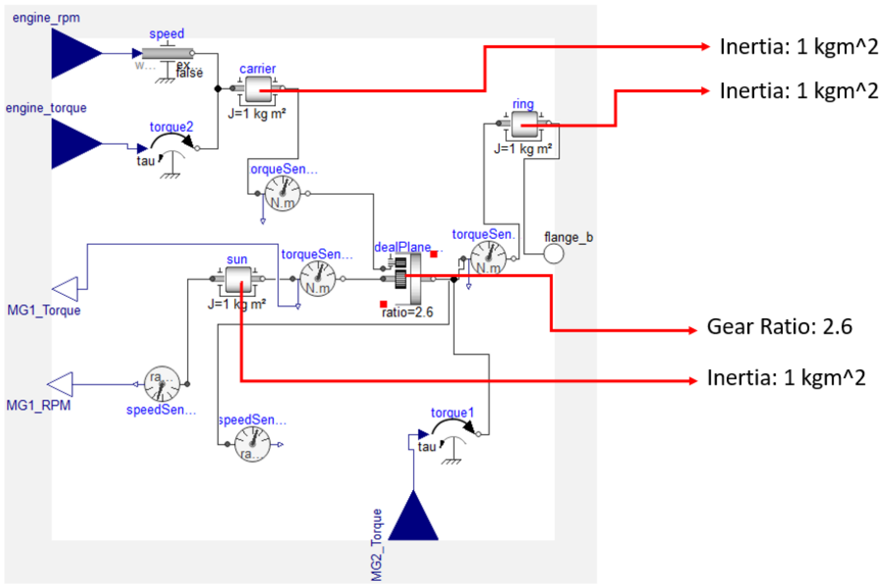

Figure 33: Inertia and gear ration used in e-CVT model

The values used in vehicle model for restive forces and final gear ratio are as below:

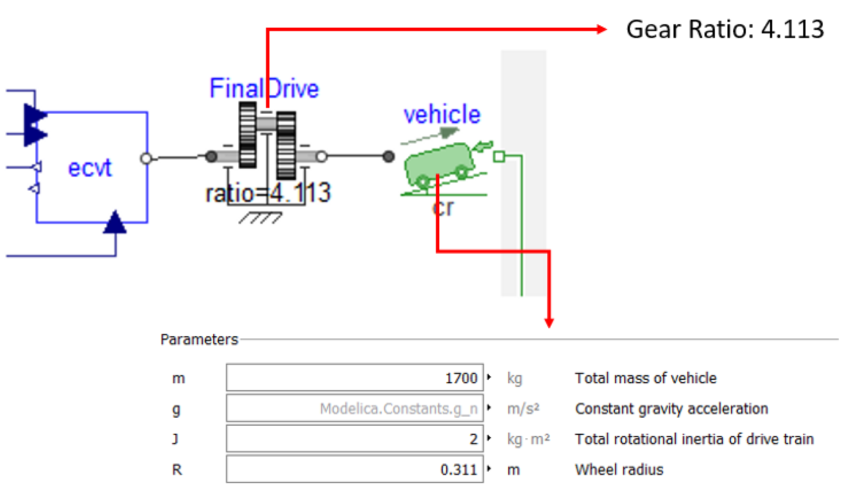

Figure 34: Final drive gear ratio and parameters used in vehicle model

A.5 Battery

The parameters used for battery in T-split are shown below [2]. The battery used in PT-split has a filter between the input and limiter with a cut-off frequency of 0.1Hz.

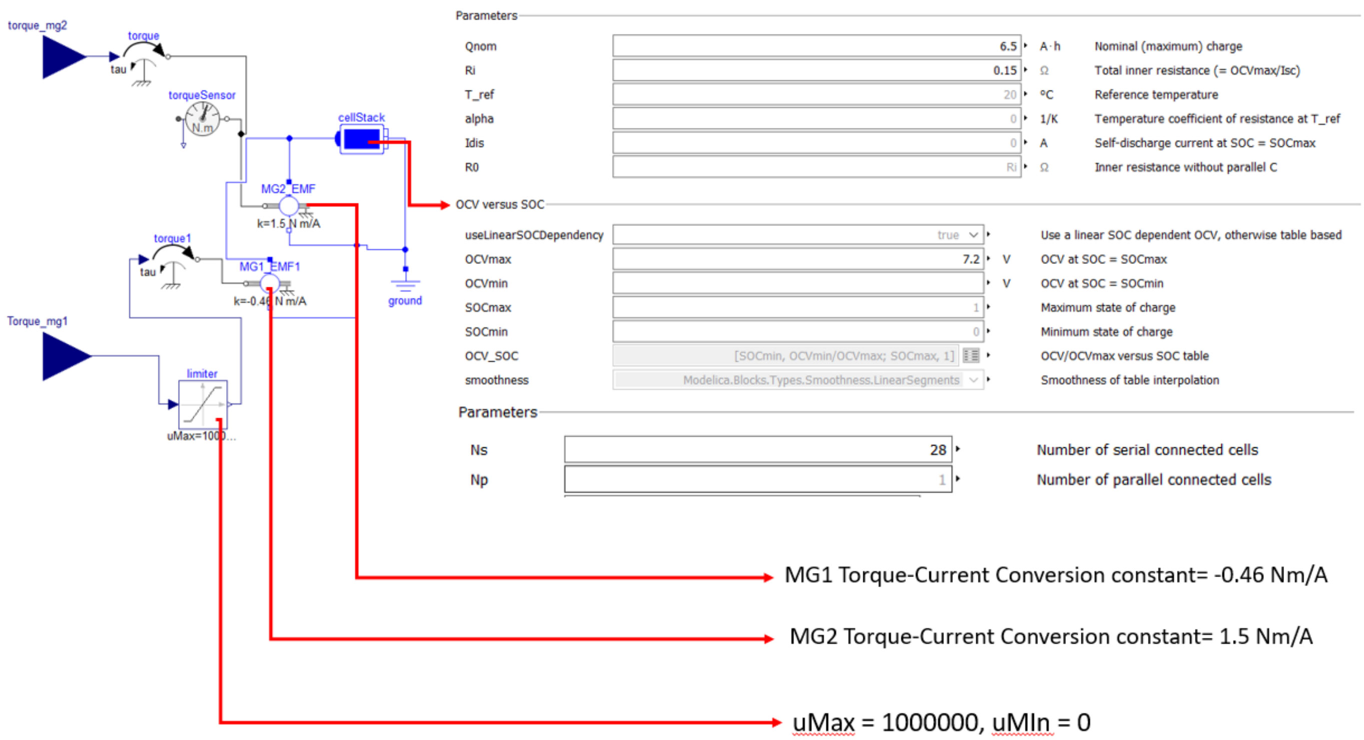

Figure 35: Parameters used in Battery Model for T-split

A.6 Filter

The parameter used to filter high value before feeding into PID has following parameter values:

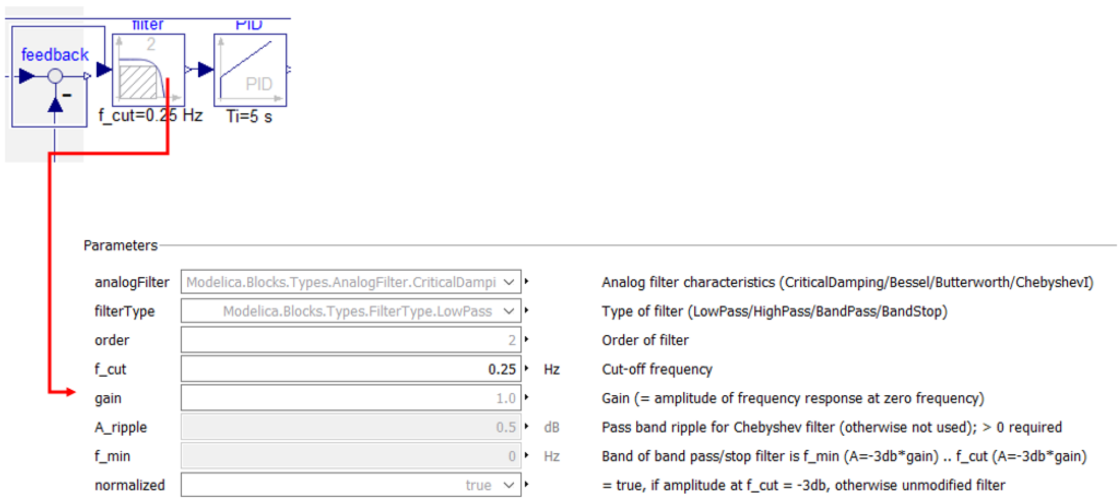

Figure 36: Showing Parameters used in Filter block