Rule Based Control

Master's Degree in Automotive Engineering

Loris Fonseca: s342696@studenti.polito.it

Nikoloz Kapanadze: s342649@studenti.polito.it

Maurizio Pio Vergara: s346643@studenti.polito.it

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1 Introduction

The aim of this project is the implementation of a Rule Based Control, by means of a quasi-static HEV powertrain model, to evaluate the performance of the vehicle equipped with the HEV powertrain over a standardized cycle, using the designed controller. The simulation requires the modeling of the powertrain subsystems as the internal combustion engine, the eletric motor, the generator and the battery.

2 Simulation model

The powertrain model tested in the simulation is a series HEV, composed by a thermal engine, an eletric motor, a generator and a battery. A qualitative representation of the architecture is depicted in Figure 1.
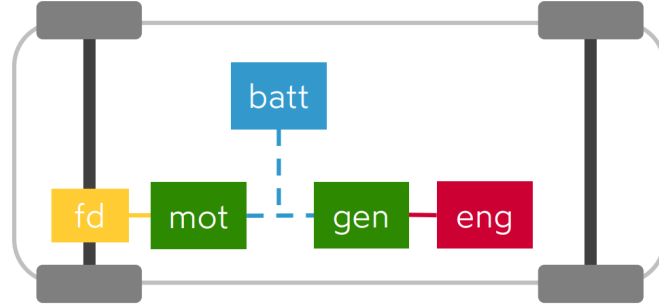

Figure 1: Series HEV architecture

The torque at the wheels is generated exclusively by the electric motor, which is connected to the wheels via a differential with a known transmission ratio. On the other hand, the internal combustion engine is responsible for supplying sufficient power to charge the battery when needed, through an electric generator. The simulation model of the powertrain can be described by a set of state variables, control variables, inputs and outputs. In particular, for the purpose of this simulation, i.e. the evaluation of the fuel consumption over a driving cycle, the following parameters are identified:

- State variables:
    - · SOC   Battery state of charge
- Control variables:
    - · ω_{eng} Engine speed
    - · T_{eng} Engine torque
- Inputs:
    - · v_{veh} Vehicle speed
    - · a_{veh} Vehicle acceleration
- Outputs:
    - · $\dot{m}_f$ Fuel consumption

The approach adopted in this simulation is the so-called backward or quasi-static approach. This energy management strategy starts from the desired output (vehicle speed and acceleration) and works backward to determine the required inputs (fuel consumption and battery current), as schematically illustrated in Figure 2.

In the case study presented in this project, the desired output is defined by the vehicle's speed profile and acceleration, based on a driving cycle, specifically the standard WLTP cycle. The driveline model takes these parameters and determines the necessary force, and consequently the required torque, to achieve the specified conditions. It accounts for factors such as aerodynamic and rolling resistance, as well as vehicle inertia. The required torque is then used to compute the energy demand from the power sources, which in this project correspond to the internal combustion engine and the battery. This step calculates the amount of fuel and/or battery power needed. Finally, the total energy consumption (fuel or battery usage) is determined based on the power demand.
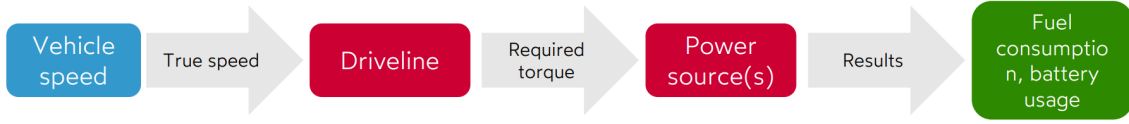
Figure 2: Backward or quasi-static approach

2.1 Driving cycle

The driving cycle to test the drivetrain performance in term of fuel consumption is the WLTP (Worldwide harmonized Light vehicles Test Procedure) which is a global driving cycle standard for determining also the fuel consumption of a vehicle. This standard cycle has been designed to be more representative of real and modern driving conditions, trying to better match the laboratory estimates of fuel consumption and emissions with the measures of an on-road driving condition. The functions of speed and acceleration characterizing the WLTP cycle are represented in Figure 3.
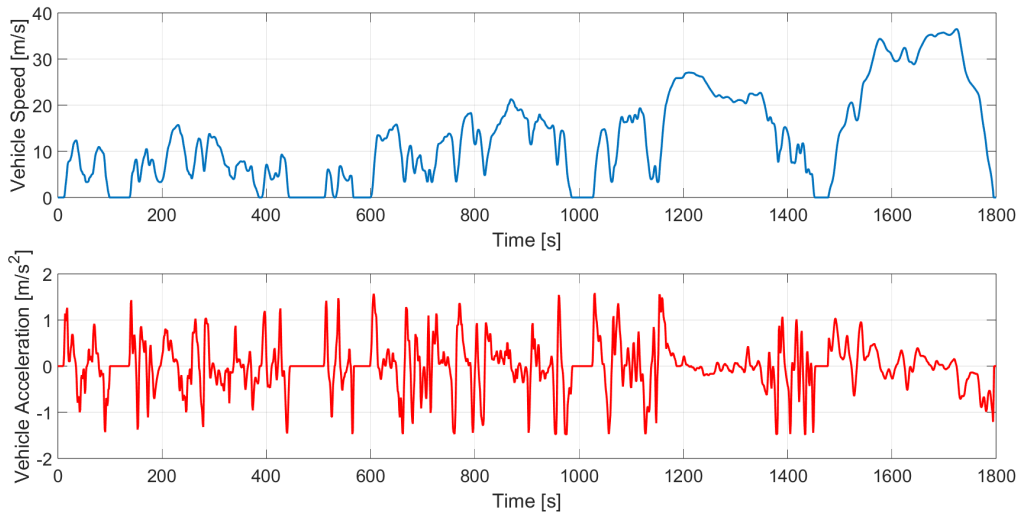

Figure 3: WLTP speed and acceleration functions

2.2 Longitudinal dynamics and driveline model

Once the vehicle speed and acceleration are known, the tractive force needed to move the vehicle and the wheel speed can be computed through the following equations:

$$F_{\text{veh}} = f_0 + f_1 \cdot v_{\text{veh}} + f_2 \cdot v_{\text{veh}}^2 + m \cdot a_{\text{veh}} \tag{1}$$

$$\omega_{\text{wh}} = \frac{v_{\text{veh}}}{r_{\text{wh}}} \tag{2}$$

where f_0, f_1 and f_2 are coefficient depenging mainly on the rolling resistance and aerodynamic resistance. From the vehicle driving force it is possible to evaluate the wheel torque as follow:

$$T_{\text{wh}} = F_{\text{veh}} \cdot r_{\text{wh}} \tag{3}$$

By knowing the transmission ratio of the differential connecting the eletric motor to the wheel's shaft, the motor torque and speed can be computed as follow:

$$T_{\text{mot}} = \frac{T_{\text{wh}}}{\tau_{\text{fd}}} \tag{4}$$

$$\omega_{\text{mot}} = \omega_{\text{wh}} \cdot \tau_{\text{fd}} \tag{5}$$

2.3 Electric motor model

By knowing the operating point of the electric motor, its efficiency can be evaluated using the motor map, which is essential for the power balance equation. The characteristic map of the motor used in the studied drivetrain is shown in Figure 6. The motor map represents torque as a function of motor speed. As is typical for electric motors, this relationship features a constant torque profile at lower speeds and a constant power profile at higher speeds, which results in a hyperbolic torque curve. In addition to the torque profile, the map also includes efficiency isolines across the entire operating range of the electric motor. It can be noted that the high efficiency zone extends along a wide are of the motor operating zone. Notably, since this type of machine can generate both positive and negative torque, its operational area extends in both directions. Furthermore, the positive and negative torque profiles are almost symmetrical with respect to the x-axis.
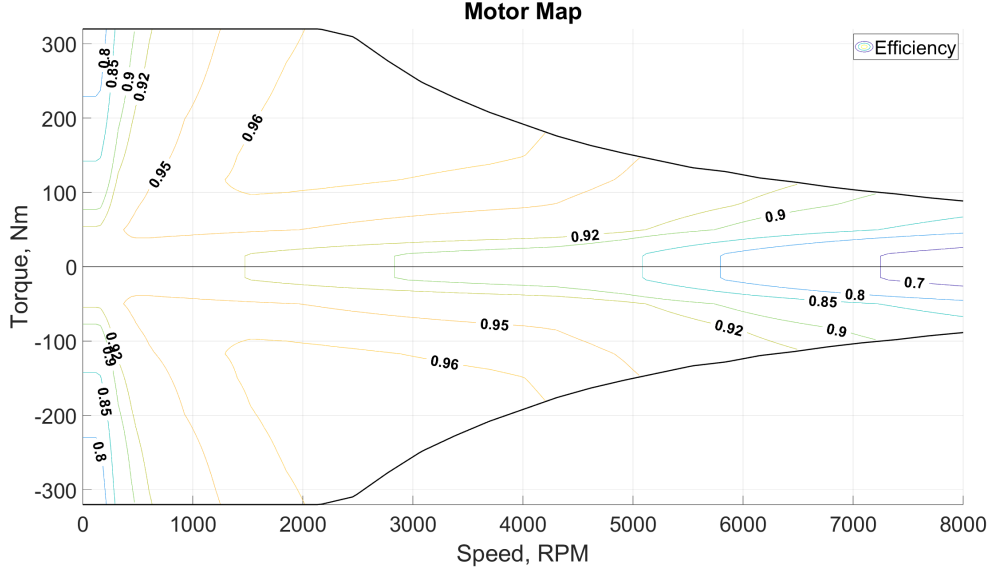

Figure 4: Motor Map

Once the motor efficiency is evaluated, the electric power that has to be provided to the eletric motor is computed as follow:

$$P_{\mathrm{mot,el}} = \begin{cases} \frac{1}{\eta_{\mathrm{mot}}} \cdot T_{\mathrm{mot}} \cdot \omega_{\mathrm{mot}} & \text{if } T_{\mathrm{mot}} \geq 0 \\ \eta_{\mathrm{mot}} \cdot T_{\mathrm{mot}} \cdot \omega_{\mathrm{mot}} & \text{if } T_{\mathrm{mot}} < 0 \end{cases} \qquad (6)$$

2.4 Engine model

The engine operating point can be determined using the characteristic engine map. This map represents engine efficiency, expressed as brake specific fuel consumption, as a function of engine speed and torque, as illustrated in Figure 5.

It is important to note that, differently from the electric motor, the speed-torque relationship of an internal combustion engine has a more complex shape, with peak torque occurring at mid-range speeds. Additionally, the highest efficiency zone, corresponding to the minimum brake specific fuel consumption, covers a much smaller area and is located at low-mid speeds under relatively high loads. Alongside the bsfc map, the Optimal Operating Line (OOL) is also plotted, indicating the operating points with the lowest bsfc for each engine speed.
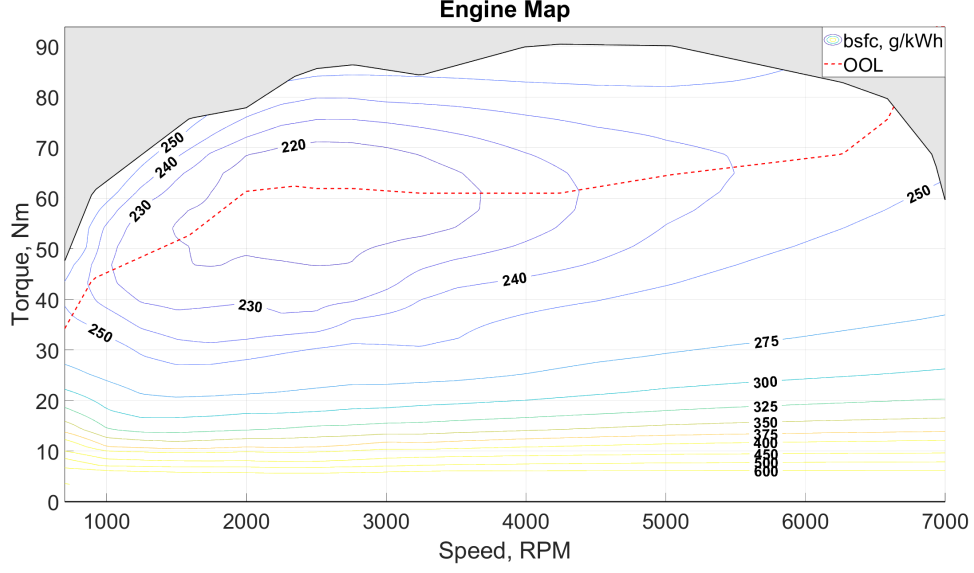
Figure 5: Engine Map

2.5 Generator model

Similarly to the electric motor, the generator map can also be plotted, exhibiting a comparable trend. The characteristic map of the electric generator used in the powertrain under study is shown in Figure 6.
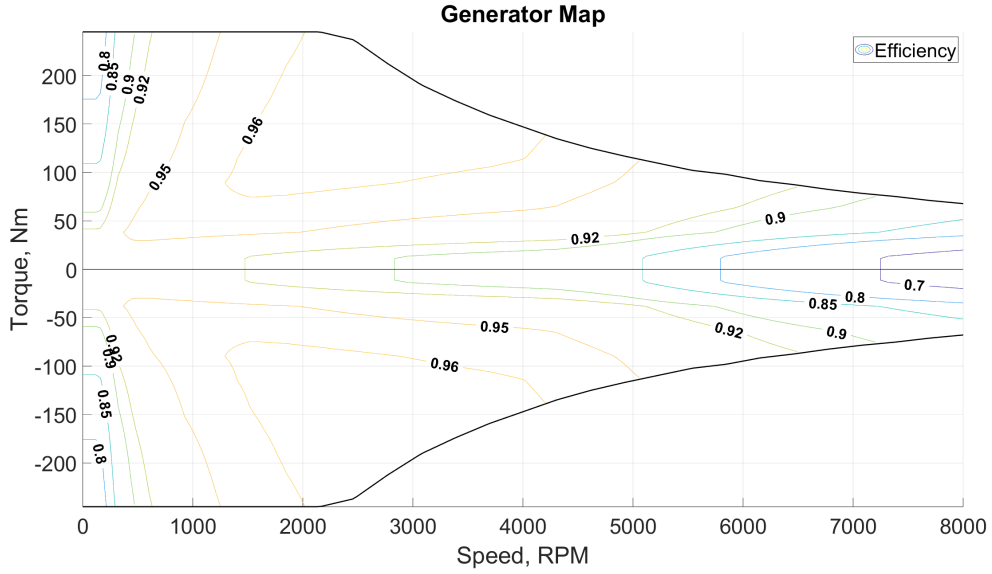

Figure 6: Generator Map

The generator map is essential for assessing the electrical power delivered to the battery when the engine is running. By determining the engine operating point, defined by its speed and torque, which serve as control variables, the electrical power generated by the generator can be calculated as follows:

$$P_{\text{gen,el}} = \eta_{\text{gen}} \cdot T_{\text{gen}} \cdot \omega_{\text{gen}} \tag{7}$$

where:

$$T_{\text{gen}} = -\frac{T_{\text{eng}}}{\tau_{\text{tc}}} \tag{8}$$

$$\omega_{\text{gen}} = \tau_{\text{tc}} \cdot \omega_{\text{eng}} \tag{9}$$

Being the engine and the generator directly connected without an intermediate gear, the transmission ratio τ_{tc} is equal to one. As a result, the absolute values of the generator's speed and torque are identical to those of the internal combustion engine, with their signs determined by the following equations:

$$T_{\text{gen}} = -T_{\text{eng}} \tag{10}$$

$$\omega_{\text{gen}} = \omega_{\text{eng}} \tag{11}$$

2.6 Battery model

As previously mentioned, the implemented control aims to regulate the battery's State of Charge (SOC), which serves as the key state variable of the drivetrain. The SOC represents the remaining battery charge and is typically expressed as a percentage. Its variation over time can be determined by analyzing the battery current evolution. Therefore, to accurately assess the battery current, a suitable battery model is required. In this control strategy, the simplest possible model is employed, consisting of a voltage source in series with a resistance that represents the internal resistance of the battery pack, as illustrated in Figure 7.
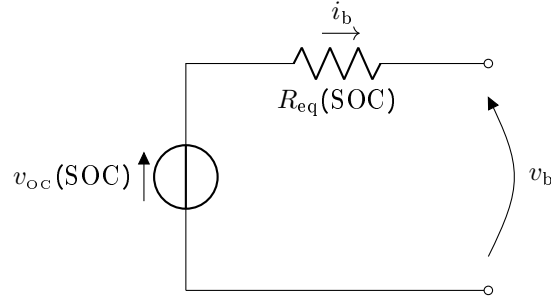

Figure 7: Battery model circuit

It is important to highlight that the open-circuit voltage (v_{OC}) and internal resistance are not fixed values but vary based on the State of Charge. Their values can be determined using dedicated lookup tables or charts. The characteristic functions representing the internal resistance and open-circuit voltage as functions of the battery's SOC in this project are shown in Figure 8 and Figure 9.
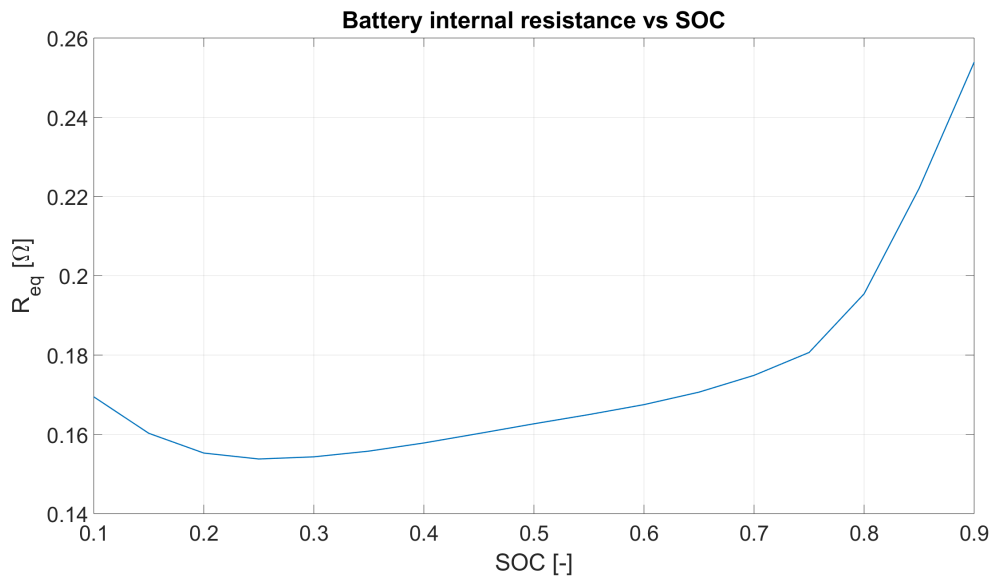

Figure 8: Battery internal resistance as function of the SOC

Once the battery circuit is defined, the battery current can be determined by applying Kirchhoff's Current Law, as expressed in the following equation:
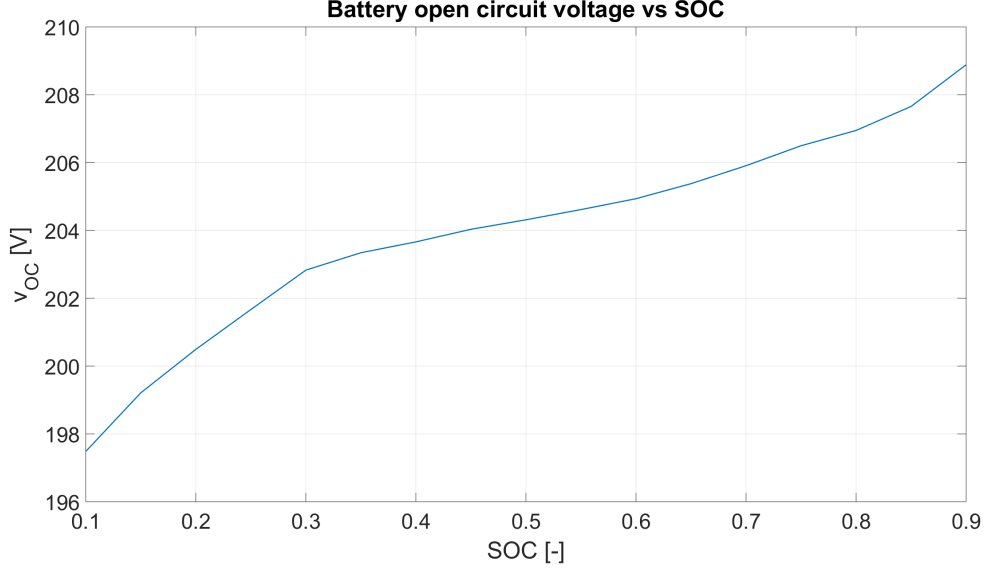
Figure 9: Battery open-circuit voltage as function of the SOC

$$v_{\mathrm{oc}} - R_{\mathrm{eq}} \cdot i_{\mathrm{b}} - v_{\mathrm{b}} = 0 \tag{12}$$

In the power domain, this can be expressed as follows:

$$R_{\mathrm{eq}} \cdot i_{\mathrm{b}}^2 - v_{\mathrm{oc}} \cdot i_{\mathrm{b}} + P_{\mathrm{b}} = 0 \tag{13}$$

From this, the expression for the battery current is derived as:

$$i_{\mathrm{b}} = \frac{v_{\mathrm{oc}} - \sqrt{v_{\mathrm{oc}}^2 - 4 \cdot R_{\mathrm{eq}} \cdot P_{\mathrm{b}}}}{2 \cdot R_{\mathrm{eq}}} \tag{14}$$

As previously mentioned, knowing the battery current, it is possible to evaluate the change in time of the battery SOC, whom dynamics is given by the following equation:

$$\dot{SOC} = \dot{\sigma} = -\frac{i_{\mathrm{b}}}{C_{\mathrm{b}}} \tag{15}$$

3 Thermostat control

Once the powertrain model has been established, the next step is to develop an energy management strategy by implementing a rule-based control approach, specifically the thermostat control. The primary objective of this control strategy is to determine the engine operating point, defined by speed and torque, at each time instant of the given vehicle cycle. The engine operating conditions are primarily determined by two key factors: the battery's State of Charge and the maximum and minimum power the battery can supply. To implement the control strategy within the controller, the following four sequential steps are followed:

1. Definition of the engine state

2. Determination of the engine power

3. Power saturation if battery limits are exceeded

4. Definition of engine speed and torque according to the determined engine power

3.1 Step 1: engine state

The first step in the thermostat control strategy is defining the engine state, which determines whether the engine is switched on or off. In this project, the engine state is managed based on the battery's State of Charge. The objective is to maintain the SOC within predefined upper and lower limits. Specifically, the engine is activated when the SOC drops below the minimum threshold to

recharge the battery, and it is deactivated when the SOC exceeds the maximum threshold. The SOC limits defined for this project are as follows:

$$SOC_{\max} = 70\ \%$$

$$SOC_{\min} = 50\ \%$$

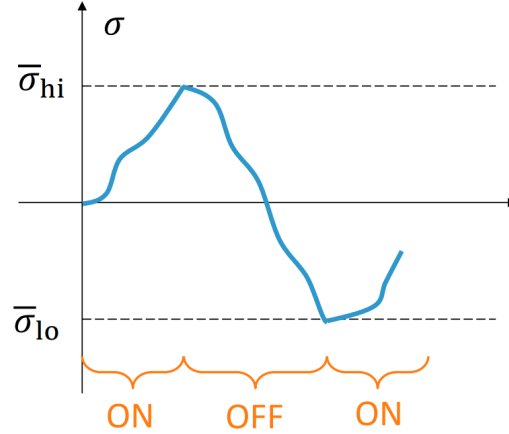A qualitative representation of the desired SOC dynamics is reported in Figure 10.

Figure 10: Qualitative representation of SOC dynamics

The MatLab code implementing the above mentioned condition is reported below.

```matlab
%% Phase 1: check if SOC is within the limits

% Definition of the SOC thresholds (max and min)
SOCmax = 0.7;
SOCmin = 0.5;

if SOC >= SOCmax
    engState = 0;        % turn off the engine if SOC exceeds the maximum
        limit
elseif SOC <= SOCmin
    engState = 1;        % turn on the engine if SOC goes below the minimum
        limit
end
```

3.2 Step 2: engine power

Once the engine state is determined, the next step is to define the engine power. In this simulation, only three distinct power levels are considered based on the operating conditions. If the engine is off, its power is naturally set to zero. When the engine is on, two possible scenarios arise. The first occurs when the required power at the wheels is relatively low, allowing the engine to operate at an optimal power level, identified in this simulation as the point where brake specific fuel consumption is minimized. The second scenario arises when the power demand at the wheels is high, making the optimal engine power insufficient to charge the battery, as the power required by the electric motor exceeds the amount provided by the engine at its optimal operating point. In this case, the engine power is set to its maximum possible value to ensure that sufficient energy is generated to recharge the battery. To summarize:

- · **Engine OFF**: engine power set to zero.

- · **Engine ON**:

    - · **Low power demand at the wheels**: engine power set to the fuel optimal operating point

    - · **High power demand at the wheels**: engine power set to the maximum engine power

The MatLab code provided below assigns the various engine power levels as previously described.

```matlab
if engState
    if  motPower <= effGen * engPowerOpt
        engPowerCmd = engPowerOpt;          % if engine is ON AND the
            optimal engine power is sufficient to charge the battery, the
            engine power is set to the optimal value
    else
        engPowerCmd = engPowerMax;          % if engine is ON BUT the
            optimal engine power is NOT sufficient to charge the battery,
            the engine power is set to the max value
    end
else
    engPowerCmd = 0;                        % if engine is OFF, required
        engine power = 0
end
```

3.3 Step 3: battery limits

After computing the engine power according to the engine state and the demand power at the wheels, a power saturation must be implemented if the battery power limits are exceeded. Indeed, the modeled battery is characterized by some constraints, either in term of power or current. Therefore, the engine power must be corrected if the battery power limits are not respected. To evaluate the amount of engine saturation, if needed, the power balance at battery DC bus must be considered. The equation espressing the power balance is reported below:

$$P_{\mathrm{b}} = P_{\mathrm{dem}} + P_{\mathrm{gen,el}} \tag{16}$$

In this project, the used convention declares that the power exting from the battery is positive, as well as the current, meanwhile the current entering in the battery is negative. Therefore, being the power of the generator a charging power, i.e. entering in the battery, the power balance equation can be rewritten as:

$$P_{\mathrm{b}} = P_{\mathrm{dem}} - \eta_{\mathrm{gen}} \cdot P_{\mathrm{eng}} \tag{17}$$

3.4 Step 4: engine speed and torque

4 Results

5 Conclusions